THE HUBBLE CONSTANT FROM THE GRAVITATIONAL LENS B1608+656¹

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ABSTRACT

We present a refined gravitational lens model of the four-image lens system B1608+656 based on new and improved observational constraints: (i) the three independent time-delays and flux-ratios from Very Large Array (VLA) observations, (ii) the radio-image positions from Very Large Baseline Array (VLBA) observations, (iii) the shape of the deconvolved Einstein Ring from optical and infrared Hubble Space Telescope (HST) images, (iv) the extinction-corrected lens-galaxy centroids and structural parameters, and (v) a stellar velocity dispersion, $\sigma_{\rm ap} = 247 \pm 35$ km s⁻¹, of the primary lens galaxy (G1), obtained from an echelle spectrum taken with the Keck–II telescope. The lens mass model consists of two elliptical mass distributions with power-law density profiles and an external shear, totaling 22 free parameters, including the density slopes which are the key parameters to determine the value of H₀ from lens time delays. This has required the development of a new lens code that is highly optimized for speed. The minimum- χ^2 model reproduces all observations very well, including the stellar velocity dispersion and the shape of the Einstein Ring. A combined gravitational-lens and stellar dynamical analysis leads to a value of the Hubble Constant of $H_0=75^{+7}_{-6}~{\rm km~s^{-1}\,Mpc^{-1}}$ (68% CL; $\Omega_{\rm m}=0.3,~\Omega_{\Lambda}=0.7$). The non-linear error analysis includes correlations between all free parameters, in particular the density slopes of G1 and G2, yielding an accurate determination of the random error on H_0 . The lens galaxy G1 is ~ 5 times more massive than the secondary lens galaxy (G2), and has a mass density slope of $\gamma'_{G1} = 2.03^{+0.14}_{-0.14} \pm 0.03$ (68%) CL) for $\rho \propto r^{-\gamma'}$, very close to isothermal ($\gamma'=2$). After extinction-correction, G1 exhibits a smooth surface brightness distribution with an $R^{1/4}$ profile and no apparent evidence for tidal disruption by interactions with G2. Given the scope of the observational constraints and the gravitational-lens models, as well as the careful corrections to the data, we believe this value of H_0 to be little affected by known systematic errors ($\lesssim 5\%$).

Subject headings: gravitational lensing — cosmology: distance scale — galaxies: elliptical and lenticular, cD — galaxies: structure — galaxies: kinematics and dynamics

1. INTRODUCTION

The physics behind gravitational lensing is well understood and primarily based on gravity, i.e., General Relativity (e.g., Schneider, Ehlers, & Falco 1992). Since Refsdal (1964) it has been known that arcsecond-scale strong gravitational lenses – those with multiply-imaged sources – provide a tool to measure the expansion rate of the Universe, i.e., the Hubble Constant (H_0), if the mass distribution of the lens(es) and the time-delay(s) between the lensed images are known. This provides an elegant one-step and global method to measure H_0 , independent of local distance-ladder techniques (e.g., Parodi et al. 2000; Saha et al. 2001; Freedman et al. 2001), which could be prone to the accumulation of unknown systematics, and seem difficult to improve beyond the current 10% precision on the value of H_0 .

More recently, CMB observations with WMAP have been combined with different cosmological data sets (i.e., Ly- α and Large Scale Structure observations) to indirectly infer a value of $H_0{=}71^{+4}_{-3}~{\rm km~s^{-1}\,Mpc^{-1}}$ (Bennett

et al. 2003; Spergel et al. 2003) similar to that from the $Hubble\ Space\ Telescope\ (HST)\ Key-Project,$ who find $H_0=72^{+8}_{-8}\ km\ s^{-1}\ Mpc^{-1}$ (Freedman et al. 2001). Because H_0 can not be measured directly from the CMB data alone, a combination with other datasets is necessary, and thus it is prone to its own systematic errors (e.g. Seljak, McDonald, & Makarov 2003; Bridle, Lahav, Ostriker, & Steinhardt 2003). Even so, the agreement between the different values of H_0 from different techniques, including those from Sunyaev-Zeldovich observations (e.g., Mason, Myers, & Readhead 2001), is striking. Since H_0 is one of the most fundamental cosmological parameters, however, its measurement should be subject to multiple cross-examinations, with the ultimate goal of breaking the 10% precision limit.

Although gravitational lensing can provide a straightforward and potentially very precise measurement of H_0 , its major problems are that it requires (i) accurately measured time-delays obtained from long monitoring campaigns and (ii) an accurate determination of the mass dis-

¹ Based on observations collected at W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California, and with the NASA/ESA Hubble Space Telescope, obtained at STScI, which is operated by AURA, under NASA contract NAS5-26555.

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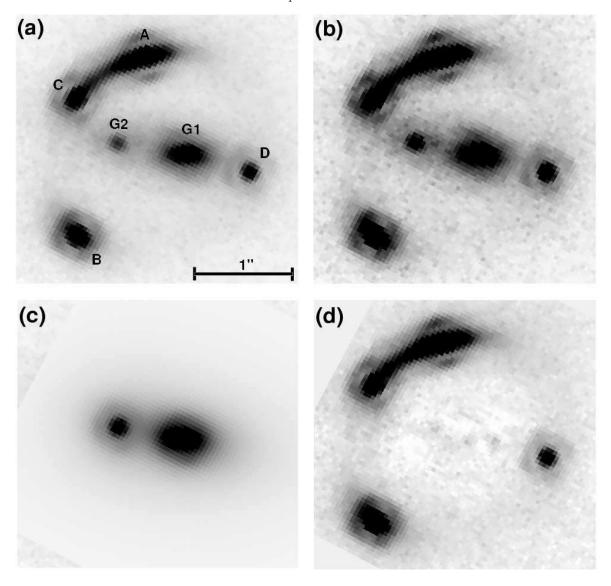


Fig. 1.— A compilation of the HST-F160W images of B1608+656: (a) The original reduced image of B1608+656. (b) The extinction-corrected image (see text). (c) The model surface brightness distributions of G1 and G2, fitted to the extinction-corrected brightness distributions. (d) The original image of B1608+656 after subtraction of the lens galaxy models extincted by the inferred dust-screen.

tribution in the lenses and the field (i.e., the "lens potential"). At present about a dozen lens systems have measured time-delays with different degrees of precision (see Courbin, Saha, & Schechter 2002, for a recent summary). This has shifted attention to understanding the often underestimated complexity of the mass distribution of the lens. For example, the first discovered gravitational lens system Q0957+561 (Walsh et al. 1979), has an exquisitely measured time-delay with an error $\lesssim 1\%$ (e.g. Kundić et al. 1997; Oscoz et al. 1997; Haarsma, Hewitt, Lehar, & Burke 1999; Colley & Schild 2000; Oscoz et al. 2001; Slavcheva-Mihova, Oknyanskij, & Mihov 2001; Goicoechea 2002; Ovaldsen, Teuber, Schild, & Stabell 2003), but a complex lens potential that includes a nearby cluster. Even though much effort has been put into constraining this particular lens system, the lens potential is still not known to adequate precision to allow a satisfactory determination of H₀ (Keeton et al. 2000, and references therein).

One of the dominant degeneracies in gravitational lens

models – even for systems that are relatively isolated and have no major external perturbers (e.g., groups or clusters) - is that between the radial mass profile and the inferred value of H₀. Often point-image constraints (i.e., positions and flux-ratios) can be satisfied equally well by mass distributions that have very different slopes of their radial mass profile (e.g., Wambsganss & Paczynski 1994; Refsdal & Surdej 1994; Witt, Mao, & Schechter 1995; Witt, Mao, & Keeton 2000; Wucknitz & Refsdal 2001; Surpi & Blandford 2001; Wucknitz 2002; Williams & Saha 2000). This is similar to the well-known mass-sheet degeneracy (Gorenstein, Shapiro, & Falco 1988). In general, steeper (shallower) mass profiles lead to higher (lower) inferred values of H₀. To break this degeneracy and reliably measure H_0 , one has to determine the mass profile of the lens galaxies. Often the most effective way is to use additional external constraints, for example from stellar kinematics of the lens galaxy (e.g., Treu & Koopmans 2002a; Koopmans & Treu 2002).

An often cited result is that of the gravitational lens system PG1115+080, which gives a value of $\rm H_0{=}44{\pm}4~km~s^{-1}\,Mpc^{-1}$ (Impey et al. 1998) for an isothermal lens mass distribution ($\rho \propto r^{-2}$). Not only is this value low compared to most other lens and non-lens measurements, but the quoted error does not include one of the major sources of uncertainty – the unknown radial mass profile. In fact, early-type galaxies can have a considerable scatter in their radial mass profiles (e.g., Gerhard et al. 2001) around the effective radius, and steeper mass density profiles can increase $\rm H_0$ well above 60 km s⁻¹ Mpc⁻¹ (Impey et al. 1998).

It was recently shown that, if one includes the observed stellar velocity dispersion (Tonry 1998) of the lens galaxy in PG1115+080 as additional constraint, the effective slope of the mass density profile can be measured directly and also properly included in the error estimate on H_0 . The effective slope of the density profile for this particular system is found to be steeper than isothermal, leading to a higher value of $H_0=59^{+12}_{-7}\pm3~{\rm km~s^{-1}\,Mpc^{-1}}$ (Treu & Koopmans 2002b). This measurement is in better agreement with most other methods and its larger error bars include the contribution of the residual uncertainty on the mass distribution of the lens. This analysis has led us to initiate a new program with Keck and the Very Large Telescope (VLT) to measure the stellar velocity dispersion of a number of additional systems with known time-delays, in order to determine a more precise value of H₀ from gravitational lensing, less affected by the radial mass profile degeneracy.

In this paper, we focus on the gravitational lens system B1608+656 (source redshift $z_s = 1.39$; lens redshift $z_l = 0.63$) (Myers et al. 1995; Snellen et al. 1995; Fassnacht et al. 1996). The system is unique in that all three time delays are known between its four lensed images (Fassnacht et al. 1999, 2002b), with accuracies of a few percent. In addition, multi-color images are available in the HST archive that show the lensed arcs of the radio-source host galaxy connecting to a full Einstein Ring (e.g., Blandford, Surpi, & Kundić 2001; Kochanek et al. 2001; Surpi & Blandford 2003). The multi-color images allow us to correct the positions and surface brightness distributions of the lens galaxies for extinction, removing a major source of systematic error common to previous modeling efforts. Finally, we have measured the stellar velocity dispersion of the dominant lens galaxy from a spectrum obtained with the Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) on the Keck-II Telescope. With this additional information and the improved constraints on the time-delays, we are well-suited to refine the lens models of this system and remove many of the major degeneracies and systematic biases in the determination of H_0 .

This paper is organized as follows. In §2 and §3 we discuss the observations and data reduction of the HST and Keck data, respectively. In §4, we describe the observational constraints obtained from VLA and VLBA radio observations¹, HST images, and the Keck spectrum. In §5, we briefly discuss a new lensing code and the χ^2 min-

imization procedure. In §6 and §7, the modeling results and inferred value of H_0 are discussed. In §8, we summarize and discuss our results. Throughout this paper, we assume $\Omega_{\rm m}=0.3$ and $\Omega_{\Lambda}=0.7.$

2. IMAGING

The main objectives of the analysis of the multi-color HST imaging are to obtain: (i) accurate extinctioncorrected images of the two main lens galaxies, from which their true centroids and structural parameters (i.e., position angle, ellipticity and effective radius) can be determined; and (ii) a deconvolved Einstein Ring after subtraction of a model of the lens galaxies. The shape of the Einstein Ring places additional constraints on the azimuthal structure of the lens model (Kochanek et al. 2001). We note that the analysis of the HST images presented here is independent of that in Surpi & Blandford (2003; hereafter SB03), but produces nearly identical color maps. Finally, we bring all astrometric data obtained from the HST images to a common "reference frame", i.e., that of the high-resolution VLBA observations. This allows us to combine the radio and optical/infrared observations in an self-consistent way, taking proper care of potential differences (i.e., offsets, rotations and scalings) between the different data sets.

2.1. Observations and data reduction

The HST images of the gravitational lens system B1608+656 are available from the HST archive. Since the primary concern here is obtaining high spatial resolution and an accurate model of the point-spread function (PSF), we select the images with the best resolution and sampling in each of the available bands (see also the discussion in SB03): 41,344s in 7 exposures with the Near Infrared Camera and Multi Object Spectrograph (NIC-MOS) Camera 1 (NIC1) through filter F160W (GO-7422; PI: Readhead); and 4 exposures on the Planetary Camera (PC) of the Wide Field and Planetary Camera 2 (WFPC2) through two filters for total exposure times of 11,500s and 11,600s in the F814W and F606W bands, respectively (HST GO-6555; PI: Schechter).

The images are first reduced using a series of IRAF² scripts based on the DRIZZLE package (Fruchter & Hook 2002). The scripts clean and combine the images, by iteratively refining the measurement of relative offsets and the identification of cosmic-rays and defects (similar to the scripts used in Koopmans & Treu 2002, Treu et al. 2003). The final F160W "drizzled" image is shown in the top left panel of Fig.1. Images of the system in the other filters are similar to the ones shown in SB03 and are not repeated here.

2.2. Dust extinction correction

The B1608+656 system is characterized by two lens galaxies, G1 and G2, with a strong color gradient in the region connecting the two galaxies. The positions of the centroids of the two galaxies with respect to the multiple images were observed to vary by as much as 86 milli-

¹ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

² IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation.

arcseconds (mas) between the F160W and F606W images (SB03; Koopmans & Fassnacht 1999; Fassnacht et al. 2002b).

To remove this source of systematic uncertainty, we assume that the observed color gradients arise from dust extinction (see SB03) and that the two lens galaxies have the same intrinsic colors. We use the available colors to measure the color excesses and correct for dust extinction based on an extinction law (see below for a discussion). To check for systematics, we perform the correction for each pair of filters, in the reference frame of each one of the filters. The results from each pair of filters are very similar and affect the results only at a very small level, which will be taken into account in the final error analysis on H₀. In the interest of space we will describe as an example only the procedure for the F814W-F160W pair in the F160W reference frame, mentioning the differences in the results for the other frames where relevant. First, we deconvolve the F814W image using a Lucy-Richardson algorithm and a PSF generated using TINY TIM (Krist 1993). Second, we align the deconvolved F814W image to the F160W image assuming that the positions of the point sources are the same in each filter and not affected by dust³, and that the transformation is a rotation and translation with arbitrary axis scaling. Third, the deconvolved and transformed F814W image is convolved with a NICMOS PSF generated by TINY TIM, to match the resolution of the F160W image. Fourth, the ratio of the matched images in the two filters is used to produce a color map, which is found to be very similar to the one shown in SB03. Fifth, it is assumed that the intrinsic colors of G1 and G2 are spatially uniform and equal to the minimum of the color measured in the region including G1 and G2 (see also Surpi & Blandford 2003). Finally, the color excess is converted into extinction in the individual filters using the following relations computed using the Galactic extinction law by Cardelli et al. (1989) for $R_V = 3.1$: A(F160W)/A_V=0.415, A(F814W)/A_V=1.091, $A(F606W)/A_V=1.561$. The extinction-corrected image⁴ in F160W is shown in the top right panel of Fig. 1.

This procedure is repeated for each pair of filters, in the reference frame of each filter. We emphasize that this procedure does not assume a particular smooth surface brightness profile for the lens galaxies, nor does it force the centroids of the lenses to coincide in the different filters. However, the production of a smooth extinctioncorrected surface brightness distribution for the lens galaxies strongly suggests, although does not guarantee, that the extinction correction has been done properly. Similarly, the consistency of the astrometry between various filters provides an additional test of the uncertainties related to the assumption of a specific dust extinction law, the assumption of coincident centroids of the lensed images, and the PSF modeling used for convolution and deconvolution purposes. These tests are discussed in the next two sub-sections, together with surface photometry and astrometry measurements.

2.3. Surface photometry

Surface photometry is performed on the extinctioncorrected F814W and F160W images, as described in Treu et al. (1999, 2001). The F606W image is not used for this task, given that it has the largest dust extinction and the lowest signal-to-noise ratio (SNR), especially on G2. The galaxies are modeled as two $R^{1/4}$ profiles - which has been shown to be a good description of the extinction-corrected surface brightness profile of G1 (Blandford, Surpi, & Kundić 2001) – that are fit simultaneously to obtain effective radii (R_e) and total magnitudes (Table 1). Only the region well inside the Einstein Ring is used in the fit, to minimize contamination by the extended ring structure. Very similar photometric parameters are obtained in the two filters, demonstrating that uncertainties in the alignment of the images and in the PSF modeling do not affect significantly the derived surface photometry. The best fitting model in filter F160W is shown in the lower left panel of Fig. 1.

To inspect the residuals from the fit, we apply the dust extinction map to the best fitting $R^{1/4}$ model and subtract the reddened model from the original image. The brightness contribution of the galaxies at the ring radius is found to be negligible. The residual image is shown in the lower right panel of Fig.1, demonstrating that indeed the data are consistent with two relatively smooth spheroids, reddened by a dust lane (Surpi & Blandford 2003) without strong evidence that the primary lens galaxy G1 is much affected by tidal interactions with G2. The ring structure is very clear in the residual image (e.g., Kochanek et al. 2001; Surpi & Blandford 2003), and is even more prominent in the deconvolved residual image (Fig.5).

	G1	G2
F160W (mag)	16.41 ± 0.08	18.18 ± 0.05
F814W (mag)	18.23 ± 0.12	19.99 ± 0.10
$R_{e,F160W}$ (arcsec)	$0.62 {\pm} 0.05$	0.27 ± 0.03
$R_{e,F814W}$ (arcsec)	$0.58 {\pm} 0.06$	0.26 ± 0.04
b/a = (1 - e)	$0.5 {\pm} 0.1$	$\equiv 1$
Major axis P.A.(°)	79 ± 2	N/A

Table 1 — Observed photometric quantities of the lens galaxies G1 and G2. All magnitudes are in the Vega system. The systematic uncertainty on the NICMOS zero point (see the NICMOS instrument handbook; Mobasher 2002) is not included. Magnitudes are the total magnitudes obtained from fitting the galaxy surface-brightness profiles with an $R^{1/4}$ law. Magnitudes have been corrected for internal extinction, as discussed in the text, but are not corrected for Galactic extinction. The axial ratio of G2 is set to unity during the fit.

2.4. Astrometry

The extinction-corrected images are used to measure the locations (in pixels) of the centroids of G1 and G2, using the task IMCENTROID in IRAF. The deconvolved residual images are used to measure the centroids of the multiple images of the lensed source, as well as the shape of the ring (see §4.2 and right panels in Fig.5).

Since we perform all measurements from the HST images in their original pixel frames, we need to align the optical and infrared frames to the much more accurate

³ Since the centroids of the lensed images are very sharp, they change very little due to extinction (see also §2.4).

⁴ Note that this correction is only made to the lens galaxies and not to the Einstein Ring.

VLBA radio frame. We determine the transformation (i.e., rotation, translation and scaling) that minimizes the positional differences between the lensed image centroids measured from the HST images, and their radio counterparts, weighting properly by the measurement errors. We allow for different pixel scales in the x/y directions on the NIC1 and PC chips. We find pixel scales of 0'.0457/0'.0456 for the PC and 0'.0434/0'.0431 for NIC1, in excellent agreement with the values in the HST instrument handbook (Mobasher 2002).

The positional differences between the optical/infrared and radio image positions are $\lesssim 10$ mas in RA and DEC for each of the individual lensed images. Since the transformation is determined from the full set of four images, we estimate an error of ~ 4 mas in x and y on the transformation between the radio and NICMOS frames. Using this transformation, we map the trace of the brightness peak of the Einstein Ring to the radio frame (see §4.2). Since the transformation errors are negligible compared with the positional determination of the brightness peak along spokes, one can assume for all practical purposes that the radio data and the Einstein Rings are perfectly aligned.

We use the same transformation to bring the galaxy centroids in F160W to the radio frame. The combined centroid errors and transformation errors quadratically add to an error of 6 mas in x and y. We adopt this value as the centroiding errors of the galaxies with respect to the lensed radio images. The measurement errors on the radio positions are negligible ($\ll 1$ mas; Koopmans & Fassnacht 1999). We repeat the same procedure for the F814W image.

After transformation to the radio frame, the positions of the lens galaxies G1 and G2 agree to within 14 mas and 20 mas between the F160W and F814W filters, respectively, as opposed to 72 mas and 38 mas in the uncorrected frame. Slightly larger differences are found using the F606W filter, as expected because this is the filter where uncertainties in the dust corrections are the most severe⁵. All astrometric measurements from the F160W and F814W filters are listed in Table 2. The deconvolved Einstein Rings in the F160W and F814W filters are shown in the left panels of Fig.5.

3. Spectroscopy

In this section we describe the spectroscopic observations of B1608+656 with ESI. The main objective of the observations was to obtain the stellar velocity dispersion of the primary lens galaxy (G1), the measurement of which allows us to determine the power-law slope of its radial mass profile and break the degeneracy with the inferred value of the Hubble Constant. Special care is required in order to determine an unbiased stellar velocity dispersion and a correct uncertainty, since G1 is a post-starburst galaxy. This is accomplished through extensive Monte Carlo simulations of artificial spectra with different fractions of "old" and "young" stellar populations.

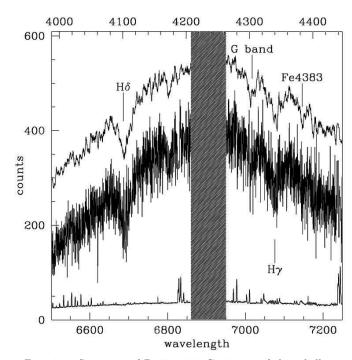


Fig. 2.— Spectrum of B1608+656–G1 in one of the echelle orders around the G–band (in counts, not flux calibrated). The lower histogram shows the noise per pixel. A boxcar smoothed version of the spectrum is shown above the original spectrum to guide the eye. The wavelength range used for the kinematic fit was 6750–7200Å (observed), which includes the G-band, H γ , and Fe4384 features, but excludes H δ . The atmospheric B-band (hatched band) and H γ were masked out in the kinematic fit.

3.1. Observations and data reduction

We observed B1608+656 using ESI (Sheinis et al. 2002) on the Keck-II Telescope on 2000 July 3, for a total integration time of 5400s (3x1800s). The seeing was good with FWHM ≈ 0.85 and the night was clear. Between each exposure, we dithered along the slit to allow for a better removal of sky residuals at the red end of the spectrum. The slit (20'' in length) was positioned at PA= 83° , i.e., aligned to within 4 degrees of the major axis of G1. The slit-width of 0.75 yields an instrumental resolution of $\sigma \sim 20 \,\mathrm{km \ s^{-1}}$ which is adequate for measuring the stellar velocity dispersion and removing narrow sky emission lines. The centering of the galaxy in the slit was constantly monitored by means of the ESI viewing camera the galaxy was bright enough to be visible in exposures of a few seconds duration – and we estimate the centering perpendicular to the slit to be accurate to better than 0.1.

Data reduction was performed using the IRAF package EASI2D⁶ as discussed in Koopmans & Treu (2002) and Sand et al. (2002,3). A one dimensional spectrum was extracted (Fig. 2) by summing the signal within an aperture corresponding to 1".7 × 0".75. The SNR of the spectrum in the vicinity of the G-band (\sim 4304Å) is 20Å⁻¹. Note the very prominent Balmer absorption features H γ and H δ , typical of a K+A post starburst population (Dressler & Gunn 1983; Myers et al. 1995; Surpi & Blandford 2003).

⁵ The maximum difference in the centroid coordinates between F606W and F160W is now 21 mas, with an rms scatter of 14 mas, as opposed to 86 and 45 mas respectively in the uncorrected images of SB03.

 $^{^6}$ developed by D. Sand and T. Treu; Sand et al. (2003), in prep.

	VLBA/	['] 8.4–GHz	HST/I	F814W	HST/I	F160W
Image	$\Delta x (")$	$\Delta y (")$	$\Delta x (")$	$\Delta y (")$	$\Delta x (")$	$\Delta y (")$
A	≡0.0000	≡0.0000	-0.0003	+0.0009	-0.0029	+0.0042
В	-0.7380	-1.9612	-0.7376	-1.9588	-0.7342	-1.9498
$^{\mathrm{C}}$	-0.7446	-0.4537	-0.7455	-0.4528	-0.7469	-0.4446
D	+1.1284	-1.2565	+1.1298	-1.2563	+1.1365	-1.2546
G1	N/A	N/A	+0.4124	-1.0592	+0.4261	-1.0581
G2	N/A	N/A	-0.3091	-0.9306	-0.2897	-0.9243

Table 2
Astrometry of the B1608+656 system

3.2. The Stellar velocity dispersion of G1

The luminosity weighted velocity dispersion $\sigma_{\rm ap}$ of G1 was measured with the Gauss-Hermite Pixel-Fitting Software (van der Marel 1994) on the spectral region covering the observed wavelength $\sim 6750-7200$ (Fig. 2) excluding $H\delta$ and including the G-band, $H\gamma$, and Fe4383 (Trager et al. 1998). As kinematic templates we used spectra of G-K giants observed at twilight with a 0.43 slit width, appropriately smoothed to match the instrumental resolution of the 0".75 slit. The regions around 6870 Å, affected by atmospheric absorption, and the H γ feature were masked during the fit. The result is robust with respect to changes in the spectral region used in the fit, the fit parameters (e.g., the order of polynomial used to reproduce the continuum level), and the adopted template. The best fit gives: $\sigma_{ap} = 247 \pm 35 \text{ km s}^{-1}$ in an aperture of 1".7×0".75 centered on G1.

To minimize the amount of corrections to the data, we will only use this measurement of the luminosity weighted velocity dispersion (as opposed to the central velocity dispersion, defined in a standard aperture) in the kinematic analysis (§4), properly taking the seeing and aperture effects into account by applying those corrections to the models. However, to facilitate comparison with earlier work and other applications of this measurement, we also give the central velocity dispersion⁷, $\sigma = 269 \pm 40 \text{ km s}^{-1}$, within a standard circular aperture of radius $R_{\rm e}/8$.

We note here that if one adopts the measured central velocity dispersion and the structural parameters measured from the extinction corrected images (Table 1), to determine the offset of G1 from the local Fundamental Plane, one finds the galaxy to be significantly brighter than quiescent early-type of the same mass and at similar redshifts. This is consistent with what is typically found for K+A galaxies (e.g., van Dokkum & Stanford 2003). In contrast, this result differs from the findings of Rusin et al. (2003a), who estimated a larger velocity dispersion from the image separation and measured a lower luminosity for G1, resulting in an offset from the local Fundamental Plane consistent with quiescent evolution.

The rest of this section describes Monte Carlo simulations aimed at ensuring that our measurement provides not only an unbiased value of the stellar velocity dispersion of G1, but also a realistic estimate of the uncertainty.

In fact, although the SNR and resolution are more than adequate to measure the velocity dispersion of a uniformly old stellar population (e.g., Treu et al. 2001), the spectrum of G1 is more challenging, because of the contamination by young stars. Our Monte Carlo approach works as follows. First, we model the spectrum as a combination of a G8III star, to represent the old population, and of an A5V star, to represent the young population (Dressler & Gunn 1983; Franx 1993). The stellar spectra are smoothed to a velocity dispersion of 250 km s⁻¹, taking into account the initial spectral resolution of the stellar spectra⁸, and then combined with variable weights. Second, for each set of weights (hereafter "old" fraction and "young" fraction) 1,000 realizations are constructed, adding noise to reproduce the SNR of our data. Third, we run the Gauss-Hermite Pixel-Fitting Software (van der Marel 1994) on each realization to simulate the stellar velocity dispersion measurement.

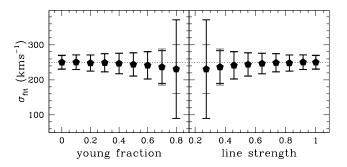


Fig. 3.— Monte Carlo simulations of the stellar velocity dispersion recovery from artificial spectral of B1608+656-G1. The dotted horizontal line shows the input value, the pentagons shows the average value measured from 1,000 realizations. The heavy error bars show the average uncertainty estimated by the code, while the light error bars show the r.m.s. scatter of the recovered values

The results of the Monte Carlo simulations are shown in Fig. 3. In the left panel we plot the average and r.m.s. scatter (solid pentagons with thin error bars) of the recovered velocity dispersion $\sigma_{\rm fit}$ as a function of the fraction of A5 V light (young fraction). For young fractions up to ~ 0.6 , the procedure recovers the input velocity dispersion to within 4%. Only for a young fraction larger than 0.7 does the procedure become biased. This happens because, as the young fraction increases, the information content

⁷ The correction from luminosity weighted velocity dispersion to central velocity dispersion is computed based on the range of observed velocity dispersion profiles of local E/S0 galaxies, and taking into account seeing effects as described in Treu et al. (2001).

⁸ The G8III star is from the ESI data, the A5 V is taken from the library of Jacoby, Hunter & Christen 1984; see Treu et al. 2001 for a discussion of the resolution of that library.

from the metal absorption features gets washed away by the contribution of the young population. Similarly, for young fractions less than 0.6, the r.m.s. scatter (thin error bars) agrees remarkably well with the average uncertainty returned by the code (thick error bars). We can estimate the fraction of young stars in the spectrum of G1 by comparing the observed depth of the G-band and of $H\gamma$ with those in the model spectra. In Fig. 4 we show that a composite spectrum with $\sim 40\%$ of young population matches the observed spectrum, while fractions $\sim 70\%$ and higher produce much deeper $H\gamma$ absorption lines than observed. We therefore conclude that the fraction of young stellar light in G1 must be smaller than $\sim 70\%$ and that the value of σ_{ap} is the correct and unbiased measurement of the stellar velocity dispersion of G1. Similarly the error estimate is unbiased.

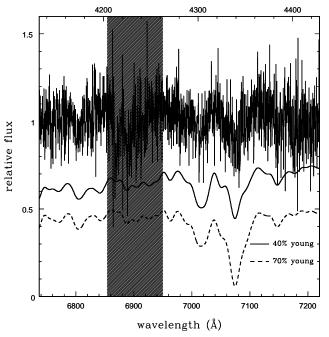


Fig. 4.— A fit of $\sigma_{\rm ap}$ for G1 in B1608+656 for two different fractions of the young stellar population (shifted for clarity). A young fraction of 70% clearly overpredicts the depth of the H γ feature.

A more quantitative confirmation of this result comes from the inspection of the line strength, which is used by the Gauss-Hermite Pixel-Fitting Software (see definition in van der Marel 1994) to measure the depth of the absorption features: the larger the line strength, the deeper the absorption features. In the models, by construction, the line strength of the old stellar population anticorrelates very well with the young fraction. In fact a very similar conclusion is drawn if line strength is used as independent variable to show the result of the Monte Carlo simulations (right panel of Fig. 3). When the line strength of the old stellar population is larger than 0.4 (corresponding approximately to a young fraction smaller than 0.7) the signal to noise ratio and resolution of our spectrum are sufficient to obtain an unbiased measurement of the stellar velocity dispersion. For a real composite population the interpretation of this parameter is more complex, since it depends on the chemical abundances and possible additional contributions to the continuum. Nevertheless, it provides a useful quantitative measure of the depth of the metal absorption features. which is the main parameter that controls the accuracy of the fit. The best fitting template yields line strength 0.5 ± 0.05 , also confirming that the measurement of velocity dispersion is unbiased.

4. MASS MODEL AND OBSERVATIONAL CONSTRAINTS

We model the lensing and kinematic properties of both lens galaxies, G1 and G2, assuming that their luminous plus dark-matter mass distributions are elliptical (i.e., oblate in three dimensions⁹) and have a radial power-law dependence, (i.e., $\rho \propto r^{-\gamma'}$). In particular, we assume for the lens models a dimensionless surface mass density of

$$\kappa(x,y) = b\left[x^2 + (y/q_\ell)^2\right]^{(1-\gamma')/2},$$
 (1)

where q_{ℓ} is the axial ratio of the surface mass distribution and γ' the slope of the corresponding density distribution ($\gamma'=2$ is designated as "isothermal" henceforth). The mass distribution has its centroid at (x_{ℓ},y_{ℓ}) and a majoraxis position angle of θ_{ℓ} (measured north through east). In addition, we allow for a single external shear for the system with strength $\gamma_{\rm ext}$ and position angle $\theta_{\rm ext}$.

We choose to use power-law mass models, since they have been successful in reproducing many of the detailed lensing observations (e.g., Kochanek 1995; Cohn, Kochanek, McLeod, & Keeton 2001; Muñoz, Kochanek, & Keeton 2001; Rusin et al. 2002; Winn, Rusin, & Kochanek 2003) and more recently also kinematic observations (e.g., Treu & Koopmans 2002a; Koopmans & Treu 2003) of lens systems and lens ensembles (e.g., Rusin et al. 2003a), even though we acknowledge that this choice might not be unique. We feel at this point, however, that there is no strong incentive to go beyond these models. From a practical standpoint, including the constraints from the Einstein Ring becomes computationally very expensive for more complex lens models (see §5 for a discussion).

For the dynamical modeling (i.e., determining the stellar velocity dispersion), we solve the spherical Jeans equations, assuming a spherical mass distribution with the same power-law index γ' as used for the lens models (i.e., Eq.(1)). We model the luminous mass distribution as a trace population - embedded in the luminous plus darkmatter potential - with a Hernquist luminosity-density profile (Hernquist 1990). We have also examined Jaffe (1983) models and find differences typically $\lesssim 1\%$ for the models that we explore. Henceforth, we only use the Hernquist profile, which closely follows a $R^{1/4}$ brightness profile over the radial range of interest and is analytically tractable. Since the break radius of the dark-matter halo is well beyond the Einstein radius, we assume it to be much larger than the latter, with negligible effects on the calculation of kinematic quantities (see Treu & Koopmans 2002a; Koopmans & Treu 2003, for a full discussion). Finally, we allow for anisotropy of the stellar velocity ellipsoid, modeling the radial anisotropy parameter β (Binney & Tremaine 1987) with a Osipkov-Merritt (Osipkov 1979; Merritt 1985a,b) model with anisotropy radius r_i . For $r_i = \infty$, the stellar velocity dispersion is fully isotropic. We also take the seeing and aperture into account. We

⁹ Some early-type galaxies show evidence for iso-surface-density twists that could be due to triaxial mass distributions.

refer to Koopmans & Treu (2003) for a further discussion of our kinematic model.

We now continue with a more detailed description of the precise set of constraints that we use in the lensing and kinematic models that are presented in §6.

4.1. The Radio and Optical Image Constraints

The positions of the four lensed radio images can most accurately been determined from high-resolution radio observations. We use the VLBA positions listed in Koopmans & Fassnacht (1999), which are consistent with VLA observations to within ~ 1 mas (Fassnacht et al. 2002b). We choose positional errors on the VLBA image positions of 1 mas, which are considerably larger than the formal measurement errors (tens of micro-arcseconds). This error is approximately that by which the most massive mass substructures in the lens (expected to be on the order of $\sim 10^9 \ {\rm M}_{\odot}$) could potentially change the image positions. Since mass substructures are "randomly" distributed such positional shifts can practically be regarded as random errors.

Radio flux ratios might not be reliable constraints on macro lens models; either because of mass substructure (e.g. Mao & Schneider 1998; Metcalf & Madau 2001; Keeton 2001; Chiba 2002; Metcalf & Zhao 2002; Dalal & Kochanek 2002; Bradač et al. 2002; Keeton et al. 2003; Bradač et al. 2003), radio microlensing (e.g., Koopmans & de Bruyn 2000; Schechter & Wambsganss 2002) or interstellar-medium (ISM) propagation effects (Koopmans et al. 2003). Hence, we conservatively adopt a large error of 20% on the individual radio fluxes (i.e., \sim 28% on the flux ratios). This is supported by the fact that the formal errors on the flux ratios within a single season are much smaller than the differences between seasons (Fassnacht et al. 2002b). For the flux ratios we adopt the approximate median value from three independent monitoring seasons of B1608+656 (Fassnacht et al. 2002b). Since previous models had difficulties reproducing the flux ratio of image D (Koopmans & Fassnacht 1999; Fassnacht et al. 2002b), it is not used as a constraint. Hence, if the refined lens models can recover the flux of image D, we would have additional confidence in the lens models.

Finally, we use the time delays between the VLA images as constraints (Fassnacht et al. 1999, 2002b). Time-delay ratios are particularly strong constraints on the mass profile, since they are almost a direct measure of the depth of the potential at the lensed-image positions. Since there are three independent time delays and one Hubble Constant to solve for, they add two constraints on the mass model (we emphasize here that time delays are affected by substructure only at a negligible level, $\ll 1\%$). All point-image constraints are listed in Table 3.

4.2. The Einstein-Ring Constraints

The F160W image of B1608+656 exhibits a fully-connected Einstein Ring around the two lens galaxies (Kochanek et al. 2001; Surpi & Blandford 2003). The structure of Einstein Rings can be used as additional constraint on the gravitational lens models (Blandford, Surpi, & Kundić 2001; Kochanek et al. 2001). In particular, the unit vector along a radial spoke at the position of the brightness peak (on the spoke), when projected on the

source plane, is perpendicular to the gradient of the surface brightness distribution of the unlensed source (Kochanek et al. 2001). When the isophotes of the source are assumed to be elliptical – often a reasonable assumption – the trace of brightness peaks (along radial spokes) places extra constraints on the lens potential at the minimal cost of adding four additional free parameters (ring-source position, ellipticity and position angle). Moreover, for an elliptical source, the trace of the ring is independent of assumptions on the radial behavior of the surface brightness distribution of the source.

Even though the SNR decreases with increasing distance from the central nucleus of the lensed source along the ring, it is still sufficient to fully trace the ring (see Fig.1 and Kochanek et al. 2001). This can be done even more accurately on the deconvolved image, where the Einstein Ring is "sharper" in the radial direction (Fig.5). We note that color gradients over the image have very little effect on the brightness peaks of the sharp ring (see also Kochanek et al. 2001). To trace the deconvolved Einstein Ring, we define 90 independent spokes, separated by 4 degrees in angle (consistent with the improved image resolution after deconvolution), radiating from a point roughly in the middle of the ring. The origin of the spokes is arbitrary. The brightness distribution of the deconvolved ring along each spoke is subsequently fitted with a Gaussian. From this fit, the position of the brightness peak and the FWHM of the ring are obtained. The resulting fitted ring is shown in Fig.5. To ensure that the ring is not significantly affected by uncertainties produced by the deconvolution, we repeat the same procedure for the F814W image. We assume that the error on the ring peak is proportional to the ring width, since it is hard to estimate an error from a deconvolved image. We adopt $0.42 \times \sigma_r$ as error for F160W (with σ_r =FWHM/2.35 from the Gaussian fit), which gives $\chi^2/\text{DOF}\sim 1$, only weakly dependent on the particular lens model. This particular choice is not crucial, however, and somewhat higher or lower scale factors can be chosen without affecting the modeling results. Hence, we put more weight on those parts of the ring that are sharpest (near the radio images) and less weight on the less well-defined parts of the ring. Notice the remarkable agreement between the traces of the ring in F160W and F814W (Fig.5), lending credit to the trace (compare also to Kochanek et al. 2001, who find a very similar trace from the original, not deconvolved, ring).

4.3. Constraints from the Lens Galaxies

As for the Einstein Ring, we use the transformation discussed in §2.4 to bring the positions of the two lens galaxies in the F160W and F814W images to that of the VLBA frame with positional errors of 6 mas with respect to the radio images (Table 3). The good agreement of the galaxy centroids from different filters – after extinction correction – seem to indicate that the extinction corrections applied to the F160W image have been done properly. Confidence in the extinction correction is further supported by the fact that, after correction, G1 is well described by a $R^{1/4}$ brightness profile (see also Blandford et al. 2001). It seems highly unlikely that an improper extinction correction would produce a well-behaved smooth surface brightness distribution from an originally patchy image. In the

			TABLE	3			
Galaxy	CENTROID	POSITIONS AN	ND POINT-IMAGE	CONSTRAINTS	ON THE	B1608+656	SYSTEM
	$\text{Image}^{a,b,c}$	Δx ("	Δy	· (")	$S_{ m norm}$	$\Delta t \text{ (days)}$	

Image	a,b,c	$\Delta x ('')$	$\Delta y (")$	$S_{ m norm}$	$\Delta t \text{ (days)}$
A	≡0.0	000 ± 0.001	$\equiv 0.0000 \pm 0.001$	2.020 ± 0.404	31.5 ± 1.5
В	-0.7	380 ± 0.001	-1.9612 ± 0.001	1.000 ± 0.200	$\equiv 0.0$
$^{\mathrm{C}}$	-0.7	446 ± 0.001	-0.4537 ± 0.001	$1.034 {\pm} 0.207$	36.0 ± 1.5
D	+1.1	284 ± 0.001	-1.2565 ± 0.001	$0.347\pm\infty$	77.0 ± 1.5
G1	+0.4	261 ± 0.006	-1.0581 ± 0.006	N/A	N/A
G2	-0.2	897 ± 0.006	-0.9243 ± 0.006	N/A	N/A

 a The positions for components A-D are from Koopmans & Fassnacht (1999). b The time delays and flux ratios are from Fassnacht et al. (2002b). c The G1 and G2 positions are from this paper.

lens models, we therefore adopt the light centroids from the extinction-corrected F160W images, transformed to the radio frame, as the final values for the mass centers of G1 and G2.

In addition, modeling of the extinction-corrected brightness distribution gives a position angle of $(79\pm2)^{\circ}$ (north to east) of G1. Since the extinction-corrected galaxies appear relatively smooth and unperturbed it is safe to assume that G1 is most likely not much affected by tidal interactions with G2. The position angle of G1 is used as a prior on the position angle of its mass distribution.

As a final model constraint, we use the stellar velocity dispersion of G1, $\sigma_{\rm ap}=247\pm35~{\rm km~s^{-1}}$ (§3,2), which provides information on the slope of its radial mass profile.

5. Lensing code and χ^2 minimization

To model the B1608+656 system, we have developed a new lens code, highly optimized for speed and accuracy. This is necessary because most of the models require χ^2 -minimization in a 22-dimensional parameter space (see §6.1 for a listing of all free model parameters). Since the structure of the Einstein Ring is included as a constraint, each iteration (i.e., χ^2 calculation) is computationally expensive, especially if there are no analytic solutions for the lens potential. Furthermore, a full non-linear error analysis of the parameters of the lens model requires a repetitive minimization of the χ^2 function for different sets of fixed lens parameters.

To maximize speed, the code is first optimized in its use of memory, which can be critical when copying large data structures (i.e., those containing all constraints and intermediate results). Second, analytic solutions are used wherever possible, as well as publicly-available fast algorithms developed for specific power-law mass models (e.g., Barkana 1998; Chae, Khersonsky, & Turnshek 1998; Chae 2002). A significant speed-up of the χ^2 minimization and error analysis is gained by using the MINUIT minimization package from CERN (James 1998), which has been optimized for finding function minima in large-dimensional parameter spaces with a minimum number of function evaluations. We have compared the results from the new code, for B1608+656 and various simple test systems, with those from a previously used code (e.g., Koopmans & Fassnacht

1999) and from the publicly-available code from Keeton (2001). We find that they all agree to within the expected numerical errors.

The increase in speed of the new code over the other codes, when we include the Einstein Ring data for B1608+656, can be several orders of magnitude, depending on the specific situation. For example, χ^2- minimization with 22 free parameters usually takes minutes, compared to hours for the code by Keeton (2001), when we use mass models that are not analytically tractable (e.g., non-isothermal power-law density profiles). A full non-linear error analysis for all parameters – a built-in option with MINUIT – takes several hours with the new code, but only several minutes extra for a single parameter (e.g., H_0). A similar analysis with the code by Keeton (2001) is expected to take several days and is clearly not feasible for systems of this complexity.

free model parameters using only the radio data as constraints. This rapidly leads to a model that fits all the radio constraints extremely well. In the second step, the Einstein Ring data are added to the constraints. Since the mass model parameters are already relatively close to the best solution, it takes only several minutes to converge to the χ^2 minimum. To check that indeed the correct global χ^2 minimum has been found, the models are started from different initial conditions and also using different minimization techniques (i.e., simulated annealing and downhill simplex methods). Monte Carlo minimization is done once a χ^2 minimum is reached. Finally, the minimum in all parameter-space directions is traced while performing a non-linear error analysis 10. None of this has led us to suspect that the global χ^2 minimum has not been found. This is also supported by the fact that the observed lens properties are reproduced well by the lens models.

6. RESULTS

In this section, we describe the results from the lens models. After listing the free parameters and adopted priors of the general model in $\S6.1$, we consider in $\S6.2$ a simplified problem in which the slopes of the galaxies are

¹⁰ The non-linear error analysis consists of re-minimizing χ^2 for a range of fixed values for the parameter of interest (James 1994). The 68% confidence limits, quoted in this paper, correspond to the parameter range with $\Delta \chi^2 = 1$ w.r.t. the minimum- χ^2 solution.

	SIE	SPLE1	SPLE2	SPLE1+D	SPLE1+D	SPLE2+D	SPLE2+D
				(iso)	(aniso)	(iso)	(aniso)
$x_{\ell} \text{ (arcsec)}$	0.425	0.426	0.425	0.425	0.425	0.425	0.426
	-0.291	-0.290	-0.290	-0.291	-0.290	-0.291	-0.290
$y_{\ell} \text{ (arcsec)}$	-1.071	-1.069	-1.069	-1.069	-1.069	-1.069	-1.069
	-0.929	-0.928	-0.928	-0.928	-0.928	-0.928	-0.928
$b (\operatorname{arcsec}^{\gamma'-1})$	0.531	0.553	0.553	0.526	0.555	0.531	0.553
	0.288	0.263	0.263	0.269	0.263	0.268	0.263
q_ℓ	0.606	0.607	0.606	0.604	0.603	0.605	0.606
	0.340	0.308	0.308	0.318	0.307	0.316	0.308
$ heta_\ell$ (°)	76.8	77.0	77.0	77.0	77.0	77.0	77.0
. ,	69.2	68.5	68.5	68.4	68.4	68.4	68.5
γ'	$\equiv 2.00$	$1.99^{+0.20}_{-0.20}$	$1.99^{+0.14}_{-0.15}$	$2.05^{+0.14}_{-0.13}$	$2.00^{+0.14}_{-0.15}$	$2.04^{+0.11}_{-0.12}$	$2.00^{+0.12}_{-0.12}$
	$\equiv 2.00$	2.12	2.12	2.12	2.12	2.12	2.12
$\gamma_{\rm ext}$	0.085	0.081	0.081	0.077	0.081	0.078	0.081
θ_{ext} (°)	6.8	10.6	10.6	13.4	10.4	12.9	10.6
x_s (arcsec)	0.095	0.103	0.102	0.088	0.102	0.090	0.102
y_s (arcsec)	-1.070	-1.070	-1.070	-1.069	-1.070	-1.069	-1.070
q_h	0.639	0.640	0.640	0.634	0.640	0.635	0.640
θ_h (°)	113.2	113.0	113.0	112.1	113.1	112.3	113.0
$H_0 (km/s/Mpc)$	71^{+5}_{-6}	74^{+10}_{-11}	74^{+7}_{-6}	76^{+7}_{-6}	74^{+7}_{-6}	75^{+6}_{-5}	74^{+6}_{-5}
χ^2	99.8	98.0	98.0	98.1	98.0	98.1	98.0

 $\begin{tabular}{ll} Table 4 \\ Lens mass model parameters for B1608+656. \end{tabular}$

Note: The first (second) line for each parameter denotes values for G1 (G2). The 68% confidence limits on H₀ and γ'_{G1} have been determined from a full non-linear error analysis, where all free parameters are varied for a range of fixed values of these parameters until χ^2 increases by unity. We limit ourself to these two most important parameters, since this calculation is computationally very expensive.

fixed to isothermal. This is done to facilitate comparison with previous work and to illustrate the effect of correcting the centroid positions for dust extinction. In Section 6.3 we explore the full range of parameter space, and hence its effects on H₀, allowing the slopes to vary to reproduce the lensing geometry. Finally, in Section 6.4 we add the dynamical constraints to reduce the uncertainties and break the mass profile degeneracy of G1. All results have been calculated using the new lens code and are based only on constraints from the radio data, the NICMOS F160W images, and the stellar kinematics. Constraints from the WFPC2 F814W images will be used as additional check on systematic effects in Section 7.3.

6.1. Free Parameters and Priors

To allow maximum freedom in the lens models and a proper calculation of the significance of the derived value of the Hubble Constant, we allow nearly all of the model parameters (i.e., position, lens strength, position angle, ellipticity, and density slope) of each lens galaxy to vary, constraining several with Gaussian priors. The source adds three additional free parameters (i.e., position and flux), the Hubble Constant adds one, and the external shear adds two. The model of the elliptical source that describes the Einstein Ring (§4.2) adds an additional four free parameters (position, ellipticity and position angle). In total there are up to 22 free parameters.

We use Gaussian priors on the galaxy positions, placing them at their observed positions and allowing for $1-\sigma$ er-

rors of 6 mas in x and y (Table 3). Hence, χ^2 increases by unity if the galaxy positions deviate by $1-\sigma$ from the observed positions. Similarly, we allow the position angle of G1 to vary using a Gaussian prior of 79 ± 2 degrees. Since B1608+656 is part of a small group (e.g., Fassnacht et al. 2002a) we allow for an external shear. The group is not massive and has a low velocity dispersion (Fassnacht et al. in prep.). We therefore place a conservative 0.00 ± 0.10 $(1-\sigma$ positive) prior on the strength of the external shear, although this prior is not particularly important.

Finally we place a Gaussian prior on the density slope of the secondary galaxy (G2), for which we have no kinematic information. We choose $\gamma'_{\rm G2}=2.00\pm0.10$, fully consistent with the spread in values of γ' found from 0047–285 and MG2016+211 (Treu & Koopmans 2002a; Koopmans & Treu 2003). Since G2 is \sim 5 times less massive than G1, its contribution to the properties of the lens system is less pronounced. We discuss this prior further in §7.3.

6.2. Isothermal lens model

To allow a comparison with previous modeling efforts (Koopmans & Fassnacht 1999; Kochanek et al. 2001; Fassnacht et al. 2002b), we first set the density slopes of both G1 and G2 to isothermal (i.e. $\gamma'=2$). The structure of the ring is included as a constraint and the priors are as discussed in §6.1.

We have listed the model parameters of the minimum- χ^2 solution in Table 4, where this model is designated as SIE. Compared with previous isothermal lens models

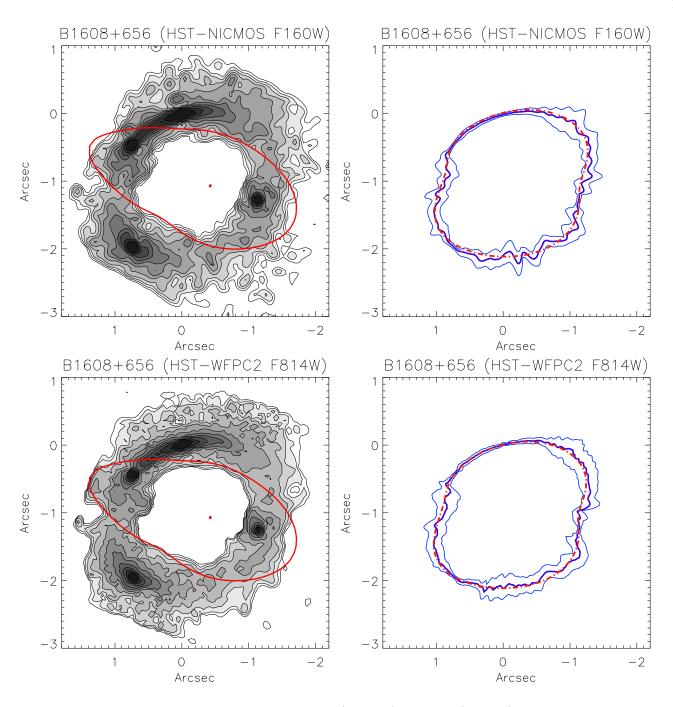


Fig. 5.— The deconvolved Einstein Rings of B1608+656 in the F160W (upper left) and F814W (lower left) bands, after extinction correction and subtraction of a model of the two lens galaxies. The contour levels increase by factors of two (arbitrary units). The solid curve indicates the outer critical curve (see text) of our best lens model (§6.4). The right panels indicate the trace of the Einstein Ring (thick solid line) and the $\pm 1-\sigma_{\rm r}$ width of the ring (two thin solid lines). To smooth the trace, we plot it for 360 spokes (only 90 are used in the modeling; see text). The dot-dashed curves show the minimum- χ^2 SPLE1+D models.

(Koopmans & Fassnacht 1999; Fassnacht et al. 2002b), we find that the inferred value of the Hubble Constant, $H_0 = 71^{+5}_{-6} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (68% C.L), has increased by about 6–8 km s⁻¹ Mpc⁻¹. The error includes all random errors and correlations between free parameters. This increase is partly due to the two main lens galaxies being closer to each other after extinction correction. Although each galaxy is isothermal, their combined potential becomes steeper, leading to an increase in H_0 (e.g., Wucknitz 2002; Williams & Saha 2000). Other contributions come

from including external shear and widening the errors on the image flux ratios and positions, which change the χ^2 surface.

Besides reproducing all point-image constraints well, an excellent fit (nearly identical to Fig. 5) to the boxy structure of the Einstein Ring is also found. A comparison by eye to the fit in Kochanek et al. (2001; their Fig. 5) shows that our fit is significantly better, in particular between the image pairs B–C and D–A. The difference can probably be attributed to the fact that we use a deconvolved Einstein

Table 5	
Recovered point-image properties from the minimum– χ^2 SPLE1+D (isotropic) model	٠.

Image	$\Delta x ('')$	$\Delta y (")$	S_{norm}	$\Delta t \text{ (days)}$
A	+0.00005	+0.00003	2.0408	32.42
В	-0.73823	-1.96125	0.9313	0.00
$^{\mathrm{C}}$	-0.74461	-0.45379	1.0869	36.20
D	+1.12845	-1.25630	0.4230	76.51

Ring shape and extinction-corrected lens galaxy centroids. We find a source axial ratio of $q_s = 0.64 \pm 0.03$ and position angle of $\theta_s = (113 \pm 2)^{\circ}$. The axial ratio is similar, but the position angle of the ring source is significantly different from the value in Kochanek et al. (2001). The optical source has a minor offset from the source for the radio images ($\lesssim 0.00$) which could, for example, be attributed to a small asymmetry (e.g. lopsidedness or m=1 mode) of the host galaxy or deviations from ellipticity. Forcing the centroid of the host galaxy to coincide with the radio source increases the χ^2 of the ring fit (by $\sim 30\%$), but changes the resulting mass model parameters only marginally. Since m=1 modes for the brightness distribution of galaxies are not uncommon and automatically accounted for in models with a free host-galaxy centroid, we choose not to force such a coincidence. We find values identical to those derived from the F160W image when the ring shape from the F814W data is used, and also when using the code from Keeton (2001).

As a further check, we calculate the stellar velocity dispersion of G1 based on this isothermal lens model. Details of the calculation method are outlined in Koopmans & Treu (2003) and §4. We also come back to this in more detail in §6.4. We find $\sigma_{\rm ap}=230~{\rm km~s^{-1}}$ for isotropic models $(r_i=\infty)$ and $\sigma_{\rm ap}=250~{\rm km~s^{-1}}$ for anisotropic models with $r_i=R_{\rm eff}$, inside the proper aperture and corrected for seeing effects. These values agree remarkably well with the measurement of $\sigma_{\rm ap}=247\pm35~{\rm km~s^{-1}}$, even though this information has not been used in the isothermal models. This suggests that the simplest isothermal lens model is probably not too far from the final model.

6.3. Power-law lens models

The next step is to allow the slope of the dominant lens galaxy (G1) to vary. Since the isothermal models show that G1 is \sim 5 times more massive than G2, the contribution of G2 to the structure of the Einstein Ring and the lensed images is relatively small. In general we find that the properties of G2 are ill-defined if we leave its density slope (or ellipticity; see §7.3) entirely unconstrained. We therefore place a prior on its slope, $\gamma'_{\rm G2}=2.00\pm0.10$, as suggested from similar mass models of other lens systems (§6.1). The slope of G1 is left fully unconstrained. We designate this model as the "Singular Power-Law Ellipsoid" (SPLE) mass model. The SPLE1 model is that model with a prior only on the power-law slope of G2.

The results are listed in Table 4. We find a slightly better fit to the data (i.e. $\Delta\chi^2 = -1.8$) than for the isothermal models. Most notably, the slope of G1 is found to be $\gamma'_{\rm G1} = 1.99^{+0.20}_{-0.20}$, nearly identical to isothermal.

The slope of G2 is somewhat steeper than isothermal, which leads to a slight increase in the Hubble Constant, $\rm H_0{=}74^{+10}_{-11}~\rm km~s^{-1}~\rm Mpc^{-1}$ (68% C.L) compared with the SIE mass models. Since the density slopes are included as free parameters, the resulting error on $\rm H_0$ is larger than for the isothermal models which have fixed density slopes. The error on $\rm H_0$ is less than 15%, even without kinematic constraints. If we include a similar prior on the slope of G1 as on G2 (the SPLE2 model), the results are again nearly identical (Table 4). The error on $\rm H_0$ decreases considerably, because it is dominated by the uncertainty on the density slopes, as discussed previously. As for the isothermal models, the point-image constraints and the shape of the Einstein Ring are reproduced well.

6.4. Lensing & Dynamical models

The final step in the modeling effort is to include the stellar velocity dispersion of G1 as an additional constraint. This is not as simple as for a case with a single lens galaxy. Since we have two lens galaxies, we can not simply attribute all of the mass within the Einstein radius (or critical curve) to only the lens galaxy G1.

We therefore follow a different approach. First we determine the minimum– χ^2 parameters for a range of models with fixed values of $\gamma'_{\rm G1}$ ranging from 1.6 to 2.4. We then calculate the mass enclosed within an aperture with a radius of 1" centered on G1, using the lens model parameters. Using the enclosed mass and the slope of the density profile of G1, we can then determine the stellar velocity dispersion inside the observed aperture (for details, see §4 and Koopmans & Treu 2003). The model velocity dispersion is compared to the observed value and the resulting $\Delta\chi^2_\sigma$, assuming a Gaussian error, is added to the χ^2_ℓ from the lens constraints alone.

Since b, q and γ' all enter into the determination of the mass enclosed within 1", the minimum of $\chi_l^2 + \Delta \chi_\sigma^2$ is not necessarily the true minimum. However, since $\gamma_{\rm G1}$ is by far the parameter that most dominates the determination of the inferred stellar velocity dispersion¹¹, for all practical purposes the difference between this approach and the correct approach (which is to calculate the dispersion at every χ^2 evaluation) is negligible compared to the final error on ${\rm H}_0$. We note that calculating the dispersion at every minimization step would slow down the minimization process by several orders of magnitude and is not feasible.

The resulting best-fit models for the lensing and dynamical models, designated as SPLE1+D and SPLE2+D, are listed in Table 4. We do calculations for two different anisotropy radii, for $r_i = \infty$ (isotropic) and $r_i = R_{\rm eff}$ (anisotropic). Since the observed stellar velocity disper-

 $^{^{11}}$ We note that the effect of changing the aperture, effective radius, etc. are completely negligible here.

sion is so close to that already predicted from the lens models alone, we see that the final results barely differ from the results presented in §6.3, except that the error on H₀ has decreased. In particular we find that the SPLE2 models have nearly identical errors on H₀ as the SPLE1+D models. Hence, both the lens and lens plus dynamics models clearly prefer an isothermal mass distribution for G1. In Table 5, we have listed the recovered point-image properties from the best SPLE1+D model, assuming $r_i = \infty$. Nearly identical results are found for $r_i = R_{\text{eff}}$. The bestfit model of the Einstein Ring is shown in Fig. 5, along with the observed ring. Fig. 6 shows the critical and caustic curves and the time-delay surface. For comparison, the outer critical curve is also overplotted on the data on the left panel of Fig. 5. Note that the critical curve is consistent with going through the saddle points of the ring, as expected. This provides a consistency check of the model, independent of the assumption of ellipticity for the source.

7. THE HUBBLE CONSTANT FROM B1608+656

In this section we discuss the value of H₀ from B1608+656 and its random and systematic errors in more detail, based on the class of models presented in §6.

7.1. Models Using Only Lensing Constraints

The SIE and SPLE1 and SPLE2 models are mass models based solely on the gravitational lensing constraints (i.e., no stellar dynamics) and give a value of H_0 ranging from 71–74 km s⁻¹ Mpc⁻¹ (Table 4). We adopt the value of H_0 =74 $^{+10}_{-11}$ km s⁻¹ Mpc⁻¹ as the best lensing-only determination, which includes the uncertainty on the density slope of the G1 without any assumptions except for a prior on the slope of G2. We discuss the latter in more detail in §7.3. We note that including a prior on G1 similar to that on G2 does not change the result, since the slope of G1 is already found to be nearly isothermal, i.e., $\gamma'_{\rm G1} = 1.99^{+0.20}_{-0.20}$ (68% CL) without a prior. The lensing-only models therefore predict an isothermal density profile for G1 to within 10%.

7.2. Models Using Lensing and Dynamical Constraints

All other models we consider include the stellar velocity dispersion of G1 as a constraint. In §6, we showed that the simplest lens models that we consider, with two isothermal galaxies, predict a stellar velocity dispersion close to the observed value (within $1-\sigma$ for both the isotropic and strongly anisotropic models). This agreement shows that the slope of the density profile of G1 can not deviate from isothermal too strongly. Indeed it is found that the slope of G1 is isothermal to within a few percent if we include the stellar velocity dispersion as an additional constraint. We finally adopt the median value of $\rm H_0{=}75^{+7}_{-6}~km~s^{-1}~Mpc^{-1}$ as the best determination. A systematic error of $\pm 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is estimated, due to the unknown anisotropy of G1. We note that including the stellar dynamics has not significantly changed the value of H_0 , but reduces its error considerably, to less than 10%. Similarly, the slope of G1 is $\gamma'_{\rm G1} = 2.03^{+0.14}_{-0.14} \pm 0.03$ (68% CL), where we take the average value of the SPLE1+D models with $r_i = R_{\text{eff}}$ and $r_i = \infty$. The latter error is the uncertainty due to the unknown anisotropy of the stellar velocity ellipsoid of G1 (Table 4).

7.3. Systematics

Finally we discuss the dominant systematic errors that could potentially be left in the models.

The results have not drastically changed since earlier models, but given the wealth of new constraints (e.g., the Einstein Ring, improved time delay measurements, stellar dynamics, etc.), the results have become more robust. The error on H_0 has shrunk even though we have included more free parameters (e.g., external shear, varying slopes and galaxy positions, etc.) in the model. The smaller error on H_0 is due to improvements in the measurement of the time delays and the inclusion of the Einstein Ring and stellar dynamics. Support for the refined models is further given by the flux ratio of image D, which is recovered to within 22% (Tables 3 and 5), even though it has not been included as a constraint on the models. All previous models had great difficulty with this. Hence, at first glance, the results appear little affected by remaining systematics.

Even so, we remain careful about assumptions, the most important of which is that for the prior on the density slope of G2 (§6.1). If we increase the width of the prior, we find that H_0 increases somewhat (i.e., the density profile of G2 becomes steeper), but also that its axial ratio decreases to very small values $\lesssim 0.2$ (PA remains similar to those in Table 4). Since G2 is most likely a disk galaxy (because of the copious amounts of dust associated with it), a small axial ratio is not unlikely, but a value of $\sim 0.1-0.2$ appears unrealistic, especially since G2 has no discernible ellipticity in the F160W image (Fig. 1). If we take priors of $q_{\rm G2} = 1.0 \pm 0.2$ and loosen the prior on the density slope to $\gamma'_{\rm G2} = 2.0 \pm 0.3$ – both of which are also reasonable, given the observations – we find that the resulting value of H_0 increases by at most a few percent.

Next, we have assumed a spherical mass distribution for G1 in our stellar dynamical models. Since we measure a luminosity-weighted dispersion within a relatively large aperture ($\gtrsim R_{\rm eff}$), many assumptions about the phase-space density of stars have little effect on the final measured stellar velocity dispersion. For example, anisotropy has little effect on H₀. A change of $\pm 5\%$ in the average dispersion would also affect H₀ on a level of $\lesssim 3\%$. We therefore believe the assumption of spherical symmetry to be of little effect, given the current error on the observed stellar velocity dispersion of G1 ($\sim 14\%$). We also notice that the slope of G1 from lensing alone and from stellar dynamics fully agree, giving no indication of large remaining systematic errors.

As a check on the astrometry, dust correction and deconvolution procedure, we have used the Einstein Ring from the F814W observations as a constraint. We follow exactly the same procedure as for the F160W image. We find that the two lens galaxies lie slightly further apart than in the NICMOS images, as discussed previously. This suggests that a smaller value of H_0 will be found. However, the best SPLE1+D model produces a somewhat steeper density profile for G1 (by 2%), which compensates for the somewhat larger lens galaxy separation and leads to an identical value of H_0 . Hence, it appears that inclusion of the ring "forces" the combined lens potential of G1 and G2 to be slightly steeper than isothermal, leading to a robust value of H_0 independent of which data set is used.

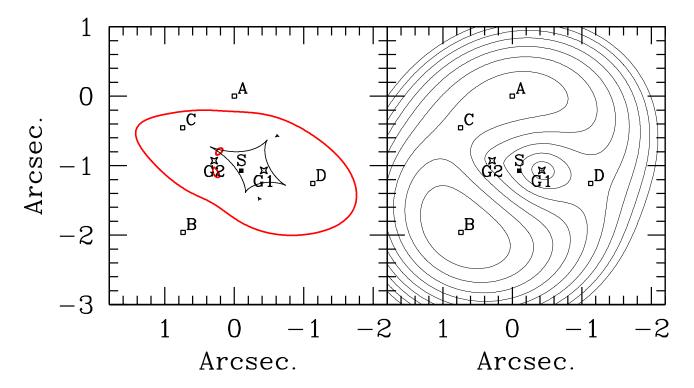


Fig. 6.— Left: Critical (thick) and caustic curves (thin) of the SPLE1+D model. The galaxy positions are indicated by stars, the images positions by open squares and the source by a closed square. Right: The contours indicate constant time delays starting at Δt =0 at image B and increasing in steps of 10 h^{-1} days.

We therefore conclude that given the assumptions and priors – which are all consistent with the observations of B1608+656 – remaining systematic errors on H_0 probably add up to not more than about 5%, dominated by those from assumptions in the stellar dynamical model and the priors on G2.

However, an important systematic error that could still affect the value of H₀ is a mass-sheet degeneracy (Gorenstein, Shapiro, & Falco 1988) due to the small group around the lens system (Fassnacht et al. 2002a). Although our model reproduces the observed stellar velocity dispersion well for an isothermal mass distribution, a strong mass-sheet could have led us to overestimate the enclosed galactic mass and therefore to underestimate the inferred density slope, given the observed velocity dispersion constraint. The observed quasi-isothermality, however, does not necessarily argue against a mass-sheet since the mass density profile does not have to be exactly isothermal. We note also that the effect on the slope partially compensates the well known scaling of H_0 with κ_c for a given mass model. We defer a precise quantification of the convergence (κ_c) and shear of this group, and their effects on the lens system and H₀, to a forthcoming publication with additional data on the group (Fassnacht et al. in prep.), but believe it to be relatively small based on the "poorness" of the group and its small velocity dispersion.

Finally, we note that the effects of the cosmological model are negligible. Changing Ω_{Λ} from 0.7 to 0.0, with $\Omega_{\rm m}=0.3$, increases H_0 by 2%. A drastic change to $(\Omega_{\rm m}=1.0,\Omega_{\Lambda}=0.0)$ decreases H_0 by 7%. However, within the current limits on the cosmological model set

by WMAP(Spergel et al. 2003), changes in H_0 are $\lesssim 1\%$.

8. DISCUSSION & CONCLUSIONS

We have presented significantly improved and refined mass models of the gravitational lens B1608+656 – compared with previous modeling efforts – with the aim of determining a value of the Hubble Constant, that is less affected by previously known systematics (e.g. radial mass profile, dust extinction, etc.).

New constraints on the mass model include: (i) the stellar velocity dispersion of the dominant lens galaxy (G1), as measured with ESI, (ii) the deconvolved Einstein Ring seen in the HST F160W and F814W images – the former of which is little affected by dust – corrected for the contribution from the lens galaxies, (iii) the extinction-corrected lens-galaxy centroids and structural parameters, the former being one of the major uncertainties in previous lens models and (iv) recent improvements in the determination of the three independent time delays in this four-image lens system (Fassnacht et al. 2002b).

Lens models have also been improved in allowing for many additional free parameters compared with previous modeling efforts (Koopmans & Fassnacht 1999; Fassnacht et al. 2002b), including the galaxy positions, the position angle of G1, an external shear and the density slopes of G1 and G2. Some of these parameters are constrained with observational priors. The freedom in the lens model (up to 22 free parameters) allows for a proper analysis of the error on the inferred value of H_0 , including all observational errors and correlations between free parameters.

The improvements in the observations and lens models

have led to a Hubble Constant from B1608+656 which is less affected by known systematic errors than previously. We obtain $H_0\!=\!75^{+7}_{-6}\,\mathrm{km~s^{-1}\,Mpc^{-1}}$ (68% CL), with a $\pm5\%$ error contributed by known systematic errors (for $\Omega_{\mathrm{m}}\!=\!0.3$ and $\Omega_{\Lambda}\!=\!0.7$). This value is higher than found from previous models (e.g., Koopmans & Fassnacht 1999; Fassnacht et al. 2002b), predominantly because, after extinction correction, the two lens galaxies are somewhat closer together than previously thought, their density profiles are slightly steeper than isothermal and external shear is included in the models.

First, we find that the new lens models reproduce all radio-image constraints to within the errors. This agreement might imply that we have been too conservative in the error estimates and might also have slightly overestimated the final error on H_0 . The flux ratio of image D is also reproduced to within 22%, a considerable improvement over previous models (e.g., Koopmans & Fassnacht 1999; Fassnacht et al. 2002b). Image D is the closest image to the dominant lens galaxy and might be affected by structure in the stellar (or dark-matter) mass distribution of lens galaxy G1 that is poorly represented by the global mass model.

Second, the lens models reproduce the observed stellar velocity dispersion of G1, and its mass profile is found to be nearly isothermal, $\gamma'_{\rm G1} = 2.03^{+0.14}_{-0.14} \pm 0.03$ (68% CL). This result is not as straightforward as one might expect, since the inferred stellar velocity dispersion of G1 depends strongly on the mass that G2 contributes to the lens properties. If the lens model predicted too large a mass for G2, the mass of G1 would decrease (because lensing tightly fixes the mass enclosed by the lensed images), as would the inferred stellar velocity dispersions. Similarly, if the mass is correct, but the density slope of G1 inferred from lensing alone is wrong, the inferred velocity dispersion would be incorrect as well. The fact that the lensing model (without dynamical constraints) already predicts a mass model for G1 that accurately reproduces the observed stellar velocity dispersions makes the models, in our opinion, very believable. The addition of the dynamical constraint therefore does not change the results from lensing alone, but significantly tightens the error on the value H_0 .

Third, the lens models reproduce the boxy shape of the Einstein Ring both in the F160W and F814W bands well and give the same value of H₀ irrespective of which of these datasets we use as a constraint. In addition, the critical curves (see Fig.5) cross the Einstein Ring at the saddle points of its brightness distribution, as required (e.g., Blandford, Surpi, & Kundić 2001).

We note that the resulting value H_0 from B1608+656 seems difficult to reconcile with Kochanek (2002, 2003), who finds that perfectly isothermal lens galaxies should lead on average to $H_0 = 48 \pm 3 \,\mathrm{km \ s^{-1} \ Mpc^{-1}}$ (see also Kochanek & Schechter 2003). We find a significantly higher value of H_0 even if the dominant lens galaxy (G1) is assumed to be isothermal. One possible explanation is that the time-delay systems examined by Kochanek (2002, 2003) have lens galaxies with luminous plus dark-matter mass profiles steeper than isothermal, enough to yield H_0 in better agreement with that obtained from B1608+656. Although indeed – on average – isothermal models appear to provide a good representation of the mass distribu-

tion of early-type galaxies (e.g. Treu & Koopmans 2002a; Koopmans & Treu 2003, Rusin et al. 2003b), significant departures in several individual cases is not necessarily inconsistent with the observed spread of mass slopes of local early-type galaxies (e.g., Fig. 1 in Gerhard et al. 2001; Bertin & Stiavelli 1993), especially at small radii where the stellar mass starts to dominate (e.g. Bertola et al. 1993). The lens galaxy in PG1115+080 (Treu & Koopmans 2002b) provides one such example of a lens-galaxy mass profile steeper than isothermal inside the Einstein radius.

Conversely, a mass-sheet degeneracy could have led us to overestimate H_0 from B1608+656, although the mass-sheet degeneracy is somewhat broken by the kinematic measurement. In this respect, we only note that a convergence of at least $\kappa_c \sim 0.4$ is needed to bring our value of H_0 in agreement with $48 \pm 3 \,\mathrm{km \ s^{-1} \ Mpc^{-1}}$, an unrealistically high value, and we defer further discussion to a forthcoming paper (Fassnacht et al. in prep.).

Another viable alternative would be that the time-delay systems examined by Kochanek (2002, 2003) have not been modeled in enough detail yet and could also be affected by nearby clusters or groups as seen near some of these systems (e.g., RXJ0911; Kneib, Cohen, & Hjorth 2000; Hjorth et al. 2002). A simple prediction is therefore the following: If these lens systems are isothermal and not affected by external perturbers, then the stellar velocity dispersion should be that predicted from a simple isothermal lens model (as for B1608+656). If, on the other hand, the observed stellar velocity dispersion is much higher that predicted from isothermal models, this would be a clear sign of a steeper mass profile (as for PG1115+080). Hence, stellar kinematics of lens galaxies is a key measurement to further study this apparent inconsistency.

Even so, the analysis of B1608+656 has demonstrated that when enough information is available, it is possible to reach accuracies of $\lesssim\!10\%$ (random) on the value of H_0 (or $\lesssim\!15\%$ when including systematic errors) taking the radial mass profile properly into account. A similar uncertainty was obtained by applying a joint lensing and dynamical analysis to PG1115+080 (Treu & Koopmans 2002b). This level of uncertainty is comparable to the accuracy achieved by the individual methods (SNae–Ia, Fundamental Plane, etc) that contributed to the final value of H_0 from the HST Key-Project (Freedman et al. 2001). Hence, obtaining sufficiently good data – including on the local environments – for a handful of gravitational-lens systems, seems to be a promising way to break the 10% limit on the uncertainty on the value of H_0 .

Finally, the analyses of B1608+656 and PG1115+080 have demonstrated that there are no simple ways to reach this goal and it does not suffice to assume a radial mass profile, without measuring it for each individual system. That approach probably does not lead to a reliable value of $\rm H_0$. High-quality observations and detailed lens mass models – that allow for many degrees of freedom – are required to obtain an accurate (and realistic) estimate of the Hubble Constant and its uncertainty. We are currently collecting spectroscopic data for additional lens systems with measured time-delays, with this aim in mind. In addition, optical and radio monitoring programs are continuing that should provide more (and/or improved) time delays in the

near future, and forthcoming observations with HST could provide improved constraints on the lens galaxies.

We thank Richard Ellis and Jean-Paul Kneib for useful comments on this manuscript and stimulating conversations. We are grateful to an anonymous referee for comments that helped clarifying the manuscript. The use of the Gauss-Hermite Pixel Fitting Software developed by R. P. van der Marel is gratefully acknowledged. The ESI data were reduced using software developed in collaboration with D. Sand. We acknowledge the use of the HST data collected by the CASTLES collaboration. LVEK and TT acknowledge support by NASA through grant AR-09960 from the Space Telescope Science Institute, which

is operated by the Assocation of Universities for Research in Astronomy, under NASA contract NAS5-26555. LVEK also acknowledges a STScI Fellowship grant. LVEK and RDB acknowledge NSF grants AST 99-00866 and 0206286, and GS acknowledges a NASA grant NAG 5-7007 and CONICET in Argentina. We thank J. Miller, M. Bolte, R. Guhathakurta, D. Zaritsky and all the people who worked to make ESI such a nice instrument. Finally, the authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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