The CASTLES gravitational lensing tool

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Abstract. We describe a series of new applications of gravitational lenses as astrophysical and cosmological tools. Such applications are becoming possible thanks to advances in the quality and quantity of observations. CASTLES (CfA-Arizona-Space-Telescope-LEns-Survey) is an ongoing project that exploits the sensitivity and resolution of the Hubble Space Telescope (HST) at optical and infrared wavelengths to study the sample of over 50 known gravitational lenses. The observational goal of CASTLES is a uniform sample of multi-band images of all known galaxy-mass lens systems, to derive precise photometry and astrometry for the lens galaxies, all the known images, and any source or lens components that might have escaped detection. With these measurements we are investigating: (1) the properties of dust and of dark matter in lens galaxies out to \( z \sim 1 \); (2) the dark matter in lens galaxies and in their environments; (3) the evolution of lens galaxies; and (4) the cosmological model, for instance by refining constraints on the Hubble constant \( H_0 \).

1. Introduction

There are now 54 known gravitational lens systems where a single, usually early-type galaxy has been identified as the dominant component. Lens galaxies are unique, because they constitute the only sample selected based on mass rather than luminosity. The population of known lenses is growing exponentially, with an e-folding time of about 5 years. The broad astrophysical utility of the lens sample rests on obtaining accurate photometry, astrometry and redshifts for the complete sample. Since these lens systems consist of 2–4 source images (AGNs, quasars, hosts), separated by \( 1'' - 2'' \) and centered on a foreground lens galaxy, quantitative studies at optical to IR wavelengths require HST.

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The CASTLES observational goals are to assemble a complete, uniform high-resolution photometric sample of all known galaxy-mass lenses. The sample yields precise photometry and astrometry for all the components in each lens system, and for source (e.g., host galaxies for lensed quasars) or lens components (e.g., galaxies near the main lens galaxy) that had previously escaped detection. With our analysis of these measurements, we are pursuing various astrophysical and cosmological goals: (1) measuring the extinction in the lens galaxies using the photometric properties of multiple images; (2) obtaining redshift estimates for all the lens galaxies without measured spectroscopic redshifts; (3) improving lens models to thus refine estimates of \( H_0 \); and (4) investigating the tidal field environments of the lens galaxies and their role in lensing.

For large population surveys of lenses like CASTLES we require a uniform data quality. Unfortunately, many archival lens observations were not dithered, had inadequate exposure times, or used idiosyncratic filter choices, all of which can make their utilization in population surveys impossible. Archival images are included in our data sample only when their quality is sufficient for our analysis. The CASTLES filters (V and I on WFPC2; H on NIC2) match the usual choices for studies of other galaxies at comparable redshifts. CASTLES began in HST Cycle 7, and is continuing in Cycles 8 and 9. Of the 54 known lenses, 60%, 70% and 80% now have V, I and H-band HST images that are useful for our scientific goals. Our source for targets has been a variety of ground-based discoveries of promising candidates. Time is being reserved in each of our proposals for systems that are discovered in the course of each HST Cycle. A significant number of targets became available in Cycles 7 and 8, for example. Thus, we are able to observe a number of targets of opportunity as ground-based observers provide us with new, promising candidates. All our data are available to the community as they arrive, as we waive all proprietary restrictions.

The WFPC2 and NICMOS point-spread functions (PSF) are complex, and can vary spatially and temporally. We used TinyTim v4.4 (Krist & Hook 1997) model PSFs for WFPC2 and NIC1 data, while for models of the NIC2 data we used a set of 13 stellar images (McLeod, Rieke & Storrie-Lombardi 1999). By comparing the PSFs to stellar images, we found that the residuals were less than 2% of the peak intensity of the stars. We used our library of empirical PSFs to find the best fit for each lens system. We homogeneously reduce and model all CASTLES and archival data, using software we have developed for these purposes, e.g. the NICRED reduction package\(^2\). In the remaining section, we present results that address several of the CASTLES goals. We describe first several “missing” lenses that were first found in our observations. We then present new detections of lensed host galaxies. Next, we present results regarding photometric lens redshifts and extinction, galaxy structure, the properties of dark matter in lens galaxies, and finally the CASTLES contribution to measurements of \( H_0 \).

\(^2\)available for download at cfa-www.harvard.edu/castles
2. CASTLES results

**Missing Lenses:** As expected, CASTLES optical and IR observations are detecting the majority of “missing” lens galaxies, even when bright quasar images and small separations make this difficult. For example, among the sample of 10 doubles in Lehár et al. (1999), we detected 9 lens galaxies, 3 of which are new detections (see Fig. 1). We failed only in the case of Q 1208+1011, due to extreme contrast problems. We also failed to detect lenses among the wider-separation ($\geq 3''$) quasar pairs UM 425, Q 1429–008, Q 1634+267 (Peng et al. 1999), MGC 2214+3550, and Q 2345+007 (see below), whose extreme limits on the lens $M/L$ make lensing improbable and point to the binary quasar interpretation (Jackson et al. 1998; Kochanek, Falco & Muñoz, 1999).

**Host Galaxies:** With our CASTLES images, we have detected lensed AGN host galaxies for 7 quasars (CTQ 414, MG 0414+0534, BRI 0952–0115, Q 0957+561, HE1104–1805, PG 1115+080 and H 1413+117), and 5 radio galaxies (MG 0751+2716, MG 1131+0456, B 1600+434, B 1608+656 and B 1938+666). Lensing provides a unique opportunity to study $z > 1$ host galaxies, because the hosts are magnified to detectable angular sizes (see Fig. 2 for an example). We find that $L_{\text{host}} \lesssim L_{\star}$, i.e., that even the most luminous quasars (e.g. PG1115+080) need not reside in particularly luminous hosts (see Rix et al., these proceedings). Our new H-band image of Q 0957+561 shows 2 images of the quasar host galaxy (Fig. 2); their geometry rules out the existing lens models for the system (Keeton et al. 1999). In combination with existing WFPC2 V-band data (Bernstein & Fischer 1999) and with new STIS imaging (Bernstein et al., these proceedings), our data yield useful new models for Q 0957+561 (Keeton et al. 1999, in preparation). For the QSO pair Q 2345+007 (Fig. 2), the host morphology proves the system is a binary quasar and not a “dark” lens, because only one of the quasars is embedded in a host (Fig. 2).

**Galaxy Structure:** CASTLES observations provide detailed constraints on lens galaxy structure, through shape and profile fitting. We find that most lens galaxies have de Vaucouleurs profiles, as well as shapes and colors consistent with passively evolving early-type galaxies; e.g. Q 0142–100, BRI 0952–0115, Q 1017–207, B 1030+071, HE 1104–1805 (Lehár et al. 1999); MG 1131+0456 (Kochanek et al. 1999a) and PG 1115+080 (Impey et al. 1998). B 0218+357 and PKS 1830–211 (Lehár et al. 1999) are spirals but present a more complex photometric picture due to the high molecular gas column densities and implied dust extinction. Another clear late-type is B 1600+434, where the lens is edge-on and a dust lane is clearly visible (Fig. 3). The photometric model in this case requires an exponential disk and a De Vaucouleurs profile for the bulge.

**Dark Matter:** We constrain and study the dark matter distribution of lenses by comparing their luminosity distribution to lens mass models based on our CASTLES astrometry and photometry. We used either a constant $M/L$ lens model matched to our photometric fits or a singular isothermal ellipsoid. We fit each model in isolation and then with an external shear to represent perturbations to the model from nearby galaxies or potential perturbations along the ray paths. Without external tidal perturbations, the constant $M/L$ models usually could not fit the lens constraints, and the dark matter models could only fit the lens constraints if misaligned relative to the luminosity. With the addition of a modest external shear, either model could fit all the lenses because
Figure 1. Missing lenses: top to bottom, the left panels show CASTLES NICMOS images of the systems SBS 0909+523 and LBQS 1009–0252 in the H band and of PKS 1830–211 in the K band (thus, the B image remains detectable, see Lehár et al. 1999). The scale is the same for all the panels. The right panels show the results of subtracting the lensed quasar images (and the stars near PKS 1830–211).
Figure 2. Host galaxies: top to bottom, the left panels show CASTLES NICMOS H band images of Q 0957+561, HE 1104–1805 and Q 2345+007. The right panels show the results of subtracting the lensed quasar images and the lens galaxy. Note that the scales necessarily vary from image to image.
Figure 3. CASTLES NIC2 H band image of B 1600+434. The 2 images A, B of a radio galaxy are extended. The lens galaxy G is an edge-on spiral. The nearby galaxy to the SE of the images presumably has the same redshift as G; it is likely to be a significant contributor to the lensing. The dust lane is easily visible along the edge of the disk of the lens galaxy G.

the two-image lenses provide so few constraints on the models. In general, the constant M/L and dark matter models predict very different time delays for the two-image lenses, and are hence distinguishable (see, e.g., Lehár et al. 1999).

We also cataloged the galaxies found within $\sim 100h^{-1}$ kpc of the lenses and estimated their local tidal environment based on the luminosities of the neighboring galaxies. If the galaxies have extended dark matter halos, they produce significant shears at the lens galaxy of $\gamma_T \sim 0.05$, while if they have a constant M/L they are a negligible perturbation of $\gamma_T < 0.01$. The dark matter estimates for the tidal shear are comparable to the shears necessary to find good lens models, but there is no clear correlation between the shear from the lens model and the estimate from the local environment. A significant problem is that the strength of the shear perturbations created by large-scale structure along the ray paths (Bar-Kana 1996, Keeton et al. 1997) is comparable to that from nearby galaxies.
Lens Galaxy Extinction: We determined differential extinctions in 23 gravitational lens galaxies over the range $z_l = 0 - 1$ (Falco et al. 1999). Only 7 of the 23 systems have spectral differences consistent with no differential extinction (McLeod et al., these proceedings). The extinction is patchy and shows no correlation with impact parameter. The directly measured extinction distributions are consistent with the mean extinction estimated by comparing the statistics of quasar and radio lens surveys. For several systems we can estimate the extinction law; the results range from $R_V = 1.5 \pm 0.2$ for a $z_l = 0.96$ elliptical, to $R_V = 7.2 \pm 0.1$ for a $z_l = 0.68$ spiral. The dust can be used to estimate lens redshifts with reasonable accuracy, although we sometimes find two degenerate redshift solutions. We find agreement within $\Delta z_L \lesssim 0.1$ with spectroscopic redshifts (Kochanek et al. 1999b).

The Hubble constant: There are now 6 lens systems with reliably measured time delays; 3 more show variability that should yield measurements within the year (e.g., Burud et al., these proceedings). To translate the time delays into $H_0$ estimates, accurate models for the mass distributions of the lenses are essential. Accurate models require precision astrometry and additional constraints to minimize systematic uncertainties and thus turn lenses into the best means of estimating $H_0$.

Among our observed targets, B 0218+357 (Biggs et al. 1999) and PKS 1830–211 (Lovell et al. 1998) have measured time delays. Unfortunately, with the short exposures necessary for a survey such as CASTLES, we were unable to measure the positions of the lens galaxies in these two systems with sufficient
precision to accurately determine $H_0$ (Fig. 4 illustrates the problem; see Lehár et al 1999). For PKS 1830–211 only longer observations are necessary: our data demonstrate that the uncertainties would be easily reduced to acceptable levels given a higher signal-to-noise ratio (SNR). For B 0218+357, we are limited by the small component separations rather than the SNR. Better image sampling combined with long exposures and concurrent PSF measurements should resolve the problem.

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