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A most useful manifestation of relativity: gravitational lenses

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Abstract. Gravitational lenses are scarce but extraordinary phenomena that yield a very high rate of return on observational investment. Given their scarcity, it is very impressive that since their discovery in the extragalactic realm in 1979, they have had such an enormous impact on our knowledge of the universe. Gravitational lensing is a manifestation of general relativity that has contributed to a great variety of astrophysical and cosmological studies. In the weak-field limit, lensing studies are based on well-established physics and thus offer a direct approach to study many of the currently pressing problems of astrophysics. Examples of these are the significance of dark matter and the age and size of the universe. I present a brief history of gravitational lensing and describe recent developments in fields such as searches for dark matter and studies of galaxy evolution and cosmology. The approach is non-specialized and emphasizes observational results, to reach the widest possible audience.

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Contents

1. Introduction

A gravitational lens system (hereafter GLS) consists of a source and the lens proper, which deflects the light of the source and forms distorted images; figure 1 shows a sketch of a typical configuration. GLS sometimes form multiple images of the source, such as those shown in figure 2. We only consider the gravitational weak-field limit, where deflections are always $\ll 1$ radian, or a few arcsec. In this limit, the deflection is achromatic (with observational caveats imposed, for example, by extinction). Therefore, a diagnostic property of a GLS is that the images are nearly the same irrespective of the wavelengths of observations. For example, lensed multiple images of quasars have very similar flux ratios in different wavebands (figure 2) and their spectra reveal a common redshift (figure 3). The examples in these and in figures 4 and 5 show cases of 'strong' gravitational lensing, where the typical scale for separation between distinct images of a quasar is a few arcsec and the lens is most often a massive elliptical galaxy.

In a different occurrence of strong lensing, the effect yields distorted (possibly multiple) images of distant galaxies, running the gamut between 'arclets' (slightly distorted) and 'giant arcs' (greatly sheared), produced by intervening clusters of galaxies (figure 6).

There are two additional classes of gravitational lensing: 'weak' lensing, where the strength of the lensing is insufficient to form multiple images and the effect is only measurable statistically and 'microlensing', where unresolved (at the micro-arcsec level) sub-images are formed and the detectable results are large, relatively rapid changes in detected fluxes.

In the following, I present a brief history of gravitational lensing. I then describe the application of observations of GLS to the study of cosmology, large-scale structure, astrophysical properties of galaxies and the search for dark matter. I conclude with the future of surveys that are or soon will be poised to make substantial contributions to these studies.

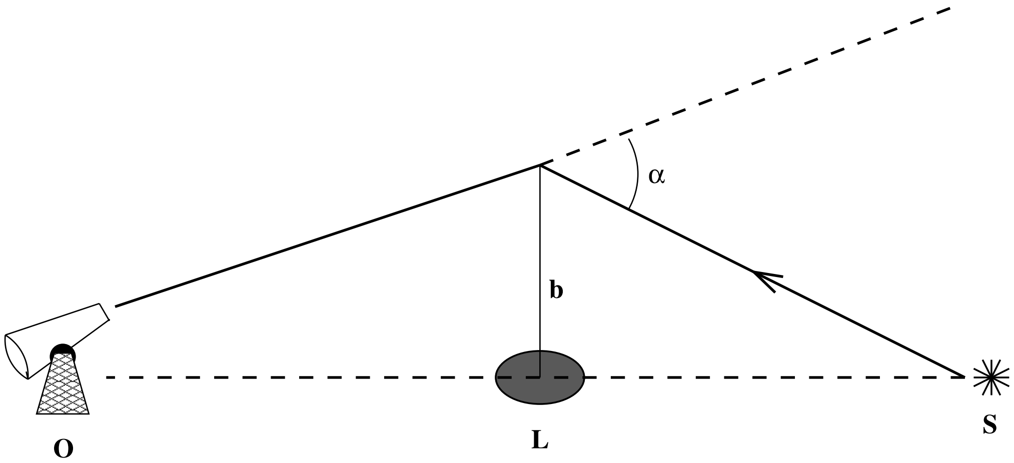

Figure 1. The sketch shows light emitted, deflected and detected, with the observer and telescope at O, the lens at L and the source at S. The impact parameter is b; the corresponding deflection angle is α ($\ll$1 radian, but greatly exaggerated in this sketch).

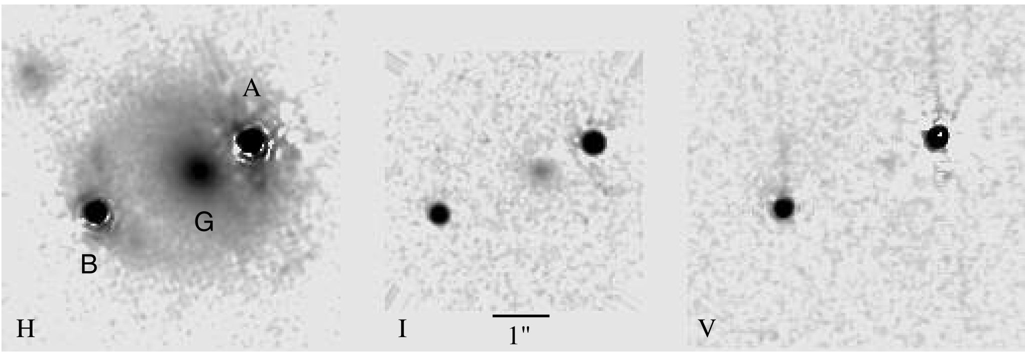

Figure 2. HE1104-1805: a double GLS. The lens is G, the images A and B. The three panels show HST views of the GLS, going from NICMOS H (centred on 1.6 μm), to WFPC2 I and V (centred on 814 and 555 nm, respectively) filters left to right. In these views, celestial North (East) is at the top (left). To create these images, we fitted a photometric model, subtracted the best-fit models for the quasar images, and added them back as Gaussians with the same width as the original point-spread function (PSF, the response of the optical system to a point source). This procedure removes artifacts due to the diffraction pattern of the HST PSF. Note the size of the image separation, about 3 arcsec, which would make ground-based observations very difficult. Note also the similarity of the image brightnesses, while the lens galaxy fades to the limit of detection of these exposures in V.

2. History

The behaviour of light rays in a gravitational field is described with Albert Einstein's Theory of General Relativity (GR). Long before his derivation of GR in 1915, it was thought that gravity should affect light. In 1704, in his *Opticks* Newton asked 'Do not bodies act upon light at

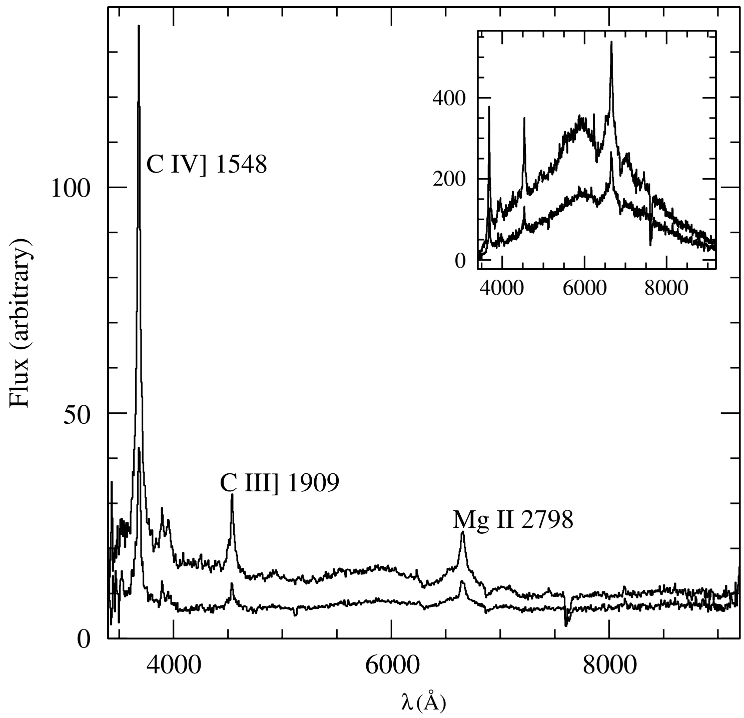

Figure 3. SBS0909 + 532: a double GLS. Spectra of the two images with redshift $z_s \sim 1.38$. The lens galaxy is at $z_l \sim 0.8$. The inset shows the spectra before corrections for instrumental and systematic effects [1]. A useful feature of quasars as lensed sources is that their spectra have multiple, easily-identified broad emission lines as in this case, of ionized magnesium and carbon.

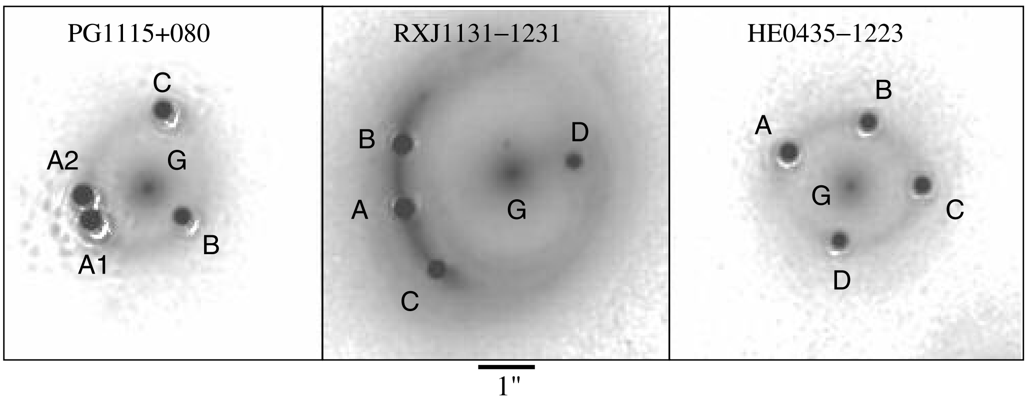

Figure 4. CASTLES (see the text) HST NICMOS H-band images of three quadruple GLS. The different configurations in the three panels arise from the positioning of the source relative to the caustic curves generated by the lens (see [2] for details). We used the same procedure as in figure 2 to remove PSF artifacts.

a distance, and by their action bend its rays; and is not this action (*caeteris paribus*) strongest at the least distance?' Over the next two centuries, there was steady interest, e.g., with bright luminaries such as Mitchell, Cavendish and Laplace in the 18th century and lesser lights such as

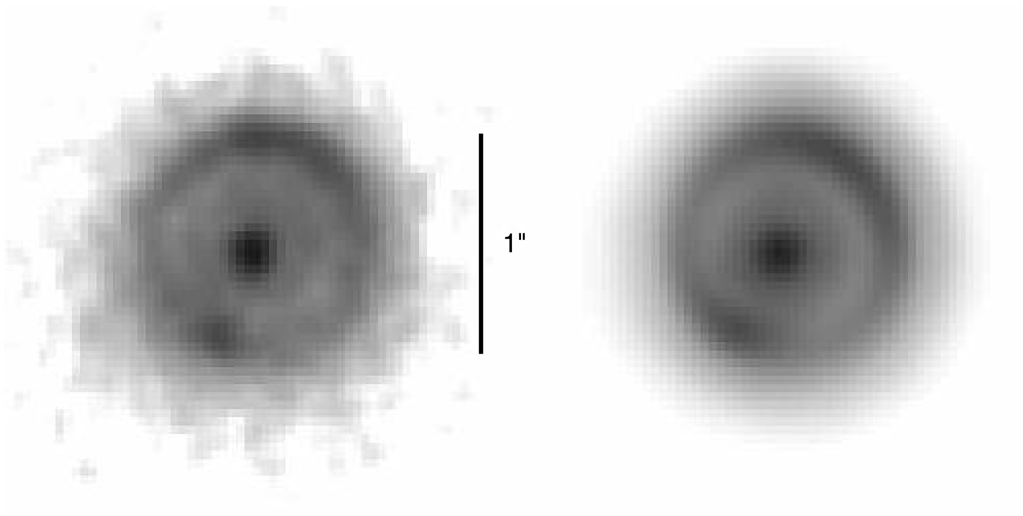

Figure 5. Left panel: CASTLES HST NICMOS image of the complete Einstein-ring BLS B1938 + 666. Right panel: a photometric model including an elliptical lens galaxy and a lensed extended source to produce the ring.

Soldner in 1801 discussing the effect of gravity on light. Soldner was in fact interested in light deflection in a modern context, where sources are displaced from what their position would be in the absence of gravity. Within the old context of a corpuscular theory of light and classical mechanics, the angle of deflection α of a light particle with velocity v by a mass M sufficiently far away at r is: $\alpha \approx (2GM)/(v^2 r)$, where G is Newton's gravitational constant. This value was only a factor of 2 less than the value Einstein first obtained with the full equations of GR. The Einsteinian value was confirmed in 1995 within 0.02% with radio-interferometric (VLBI) methods [4].

The subject remained alive until 1936, with Lodge, Eddington and Chwolson discussing the possibility of multiple images. In 1936, Einstein published a calculation [5] of the properties of the 'lens-like action of a star' but he found there was 'no great chance of observing this phenomenon.' Einstein's analysis included the first correct reference to 'a luminous circle' arising from a perfect alignment of a point mass and a source, which has come to be known as the Einstein ring. Following that, the year 1937 was seminal: Zwicky published his own estimations [6, 7], finding that 'extragalactic *nebulae* offer a much better chance than *stars* for the observation of gravitational lens effects' and 'the probability that nebulae which act as gravitational lenses becomes practically a *certainty*.'

Zwicky's papers considered only lensed galaxies but were otherwise prescient. However, it was not until 1963 that the topic was revived in the literature, just after the discovery of quasars [8]. Klimov [9], Liebes [10] and Refsdal [11] independently rekindled interest in the subject. Refsdal, in particular, calculated in detail the properties of the point-mass GLS and first considered the measurement of the time delay for the two images that such a point-mass always forms of a supernova [12] or a quasar (see below for details). Refsdal [13, 14] extended the subject and first considered the possibility of testing cosmological theories with the lens effect. In particular, he showed that it is possible to determine the value of the Hubble 'constant' $H_\circ$ utilizing measurements of time delays (see below).

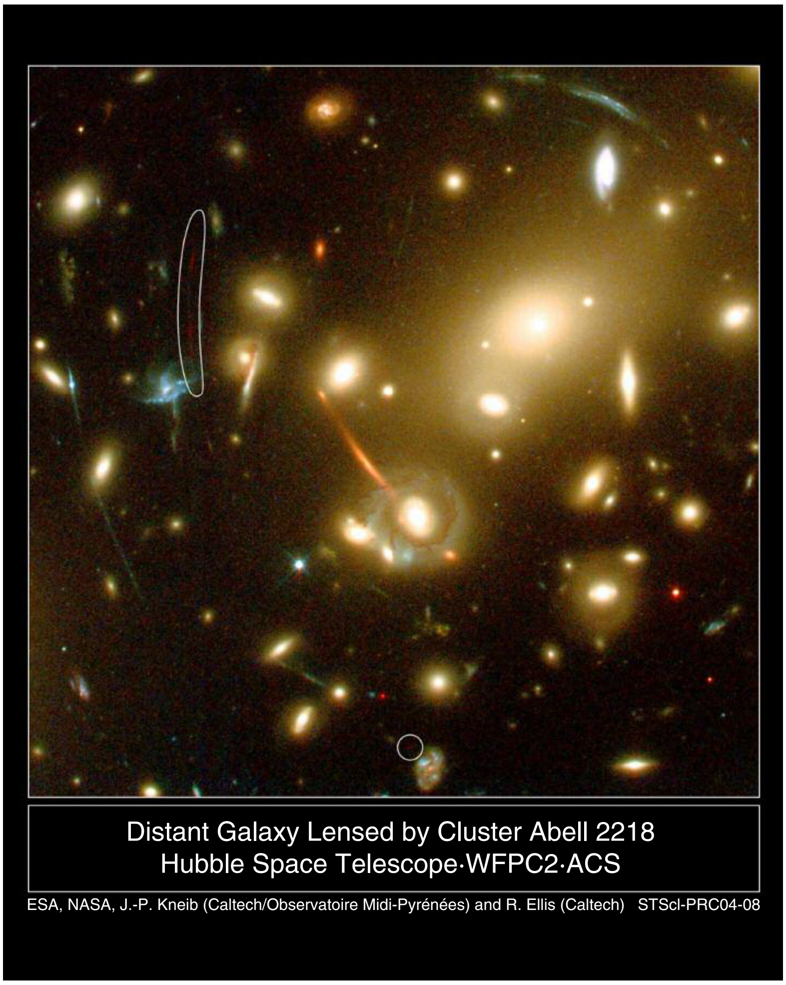

Figure 6. HST/ACS view, ∼200 kpc on a side, of part of the cluster of galaxies Abell 2218 (ESA/NASA image STScI-PRC2004-08; see also [3]). The image is a combination of exposures through long, medium and short-wavelength filters, for an approximately realistic colour rendition. Note the extreme elongation of several of the objects in the frame, which can still be recognized as galaxies. These are greatly sheared images of galaxies in the background of the cluster. The colours of the lensed galaxies are functions of their distances and types. The orange arc is an elliptical galaxy at moderate redshift ($z \sim 0.7$). The blue arcs are star-forming galaxies at intermediate redshifts ($z = 1$–2.5). The circle and curved oblong outline indicate the multiple images of a lensed galaxy at $z \sim 7$. Without the magnification of the cluster acting as a lens, the spectrum of this galaxy would be undetectable, even with the largest telescopes such as Keck.

Barnothy [15] proposed that quasars 'are nuclei of Seyfert I galaxies intensified through the gravitational lens action of foreground galaxies'. His idea was not well received by the astronomical community, in particular because of his penchant for his unusual 'FIB' cosmological model. However, the suggestion was interesting and did have merit after significant modifications (see, e.g., Schneider, Ehlers and Falco [16], hereafter SEF).

During the following decade or so, there was significant theoretical activity in the subject, in particular by Bourassa and Kantowski [17] and by Chang and Refsdal [18]. But until 1979, gravitational lenses were a theoretical subject. That changed suddenly in 1979, when Walsh *et al* [19] announced their discovery of the first gravitational lens candidate. The radio source 0957 + 561 at $z \approx 1.4$ apparently consisted of 2 quasars with that same redshift; furthermore, the ratios of optical and radio fluxes of the 2 quasars were indistinguishable up to measurement errors. Stockton (1980) and Young *et al* (1980) [20] uncovered the lens, a cD galaxy embedded in a cluster of galaxies at $z \approx 0.36$. The two quasars turned out to be two images of the same quasar. The first GLS would prove to be rather unique: the large separation of 6 arcsec could not be due to a single galaxy, but was due to an otherwise unremarkable cluster of galaxies.

In 1980, Young *et al* [20] discovered PG1115 + 080, the first quadruple GLS (four images of a single quasar). Since then, the pace of discovery of strong lenses (or galaxy lenses) has risen exponentially. The first Einstein ring GLS, MG1131 + 0456, was discovered in a radio survey in 1986 [21]. A full radio (and later, infrared (IR)) ring and the lensing galaxy (in the optical and IR) were clearly visible. More were soon discovered (see figure 5). That same year, the first case of lensing of galaxies by intervening clusters of galaxies was found in Abell 370 [22]. Imaging revealed extremely elongated images in a tangential direction (relative to the centre of brightness of the cluster) of distant galaxies. A redshift measurement for one of the arcs confirmed that it was an image of a background galaxy, as expected.

About two decades ago, it was realized [23] that the large-scale distribution of matter in the universe gives rise to a 'weak' lensing effect, also called 'cosmic shear' which can only be measured statistically, from surveys with at least 10^6 galaxies (e.g., [24]). In this context, lensing is weak because it produces only single, slightly distorted images. It is now also clear that, if one looks to sufficiently faint brightness limits, one will see tangentially sheared images of galaxies in the background of almost any cluster. That idea gave rise to studies of 'weak' lensing that can yield the distribution of mass in clusters (e.g., [25]), estimates of the sizes of galaxy halos using galaxy–galaxy weak lensing (e.g., [26]) and estimates of cosmological parameters (e.g., [27]). Statistical gravitational lensing can only be detected with great observational effort, but the potential payoff for direct measurements of cluster masses, galaxy halos and of cosmological parameters such as the power spectrum of matter fluctuations, is quite attractive.

In 1986, Paczyński [28] suggested that gravitational lensing of stars in galaxies in the Local Group (galaxies of various types within ∼3 Mpc of the Milky Way, including Andromeda and the Large and Small Magellanic Clouds) could be used to test the premise that the dark matter in the halo of the Milky Way is composed of unseen, compact (roughly the size of a planet) objects. The optical depth for such lensing would be very small and would require observations of $\sim 10^6$ stars. Such a feat was accomplished by several groups and yielded the first detection in 1993 (see [29] for a report on the first discovery) of 'microlensing' events, where the source was a star in the Large Magellanic Cloud (LMC).

The current, growing total of strong GLS as of this writing is 82 with multiple (generally two or four) quasar images, with separations of up to about 10 arcsec. Examples of strong lensing by clusters of galaxies are spectacular (figure 6), but few and far between compared to the sample of lensed quasars. The lensed quasar sample continues to grow irregularly, as serendipity continues to play an important role in the discovery of GLS. However, systematic surveys are beginning to contribute significantly also (e.g., CLASS, see [30]). The field now encompasses the study of these more common strong lenses, of lensed arcs (multiply-imaged or not, with separations of tens of arcsec) produced by clusters of galaxies, of weak lensing (not multiply-imaged) and of microlensing, due to massive compact objects including stars (possibly multiply-imaged but unresolvable with image separations of μarcsec).

3. Cosmology

Even as it expands, the universe appears homogeneous and isotropic on its largest scales. The past, present and future of its expansion are encapsulated in the distance scale factor $a(t)$ as a function of cosmic time t. The mean separation of galaxies is proportional to $a(t)$. One of the principal goals of observational cosmology is the measurement of $a(t)$ with ever-refined accuracy. Another is the derivation of the equations of motion for cosmic expansion and their implications for its matter and energy contents. Over the previous several decades, cosmology has evolved from a data-poor theoretical discipline, to an extremely data-rich one, based on a solid and always growing empirical basis.

A natural model of the early universe is based on inflation (e.g., [31, 32]). It implies that the universe we enjoy today has a flat spatial geometry, i.e., the total mass-energy density $\Omega_{tot} = \Omega_\Lambda + \Omega_m$ is unity. The fraction Ω_m of this density is interpreted to be 'cold' matter that was nearly at rest as galaxies were forming. The rest Ω_Λ is interpreted as 'dark energy.' The normalized first derivative of $a(t)$ is $H_\circ = \dot{a}/a$, the well-known Hubble 'constant'. On a human timescale, $H_\circ$ is constant and for the present discussion we can adopt its present value, but in fact, it changes with cosmic time. The normalized second derivative $\ddot{a}/a = -H_\circ{}^2(\Omega_m/2 - \Omega_\Lambda)$ is the cosmic acceleration. Until a decade ago, the acceleration was expected to be negative because of the gravity of matter. However, the Wilkinson Microwave Anisotropy Probe (WMAP) data support strongly the inflationary paradigm, with a universe consisting of about 4.4% baryons, 22% in an unknown, non-baryonic form of dark matter and 73% dark energy [33] that causes a positive acceleration. It means the dark energy yields a negative pressure, or a kind of anti-gravity. Furthermore, the properties of Cepheid variable stars, distant supernovae, and the large-scale structure of matter and microwave background fluctuations are consistent with a flat universe, with $H_\circ = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from the results of the HST Key Project [34]. This particular set of parameters has come to be known as the 'concordance cosmology.' Much testing remains to be done to test the new cosmology in a variety of complementary ways, and to refine the accuracy of measurements.

Our understanding of the tenets of the model also needs improvement. A yawning gap is that the components of dark matter and dark energy remain unknown. The dark energy density, unlike Einstein's cosmological constant Λ, may vary with time in a complex fashion. Current candidates for the gravitationally self-repulsive dark energy are a vacuum energy density (Λ) and quintessence, a time-evolving, spatially inhomogeneous component with negative pressure [35]. Unfortunately, there is as yet no test to distinguish between these possibilities. There may also be alternatives to dark energy: observers may be detecting the effect of gravitational-field leakage into undetectable additional dimensions [36]. Deciding between those and even more exotic proposals is a central challenge, one in which gravitational lensing is starting to help in many ways, as we see next.

3.1. Models

The number of strong GLS one expects to find in a large survey can be estimated as a function of the geometry and kinematics of the universe. Necessary requirements are the redshift distribution of the lensed sources, the local density of the lens galaxies and the mass-density profiles of the lenses. As we vary the values of cosmological parameters, the volume of space contained between us and the most distant sources, as well as the distribution and numbers of such sources and of potential lens galaxies vary accordingly. For example, increasing the dark energy increases the volume and, thus, the number of GLS one could find in a survey. By comparing model predictions with results from lens surveys, we are able to constrain cosmological parameters. A recently completed search for strong GLS, the CLASS survey, is consistent with the concordance cosmology [37]. These results are in good agreement with the independent determinations from, for example, distant supernovae [38]. However, these results still carry significant uncertainties such as the changing radio source population as a function of survey flux limit [39].

A different technique, insensitive to the overall matter density of the universe, utilizes weak gravitational lensing. The gravitational potential fluctuations of weak lenses cause generally small distortions in the shapes of background sources. By measuring these distortions, one can determine the amplitude of density fluctuations. Tomographic surveys that include the radial cosmic coordinate yield three-dimensional (3D) information; otherwise, one determines 2D variations, where the radial coordinate is integrated out. The current weak-lensing measurements are degenerate: measurements may be consistent with small (large) fluctuations in a high (low) density universe. Microwave background observations do yield unique estimates of the density fluctuations at early cosmic times. By combining microwave-background and weak-lensing observations, one can then determine the mass-energy density of the universe (e.g., [40]). The current weak-lensing determination is $\Omega_m \approx 0.3$ with a 10% error [27].

The nature of the mass fluctuations is also of interest. Structures such as clusters, galaxies and stars appear to have originated from cosmic matter-energy fluctuations. Those structures grow and evolve under the influence of their own gravity. Weak and strong gravitational lensing both provide valuable tools for measuring the mass distribution in the universe, from the largest to the smallest scales. Because the deflection of light does not depend on the nature or dynamical state of the deflecting mass or energy in the weak-field limit, one can investigate the distribution of all mass, dark or light. Gravitational lensing thus provides a new technique, superior in many ways to galaxy-distribution studies that only trace luminous matter and hence need to be scaled with an assumed factor called bias, σ_8, which allows one to relate light fluctuations to matter fluctuations and thus identify where galaxies form [32, 33].

3.2. The quest for $H_\circ$

The Hubble 'constant' $H_\circ$ is one of the essential parameters of physical cosmology. It reflects both the size and the age of the universe. However, estimating $H_\circ$ has proved quite a challenge since the 1920s, when Edwin Hubble discovered that the universe is expanding.

The classic approach has been to build a cosmic distance ladder. Astronomers use nearby celestial objects, for which distances can be measured relatively easily, to calibrate the distances to objects farther away. In that fashion, they can bootstrap to distances to far-off objects that move predominantly with the Hubble flow (i.e., for which the cosmic expansion velocity is much larger than their peculiar velocities). Unfortunately, we have a limited understanding of the underlying physics of many of the objects that are used to construct the distance ladder. Therefore, the empirical corrections that need to be applied to observations can hide biases that limit the reliability of the results.

GLS promise an accurate, independent measurement of $H_\circ$ in a way that bypasses the distance ladder. The concept, as first proposed by Refsdal [11], is to observe a multiply-imaged

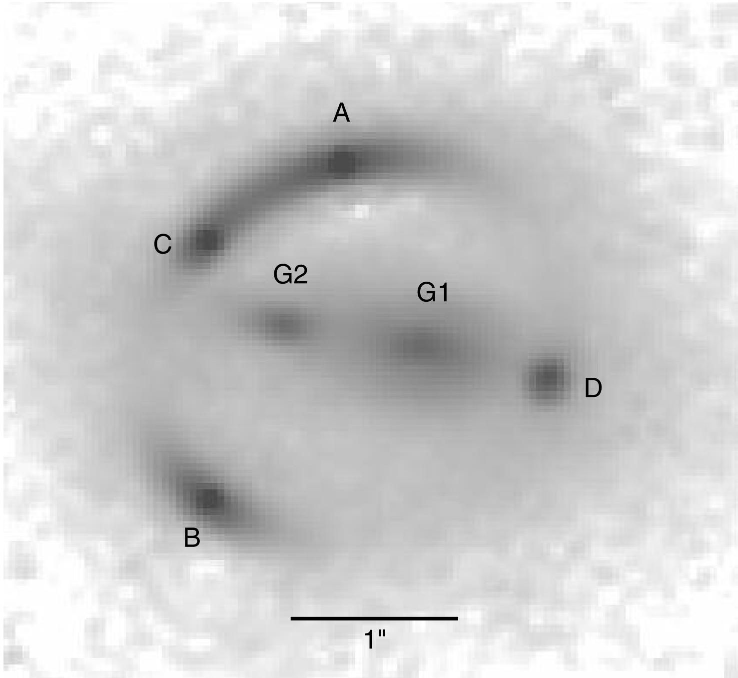

Figure 7. HST NICMOS H-band image of the quadruple GLS B1608 + 656. The same procedure as that of figure 3 removed PSF artifacts. Note that in this case, the lens consists of a pair of elliptical galaxies, G1 and G2. Note also the partial Einstein ring, or arc, joining images A and C.

variable source created by a strong lens such as those in figure 4. The travel times associated with the different images formed by such lenses differ from the single travel time in the absence of the lens. The differences in the geometrical pathlength for each image and in the gravitational potential experienced by deflected light rays account for the differences in these travel times, or time delays Δt. These delays range from days to years, and are inversely proportional to $H_\circ$. Thus, they are well suited for measurements by ground-based telescopes in dedicated monitoring programs. The physics of gravitational lensing is well understood. Moreover, astronomers can conduct lensing measurements on relatively nearby sources ($z < 2$, say), which allows them to determine a value for $H_\circ$ that depends only weakly on other cosmological parameters such as Ω_m and Ω_Λ (SEF).

The determination of $H_\circ$ by measuring time delays does require that the mass distribution of the lens be determined accurately. Small perturbations to the gravitational potential from other galaxies near the lens must also be taken into account. Observational efforts have often focused on measuring time delays and have neglected the systematics of the mass distributions. Consequently, measurements of $H_\circ$ inferred from different lens systems have been inconsistent. At present, about a dozen GLS have accurately measured time delays and more are in the pipeline. Given the increased abundance of time delays, astronomers have shifted their attention to refined modelling of the stellar and dark-matter distributions in lens galaxies to improve the determinations of lensing gravitational potentials.

The strong GLS CLASS B1608 + 656 (a quadruple, see figure 7) is particularly interesting because observers have measured all possible time delays [41]. These range from ∼30 to ∼77 days with uncertainties between 2 and 5%. Combining time-delay and mass estimates yields an estimate of $H_\circ$ of 75 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with an error of about 10%, in agreement with the estimate of the HST Key Project [34]. In recent years, additional 'clean' lens systems (where the mass distribution of the lens is well constrained) have been analysed in detail and the corresponding estimates of $H_\circ$ seem to be converging. That is encouraging for further improvements in the technique and for observational programs to add to the sample of measured time delays.

Because of the large separation of the images in Q0957 + 561 and the asymmetry in the image configuration, the time delay Δt for the two images is large, ≈1.1 year. Thus, long campaigns to measure Δt were started, in particular that of Rudy Schild for well over a decade (e.g., [42]). The meek variations of the quasar contributed to a long but now faded controversy on the true value of the delay [43, 44]. The complications in the modelling of the mass distribution of this first GLS are such that the estimates of $H_\circ$ agree with newer ones, but the uncertainty of 25% detracts from its usefulness as a test of cosmological models [45].

Currently, there are 11 GLS with measured time delays. The relative uncertainties in the delays range between ∼1 and 37%, although 10 are below 15%, 7 below 5% and 1 below 1%. The range reflects the difficulties of measurements that require prolonged monitoring of signals that can be weak. Ideally, we want uncertainties of 1% so that the errors in the time delays will be smaller than mass modelling errors. That is achievable because once a delay is identified, intensive monitoring with observations phased by the delays can reduce the errors. So far, the four 'cleanest' lenses (see below) yield $H_\circ = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ only if their mass profiles follow their light distributions. The expected presence of dark matter in these profiles yields instead $H_\circ = 48 \pm 3\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [2]. This dichotomy can only be addressed experimentally with a much larger sample of time delay measurements.

For the application of time-delay measurements to estimates of $H_\circ$, a robust determination of the mass profile of the lens is essential. Therefore, 'simple' systems with a single galaxy are preferable, rather than complicated clusters such as that in Q0957 + 561. Mass perturbations near the line of sight of a given GLS are unavoidable, but a sufficiently large sample of GLS will yield sufficient numbers of systems, where such perturbations are minimized. These will need to be observed with telescopes such as HST or similar space platforms, to obtain the best possible astrometry, and monitoring will be required from the ground. Once we have a robust measurement of $H_\circ$, we can turn around the approach and use that to help constrain the mass distributions of GLS. Therefore, it is also worthwhile to monitor GLS even if they are not simple.

For two years, we have monitored several GLS to estimate time delays and identify microlensing when it occurs (with J Heinmueller (University of Potsdam), J Wambsganss (ARI Heidelberg) and C Kochanek (Ohio State University)). Among our targets, we have observed a new, relatively wide-separation quadruple GLS, SDSS J1004 + 4112 [46] for the past 7 months. Figure 8 shows the lightcurves of the brightest two of the four images. First attempts at estimating the time delays were successful only for the two brightest images, yielding a value of about 25 days. The obstacle to a final determination is that the quasar became active towards the beginning of July 2004, as it started to set early and become unobservable for a few months. In this case, the time delay is relatively small for such a large-separation GLS, because the bright images are in close proximity, due to the lens configuration. We hope to improve on these measurements during the next observing season.

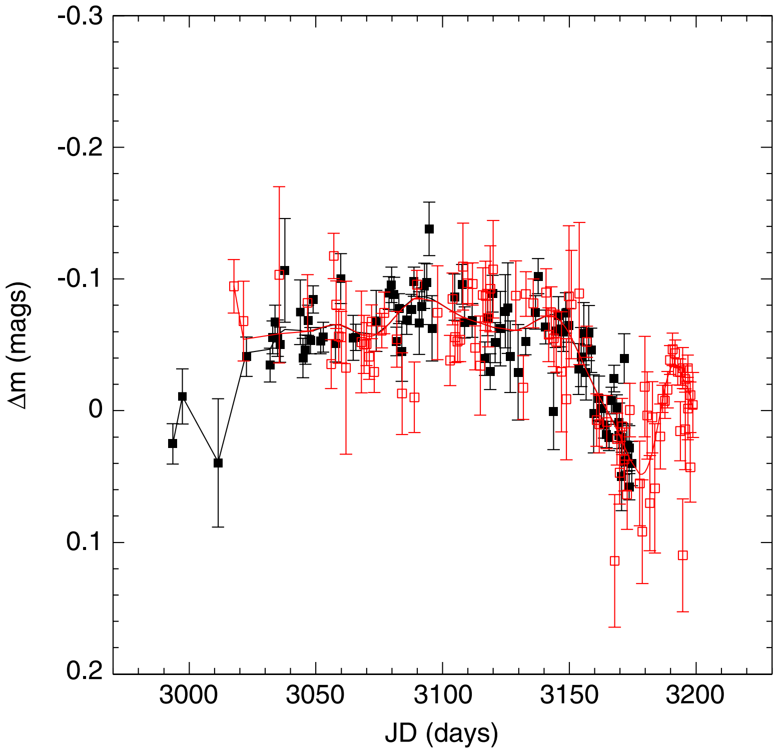

Figure 8. Light curves for A (black) and B (red), phased by ∼25 days. We obtained observations between December 2003 and July 2004 with the FLWO 1.2 m telescope and the 4shooter CCD mosaic, with a Johnson R filter.

4. Structure at the largest scales

The growth of density fluctuations from the time when the microwave background decoupled from matter, $t \approx 0.0004$ Gyr, to the present, $t \approx 14$ Gyr, appears to be well understood. Theory yields a consistent interpretation of observations such as those of WMAP (see, e.g., [32]). A new method is to measure the cosmic shear, or weak-lensing distortions of distant galaxies encompassing a wide range of angular scales. Such distortions can be measured statistically, because the universe should impose no special orientation on galaxies. The technique is most sensitive to the amplitude of density fluctuations of matter over the last ∼7 Gyr of the lifespan of the universe.

For density fluctuations $\delta\rho/\rho$ in a spherical region subtending angle θ on the sky, the angular distortion imposed on an image of a galaxy scales as $\Omega_m \theta(\delta\rho/\rho)$. About θ^{-1} independent spherical regions can be found along the line of sight; their distortions add stochastically. Therefore, the amplitude of measured shear is about $\Omega_m \theta^{1/2}(\delta\rho/\rho)$. Over angular scales between 0.5 and 100 arcmin (corresponding to ∼0.5–100 Mpc), the overall average distortion is $\sigma \approx 0.002$. That is, cosmic shear induces that much (or little!) excess distortion over random. Detections of cosmic shear are now confirmed by several independent groups (e.g., [27] and references therein).

To assess the properties of large-scale density fluctuations, the technique dubbed 'aperture mass statistic' consists of imaging regions on the sky subtending an angle θ [47]. One measures the shapes and orientations of as many galaxies as possible within those regions and determines the average distortions. If the sample contains N galaxies, the statistical error is $\sim N^{-1/2}$. In theory, that is all one needs, but the atmosphere, the telescope and the detector introduce systematics with amplitudes comparable to that of the weak-lensing signal, and thus compromise the simplicity of the technique. The necessary sample sizes are $\sim 10^6$ galaxies to obtain sufficient accuracy. Recently, samples of that size have yielded measurements of the amplitude of the density fluctuations as a function of angular scale that agree with theory [27].

Cosmic-shear measurements so far have covered areas $\ll 1\%$ of the sky. Therefore, the technique remains in its infancy. However, in the next decade or so, wide-field surveys and tomographic weak-lensing studies should yield detailed mass maps of the universe from its largest scales (several $\times 10$ degrees), down to cluster scales.

5. Clusters and galaxies

Clusters of galaxies are the largest bound structures in the universe. They are the most recently collapsed structures and they preserve the history of their formation; thus, they are of singular value in the study of the evolution of structure from the linear ($\delta\rho/\rho \ll 1$) to nonlinear ($\delta\rho/\rho \gg 1$) regimes. Their masses range up to nearly $10^{15} M_\odot$ (solar masses), 85% of that in dark matter. Combined with predictions from large numerical simulations, observations of clusters of galaxies are a useful tool for testing cosmological models.

Weak-lensing measurements help resolve cluster mass distributions at radial distances from their centres r as large as ~ 10 Mpc. At that radius, clusters start to mingle with their surroundings, which eventually become the large-scale structure. Weak-lensing is now being combined with x-ray observations, measurements of galaxy velocities, and detections of the Sunyaev–Zeldovich effect on the microwave background. With such data, one can map the distribution of galaxies, dark matter and gas that compose clusters.

The inner regions ($r < 100$ kpc) of rich clusters produce strong gravitational lensing of background galaxies, which may appear as giant arcs that may be multiply imaged (e.g., see figure 6). Generally, these are tangential arcs (relative to the radial direction towards the centres of the clusters), but they may also be radial, smaller arcs, as predicted by theory. Measurements of such arcs can be combined with x-ray observations and stellar kinematic studies of the central galaxies to determine the central mass distributions of the clusters. Simulations predict cusps in these distributions, i.e., highly anisotropic inner density profiles with $-\mathrm{d}(\ln\rho)/\mathrm{d}(\ln r)$ in the range 1.0–1.5. Recent observations are in accord with this range of slopes. These results imply that the distribution and amount of dark matter are well-represented in current models.

Lensing makes a clear and significant contribution to our understanding of matter at the scale of galaxy clusters. At the scale of the components of clusters, galaxies, lensing is equally propitious. Galaxies trace the matter distribution in the universe for the benefit of observers. Just as for clusters, our current understanding is that galaxies undergo hierarchical merging as a function of cosmic time. Our understanding of how their formation and evolution is strongly model-dependent, even more so than for the large-scale structure and for clusters: gas-dynamical, stellar, radiative and nuclear processes can segregate gas, stars and dark matter and can affect galaxy mass and energy content in a way that is difficult to quantify. GLS measurements are thus especially important, because they can provide an accurate measurement of galaxy masses on radial scales from 1 to 1000 kpc. Estimates of the lens mass in strong GLS are insensitive to the type of mass (light or dark), and are the most accurate estimates obtainable.

Gravitational lensing plays a dominant role in the determination of the mass and its distribution for galaxies beyond our vicinity, i.e., at redshifts $z \geqslant 0.1$. We know that the halos of galaxies (their outermost regions) are dominated by dark matter, but we do not have a good understanding of their extents and shapes. A particularly good way to explore halos on scales of 50–1000 kpc is to use galaxy–galaxy lensing. The technique involves statistical measurements of the weak-lensing distortions near galaxies. This subtle effect consists of apparent slight elongation and alignment of background galaxies due to galaxies in the foreground. The effect has been used successfully to trace dark-matter halos well beyond the light distribution of the galaxies and to show that the radial dependence of the density is consistent with numerical simulations. For typically bright galaxies, observers have determined the half-mass radius and have demonstrated that dark matter is elongated in the same direction as the light distribution (e.g., [26]).

Observations of strong lensing can determine how mass is distributed in the regions of galaxies within $r \leqslant 10$ kpc. Through detailed mass modelling combined with accurate photometry and pectroscopy, one can determine the distributions of stellar and dark matter within individual galaxies (e.g., [48]). Telescopes such as HST, in consort with radio telescopes, produce high-resolution images and large ground-based optical telescopes supply stellar velocity distributions. Recent results show that distant galaxies have isothermal densities satisfying $\rho \propto r^{-2}$, but the exponent has large scatter, about 15%. The results for distant galaxies are consistent with those obtained for nearby ones [49].

At smaller scales within the dark-matter halos of galaxies, simulations with only cold dark matter predict that ∼10% of the dark matter should occur in a great many small compact satellite galaxies. So far, only a handful of them have been observed near the Milky Way. Satellites may be present but dark, and may have escaped detection. Such satellites affect how individual lens galaxies produce multiple images. A lens galaxy with a sufficiently smooth mass distribution has a remarkable property: if it produces two or three highly magnified images (e.g., figure 7) that merge, then a combination of signed image fluxes adds to zero. However, if the mass in the lens galaxy contains significant numbers of dark-matter satellites, with their related small-scale gravitational-potential perturbations, the relation does not hold. For many GLS with highly magnified images, the sum is not zero [50], which has been interpreted as a detection of these dark-matter satellites [51]. The flux relations have been checked for only a small number of GLS, so the indications of dark-matter satellites are preliminary. To confirm their existence, observers need to find their direct effects on the fluxes and shapes of multiply imaged sources. High-resolution radio observations (∼0.001 arcsec level) could reveal such effects, as could observations of lensed quasars in the mid-IR waveband, where propagation effects such as absorption, scattering and microlensing are negligible.

Recently, Pelló *et al* [52] reported on the first likely spectroscopic confirmation of a $z \sim 10.0$ galaxy in their search for galaxies at $z > 7$ with the ISAAC near-IR imager and spectrograph on the ESO Very Large Telescope (VLT). More recently, their results were contested [53], but Pelló *et al* ([54]; see also online reference therein) made a strong case for their result, which depends critically on following the proper analysis procedures. In spite of this apparent controversy, these tantalizing results will likely be confirmed, and I will assume they are correct, at least for illustration purposes. Pelló *et al* [52] found a very faint galaxy behind a cluster of galaxies, Abell 1835, which is a known GLS. Their spectroscopy yielded a faint emission line in the near-IR J band that they identified as the Lyman-α hydrogen line at 1216 Å. Its redshift agreed with their photometric redshift determination for the galaxy. Because photometric redshifts are based on imaging through different filters, they are a coarser determination. But the agreement with the spectroscopic measurement was a strong confirmation of the redshift. Pelló *et al* estimated that the galaxy in question is magnified by a factor between 25 and 100. They were also able to estimate several of its physical properties such as star formation rates, which indicate a young 'protogalaxy' undergoing a burst of star formation. These results show that the natural telescopes provided by lensing, together with ∼10 m class telescopes, allow astronomers to study galaxies near the cosmic 'dark ages', a few hundred Myr (about 3% of the age of the Universe) after the big bang. The lensing magnification in this case illustrates the great utility of lensing in high-resolution spectroscopy of 'Lyman-break' galaxies, compared to what is achievable with unlensed galaxies.

6. CASTLES: a lensed quasar sample

The CASTLES project (CfA/Arizona Space Telescope LEns Survey[1]) is a non-proprietary survey of known galaxy-mass GLS using the Hubble Space Telescope (HST) and a uniform set of filters. As the characteristic size of galaxy-scale lenses is $\Delta\theta \sim 1$ arcsec, precision photometric studies of the lensing galaxies and of lensed quasar host galaxies (remembering that quasars are active galactic nuclei, AGNs) are only practical with HST. HST also provides the best possible refinement of astrometry at optical and IR wavelengths for GLS components. Before CASTLES, HST images existed for very few of the known galaxy-mass lens systems. Furthermore, the broad range of filters and exposure times that had been used severely limited the usefulness of these observations.

The goals of CASTLES are: (i) accurate astrometric measurements to refine lens models, particularly for systems where a time delay may provide a direct measurement of $H_\circ$; (ii) photometric redshift estimates for all the lens galaxies in the sample, to sharpen lensing constraints on Ω_Λ and galaxy evolution; (iii) direct estimates of the mass-to-light ratio (all of the mass divided by all of the light, within a given volume and a given waveband) M/L of lens galaxies up to $z \sim 1$, to derive new constraints on their mean formation epoch and star formation history; (iv) a comparison of the dark matter and stellar light distributions in the lens galaxies, and thus new constraints on the structure and shapes of galaxies, for a mass-selected, rather than luminosity-selected sample; (v) measurements of the properties of the interstellar medium in distant galaxies, using differential extinction between the lensed images; (vi) identification of as yet undetected lens galaxies in known multiple-image systems, which confirms lensing and enlarges the sample for cosmological studies; (vii) understanding of the environments of lens galaxies and their role in the lensing phenomenon; and (viii) estimates of the photometric properties of lensed quasar host galaxies.

The survey currently contains all ∼80 small-separation ($\Delta\theta \leqslant 15$ arcsec) GLS. See figures 2, 4, 5 and 7 for examples of CASTLES images. The GLS in CASTLES were found as a product of optical quasar surveys, radio lens surveys and serendipity. In all cases, there is a dominant lens galaxy which may be a member of a group or small cluster. The heterogeneity of the overall sample is important for some questions (e.g., the separation distribution), but relatively unimportant for others (e.g., the evolution of the lens galaxies). We observed our targets in the near-IR (principally the H band, but in a few cases, J and K) with the NICMOS camera NIC2. The IR observations are complemented by new or archival WFPC2 imaging in the optical I and V bands to obtain uniform VIH multi-colour photometry of the systems. In the latest HST cycle,

[1] See cfa-www.harvard.edu/castles.

we continue to use NIC2 and we are also using the ACS (Advanced Camera for Surveys) with its wide-field camera (ACS/WFC) and V and I filters.

6.1. CASTLES results

CASTLES observations have yielded studies of dark matter and of the interstellar medium in lens galaxies at redshifts up to redshifts $z \sim 1$, as well as the properties of lensed quasar hosts at $z > 1$. Gravitational lensing enables such studies at high redshifts.

6.1.1. Dark matter. Significant progress has recently been achieved in studies of early-type (elliptical) galaxies. The homogeneity of these galaxies results in a strong constraint on formation models. Firstly, the population exhibits very uniform colours both locally and at $z \sim 1$. Secondly, early-type galaxies follow a tight correlation among their central velocity dispersion, effective (half-light) radius and surface brightness known as the fundamental plane (FP, e.g., [55]). The scatter in the FP, which is closely related to the scatter in mass-to-light ratio, is locally small, does not evolve significantly with redshift, and shows little dependence on the environment of the galaxies. In current hierarchical models of galaxy formation, the mergers of late-type (spiral) galaxies create elliptical galaxies. Support for the model is provided by the observation that high-redshift clusters exhibit both larger merger rates and smaller fractions of elliptical galaxies, compared to their present-day counterparts. Semi-analytic CDM models (e.g., [56]) predict that early-type galaxies in the field should contain recently formed ($z_f < 1$) stellar populations, while those in clusters should have significantly older stellar populations. Local studies have difficulty separating the effects of age and metallicity (e.g., [57]), but such degeneracies can be broken by measuring the evolution of mass-to-light ratios with redshift.

We recently completed an analysis of the evolution of 28 mass-selected early-type field galaxies spanning the redshift range $0 < z < 1$ [48]. We measured an evolution rate for the mass-to-light ratio in the rest-frame B band of $\mathrm{d}\log(M/L)B/\mathrm{d}z = -0.54 \pm 0.09$, consistent with other recent determinations. However, our study shows that the stellar populations of early-type field galaxies formed at $z_f > 1.8$ and argues against significant episodes of star formation at $z < 1$.

6.1.2. Extinction. An understanding of the interstellar medium through extinction laws is required for models of galaxy evolution, to establish a global history of star formation. Extinction also affects the light curves of γ-ray bursts for example; deriving the extinction law from afterglows requires theoretical assumptions about the intrinsic spectrum of the burst. Precision measurements of extinction curves are generally limited to the Galaxy and the Magellanic Clouds (Small, SMC and Large, LMC), because at greater distances it is impossible to obtain the precise photometry or spectroscopy of individual stars needed for accurate extinction law measurements. In the SMC and LMC, the UV extinction curves can deviate significantly from the Galactic models, most obviously in having a far weaker 2175 Å feature. Physically, the extinction law depends on the mean size and composition of the dust grains along the line of sight, so it should not be surprising that it varies with the environment. With the increasing need for extinction corrections at increasingly higher redshifts, it is clear we need more quantitative measurements of dust properties at similar redshifts. GLS allow estimates of the extinction properties of high redshift galaxies.

In most of the known lens galaxies we see two or four images of a background quasar produced by the deflection of light by a foreground lens galaxy. When light from each image traverses the lens galaxy, it is extincted by the dust at that position. As the dust distribution is generally not uniform, each image suffers a different amount of extinction; the observational signature is that the flux ratios of the images depend on wavelength. We demonstrated a method using these properties in Falco *et al* [58], where we determined differential extinction in 23 gravitational lens galaxies over the range $0 < z_l < 1$. Of the 23 systems we analysed, 16 have spectral differences consistent with differential extinction. 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 GLS surveys, thereby confirming the need for extinction corrections when using the statistics of lensed quasars to estimate the cosmological model.

Recently we showed that GLS can be used to measure extinction curves at intermediate redshifts with high accuracy [1]. In that study, we derived the extinction curve of a distant galaxy ($z = 0.83$) by comparing two images of a gravitationally lensed quasar that are differentially reddened by the lens galaxy. We observed the double-image GLS SBS0909 + 532 with the 2D spectrograph INTEGRAL-WYFFOS. From the spectra in our integral-field data, we derived the differential extinction curve between the two images of the quasar (figure 9). Ours is the first determination of an extragalactic extinction curve with confidence and quality similar to those derived for galaxies in the Local Group. The presence of a significant 2175 Å feature (bump) in the extinction curve is noteworthy, for it has been considered weak or non-existent outside the Milky Way. The average Milky Way extinction curve also fits well the SBS0909 + 532 extinction curve with $R_v = 2.1 \pm 0.09$. The dust redshift estimated using as reference the zero redshift extinction curve is $z = 0.88 \pm 0.02$, in good agreement with the spectroscopic redshift of the galaxy.

In Muñoz *et al* [59] we estimated the dust extinction laws in two intermediate-redshift galaxies. The dust in the lens galaxy of LBQS1009-0252, which has an estimated lens redshift of $z_l \simeq 0.88$, appears to be similar to that of the SMC with no significant feature at 2175 Å. Only if the lens galaxy is at a redshift of $z_l \simeq 0.3$, completely inconsistent with the galaxy colours, luminosity or location on the fundamental plane, can the data be fit with a normal Galactic extinction curve. The dust in the $z_l = 0.68$ lens galaxy for B0218 + 357, whose reddened image lies behind a molecular cloud, requires a very flat ultraviolet extinction curve with (formally) $R_V = 12 \pm 2$. Both lens systems seem to have unusual extinction curves by Galactic standards.

6.1.3. Photometry of quasar host galaxies. Peng [60] examined the properties of quasar host galaxies observed for CASTLES. Little is known about these galaxies at high redshifts. Fortunately, the combination of gravitational lensing with HST/NICMOS in CASTLES yields detections of many of these. The magnification provided by the lensing allows measurements of much fainter lensed hosts than otherwise possible. Figure 10 shows the spectacular example of Q0957 + 561.

The current sample of quasar host galaxies at $z > 1$ is small and difficult to interpret. Diverging interpretations of their properties can begin to be addressed with the CASTLES sample. Peng [60] analysed 29 GLS observed with HST/NICMOS to determine their intrinsic luminosity, size and morphology. This sample included host galaxies up to $z \sim 4$, with 17 (12) secure (marginal) detections. The analysis included modelling the mass distribution of each GLS, to establish the properties of the unlensed host galaxy. A very interesting conclusion of this study was that, after evolution is taken into account, host galaxies are a less extreme sample in terms

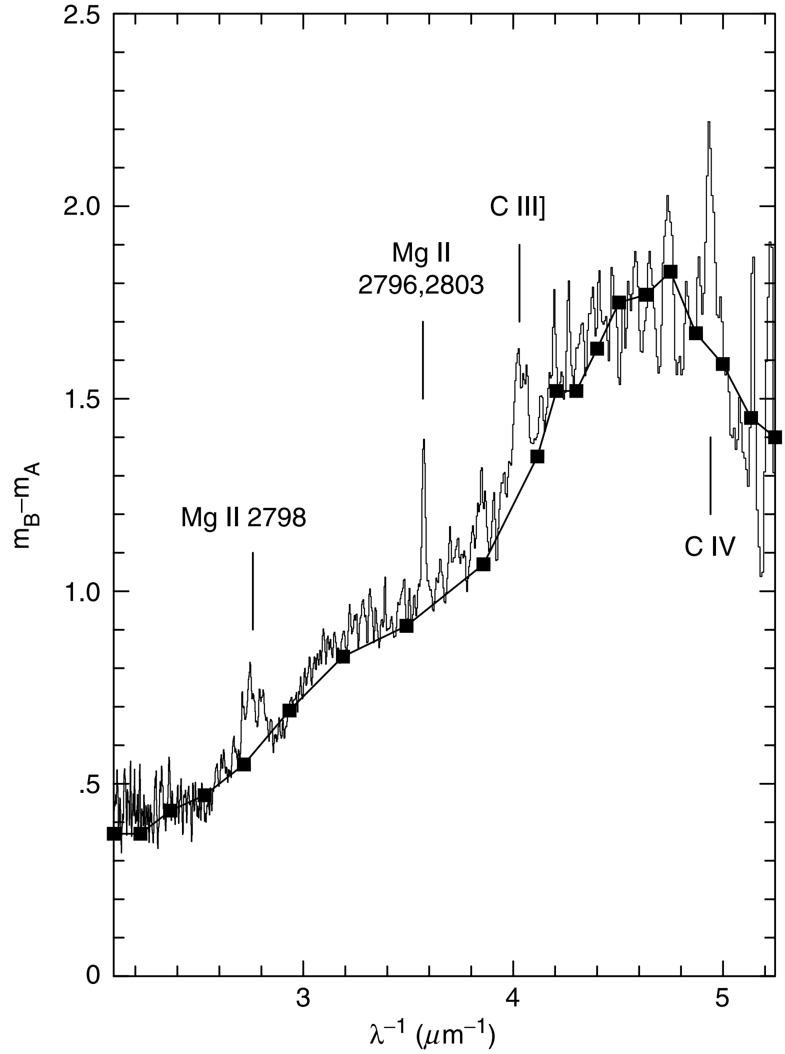

Figure 9. The differential extinction curve for SBS0909 + 532. The continuous line is the $m_{B_u} - m_{A_u}$ magnitude difference curve obtained from the spectra of A and B. The abscissa is the inverse wavelength at the lens galaxy rest frame (the standard method to display extinction properties).

of luminosity than the average luminous galaxy at $z \sim 0$. Their morphologies are a mixture of late-type (spiral) and early-type (elliptical) galaxies. Still to be established are the evolutionary paths for these galaxies to those we see in our vicinity.

Kochanek *et al* [61] analysed a handful of GLS in the CASTLES sample that showed IR Einstein ring images, i.e., lensed quasar host galaxies. They developed a technique to analyse the rings, and obtain morphological properties of the host galaxies. Their technique combined with sufficiently deep high-resolution observations (HST or JWST) of Einstein rings yields the strongest constraints on mass models for the lens galaxies.

Lensed quasar host galaxies provide a large number of additional constraints for lens models. However, such modelling is significantly more complex than models containing only point-like sources. Q0957 + 561 provides a sobering example, as shown by Keeton *et al* [62].

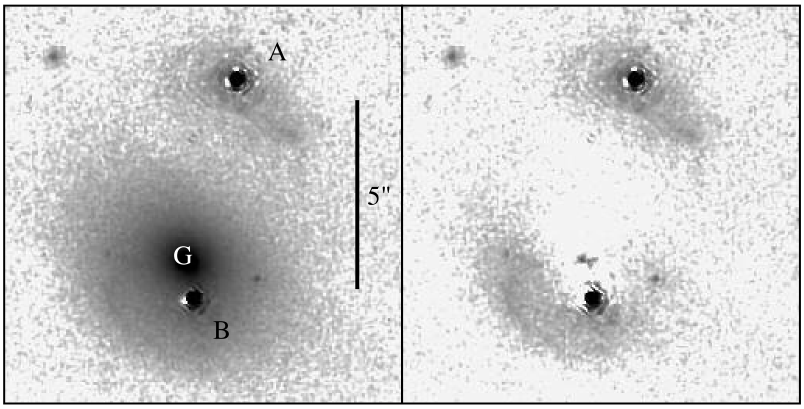

Figure 10. The double GLS Q0957 + 561. The two images are A and B at $z_s = 1.41$. G is the main lens galaxy, a cD at the centre of a cluster of galaxies at $z_l = 0.36$. The left panel shows our CASTLES NICMOS H-band image after removal of PSF artifacts, as in figure 2. The right panel is the image from the left panel, after subtraction of a photometric model for G. The arcs centred on A and B are images of the host galaxy of the quasar.

7. Microlensing

Microlensing forms multiple images, but with very small separations, 10^{-6}–10^{-3} arcsec, usually unresolvable with current optical telescopes. But these telescopes can easily detect the corresponding large increases in the total brightness of the lensed source. Fortunately, massive objects as light as planets have detectable, distinct microlensing signatures. The required measurements are of large flux changes in compact background sources due to the passage near the line of sight to intervening compact masses. Such measurements are relatively straightforward.

Luminous stars and compact dark objects may both act as microlenses. The densities of compact objects in galaxies are low: the probability that a given background source is microlensed by the foreground constituents of the Milky Way is very small ($\approx 10^{-6}$). Very large surveys are required to find such sources. Observers have adopted the promising strategy of looking either near the centre of the Milky Way or towards other nearby galaxies such as the LMC, where millions of stars are susceptible to being micro-lensed.

A slew of interesting results came from the pioneering work of several projects, the Massive Compact Halo Object (MACHO), Expérience de Recherche d'Objets Sombres (EROS) and Optical Gravitational Lens Experiment (OGLE) collaborations. Additional spectacular results have recently followed from the subsequent world-wide monitoring collaboration dubbed Probing Lensing Anomalies NETwork (PLANET). These groups monitored stars in the LMC and attempted to find rapid brightness (thus, magnification) variations due to compact dark matter in our own galactic halo (e.g., [63]). The MACHO team concluded that about 20% of the Milky Way halo is in compact objects of about 0.5 solar masses. Such a high mass content exceeds the total mass of the known stars. Self-lensing, where both the source and the lens are in the Magellanic Clouds, may explain the MACHO results. The EROS team found fewer microlensing events than the MACHO team, and set an upper limit of 25% for the compact dark matter content

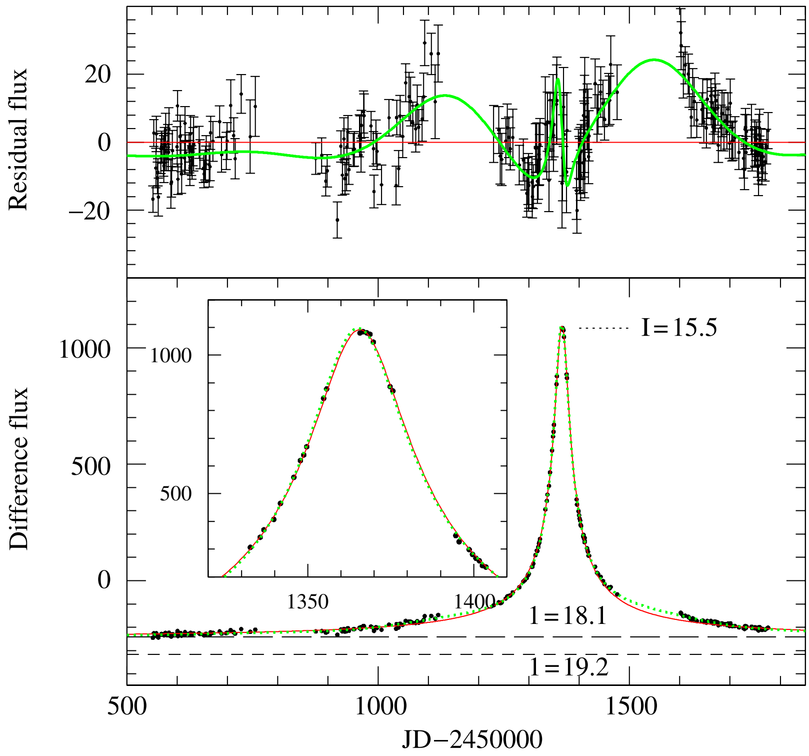

Figure 11. A possible black hole from microlensing evidence: I-band light curve for OGLE-1999-BUL-32 from Mao *et al* [64]. Their analysis of this spectacular event (note the scale on the left and the long timescale) yielded a lower limit for the mass of the microlensing star, $\sim 40 M_{\odot}$, that puts it in the stellar-mass black hole range.

of the halo. Thus, only a small fraction of the dark matter in the halo of the Milky Way appears to consist of MACHOs: dark matter must be a still undiscovered type of particle.

Microlensing is also useful as a probe of black holes. A potential 'dark star' is recognized when a lens mass is measured to be more than about $3M_{\odot}$, too heavy to be a neutron star or white dwarf. If the lens is sufficiently nearby, one might be able to rule out a luminous star as an explanation, which would leave only a black hole as a viable candidate. The microlensing technique is the only tool astronomers have for measuring the density of isolated black holes in the Milky Way. It has already been used to find three reasonably convincing stellar-mass black hole candidates, one of which is shown in figure 11 [64].

A binary microlens yields a more complex flux distribution, such as that shown in figure 12 [65]. These complex light curves are the only means to infer the presence of planets, which are too faint to be seen directly: the planet and its star are the imaged binary. The first convincing case of a microlensing event by a star with a Jupiter-mass companion (presumably a planet) was found recently by the OGLE and Microlensing Observations in Astrophysics (MOA) collaborations (figure 12).

Recently, Gould *et al* [66] obtained a direct measurement of the mass of a star. Such measurements are few and difficult, with fairly large uncertainties. It is essential to obtain such measurements for the sake of stellar evolution theory, because most measurements of stellar

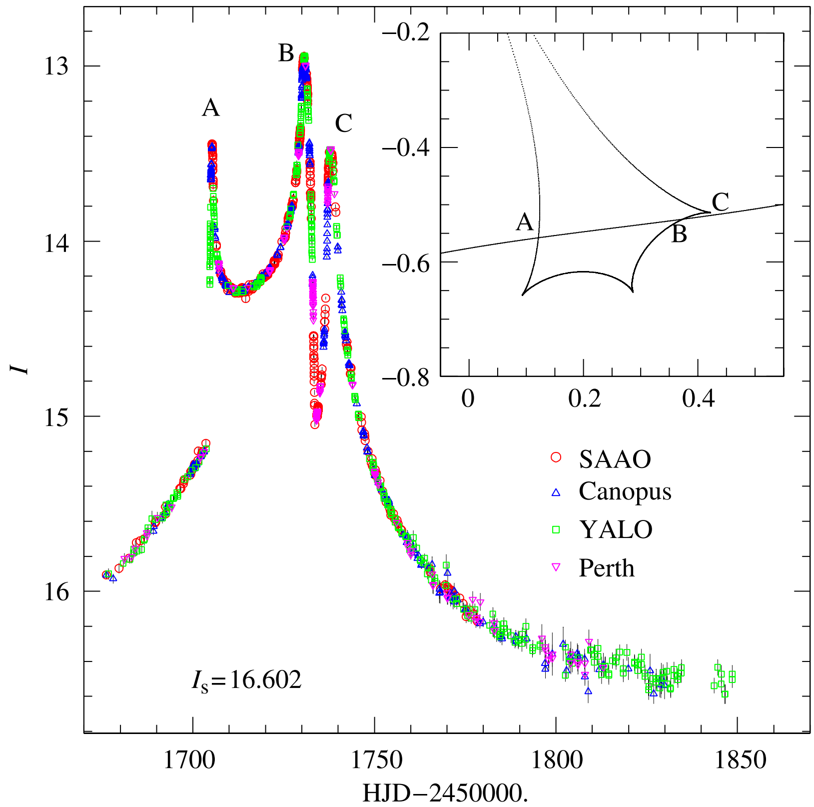

Figure 12. A binary microlens example: the I-band light curve of EROS BLG-2000-5 from PLANET, with different symbols representing different telescopes ([65], figure 1). Peaks A and B are typical of ingress and egress caustic crossings, while C corresponds to a passage near a caustic cusp (SEF). The inset shows the positions of the source that correspond to the peaks A, B and C, relative to the microlensing caustic curve.

masses derive from observations of binary systems and the properties of isolated stars may differ from those of binaries. Gould *et al* showed that the MACHO-LMC-5 microlensing event yields a measurement with unprecedented accuracy. Their technique combines HST/WFPC2 and HST/ACS astrometry and photometry with the properties derived from the microlensing lightcurve. The available observations had astrometric accuracy sufficient to determine the relative parallax and the proper motion of the source and the lens. In the end, their technique yields an estimate for the mass of the lens of $M = 0.097 \pm 0.016 M_{\odot}$. Gould *et al* also showed that the accuracy may be improved further, to $\sim$10% errors, by an improved re-analysis of the photometry and with new observations with the Space Interferometry Mission (SIM).

The probability of microlensing in the Milky Way is very low, but stars in other galaxies that already act as strong lenses can form a caustic network that can magnify or demagnify compact sources on μarcsec scales [67, 68]. The accretion disks in lensed quasars or the shock fronts in lensed radio jets, for example, could be highly magnified. Observations of microlensing of such objects could reveal their size and structure on very small angular scales. From microlensing studies, astronomers have learned that massive black holes contribute only a small percentage of the mass in distant galactic halos (e.g., [69]).

8. Conclusions

The rapid transformation of gravitational lensing from a curiosity to a cosmological and astrophysical tool has been possible through painstaking observations at radio, near-IR, optical, UV and x-ray wavelengths. However, much work remains before GLS can be used to provide more complete answers to many interesting questions in the astrophysical and cosmological realms. Some examples are studies of: the galaxy halo mass function; the central surface mass densities of galaxies, including the possibility of the presence of supermassive black holes; dark satellites of lens galaxies; and lensed quasar hosts [2].

There is one simple step that is always required for strong lensing to achieve its full potential as a tool: redshifts need to be measured with 10-m class telescopes. At present, only about one-half of the extant sample consists of GLS with measured source and lens redshifts. A modest investment in observing time would yield a very significant scientific return by allowing complete analyses of GLS. A step that requires a larger commitment of telescope time is the monitoring of GLS. Such monitoring continues at various sites under many projects (e.g., FLWO, Canaries, MDM, SMARTS, the many microlensing collaborations). The potential payoff is very high for a refined understanding of light and dark matter distributions in galaxies, and for estimates of $H_{\circ}$.

The current, continually growing sample of ≈80 strong lenses must grow significantly larger, at least to the level of a few hundred GLS. When that level is reached, selection biases (e.g., radio, optical, serendipitous discovery) should become well understood and come under our control.

Wide and deep surveys are now being conducted with ground-based telescopes, which will observe $\sim 10^7$ galaxies and measure their weak-lensing distortions on $\sim 1^\circ$ angular scales. They should also discover many new cases of strong lensing. Some of those surveys will also be able to determine the distances of the galaxies based on photometric (rather than spectroscopic, more costly) redshifts, and thus enable tomographic studies. The ongoing surveys will provide data on the evolution of mass fluctuations. The data can then be compared with simulations that make accurate predictions as a function of the cosmological model and of the parameters of various models. Finally, the availability of large numbers of lenses from systematic surveys will lead to an improvement of the remaining systematic problems in the interpretations of the results.

Further advances can be expected from new space and ground-based telescopes with large effective apertures and wide fields of view that are under design. These will conduct gravitational lensing studies among others. The 2-m class SuperNova Acceleration Probe (SNAP) is designed to detect ∼2000 supernovae up to $z \sim 1.7$, and to provide the best weak-lensing dataset possible. SNAP should also discover $\sim 10^5$ galaxy-sized strong lenses and advance our understanding of galaxy mass distributions.

The Space Interferometry Mission (SIM) is designed as a space-based 10-m baseline optical Michelson interferometer operating at visible wavelengths. SIM astrometry will have unprecedented accuracy, a few microarcsec over the sky and down to $1\,\mu$arcsec in single measurements within 1° fields. In this mode, SIM will search for planetary companions to nearby stars, by detecting the astrometric 'wobble' relative to nearby reference stars. It will be essential for measurements such as those of Gould *et al* [66].

The proposed Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) surveys will take a complementary approach. Those projects will survey about half of the sky from the ground, but atmospheric blurring will yield a resolution somewhat inferior to that of space-based telescopes. They should generate $\sim 10^9$ galaxy images, and may be able to look at the largest-scale mass structures in the local universe. Large numbers of clusters should be found through weak lensing, and the evolution of their density with cosmic time would provide an independent measurement of the dynamics of the universe.

Radio telescopes could match the capabilities of their optical counterparts. Current telescopes are improving, and there are good prospects for two larger radio telescopes, the Low-Frequency Array and the Square Kilometer Array.

The availability of new, enormous, ground- and space-based databases with both spatial and dense temporal sampling will at least double the existing sample of strongly lensed quasars and will allow new studies of microlensing. Expecting the unexpected from such data should become the norm. For example, recent theoretical studies of the lensing properties of 'boson stars' [70] show that these, if they exist, could be a significant part of the dark-matter component of galaxies. Such objects could account for the apparent population of MACHOs (Massive Compact Halo Objects) that produce observed microlensing events in the LMC ([71] and references therein).

The study of gravitational lensing has proceeded as a typical scientific inquiry. Theory and observation have alternated as leaders in the endeavour, and great progress has been made. However, the history of the field is rife with unanticipated phenomena. We should expect the unexpected. Ongoing observations are aimed at exploring dark energy, matter, galaxies, stars, planets. Many discoveries will indeed prove to be unexpected. Gravitational lensing will arise from these observations as a beacon for our understanding of the universe.

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