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# The Hubble Constant from (CLASS) Gravitational Lenses

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**Abstract:** One of the main objectives of the *Cosmic Lens All-Sky Survey* (CLASS) collaboration has been to find gravitational lens (GL) systems at radio wavelengths that are suitable for the determination of time delays between image pairs. The survey is now near completion and at least 18 GL systems have been found. Here, I will discuss our efforts to measure time delays from several of these systems with the ultimate aim of constraining the Hubble Constant ( $H_0$ ). Thus far three CLASS GL systems (B0218+357, B1600+434 and B1608+656) have yielded measurements of time delays, from which values of  $H_0 \approx 60\text{--}70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  have been estimated. Although most GL systems give similar values of  $H_0$ , statistical and systematic uncertainties are still considerable. To reduce these uncertainties, I will mention two monitoring programs that we are undertaking to (re)measure time delays in 14 CLASS GL systems and address several important issues for the near future.

**Keywords:** cosmological parameters — gravitational lensing

## 1 The Hubble Constant from Gravitational Lensing

Refsdal (1964) showed that to first order the Hubble Constant can be measured from a multiple-image GL system, if the time delay between an image pair and the mass distribution of the deflector is known. This has prompted the monitoring of and search for new GL systems, after the discovery of the first GL system Q0957+561 (Walsh, Carswell & Weymann 1979). Only recently has the time delay in Q0957+561 been measured unambiguously (e.g. Kundic et al. 1997). Since then time delays from seven other GL systems have been reported, of which five (including Q0957+561) have  $1\sigma$  time-delay errors that are claimed to be less than about 10% (e.g. Schechter 2000). Hence, if the uncertainty on the value of  $H_0$  was *only* due to the measurement error on the time delay, the technique of gravitational lensing would already have surpassed that of the local distance-ladder techniques in accuracy, which in the case of the HST Key-Project is about 10% on their final value of  $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (e.g. Freedman et al. 2001). Unfortunately, however, it is not the measurement of the time delays, but the determination of the deflector potential<sup>1</sup> which is at present the ‘bottle-neck’ in the attempt to accurately determine the value of  $H_0$  from GL systems.

To solve the latter problem, it is clear that one would like to have a significantly larger sample of GL systems with measured time delays than is currently available. This will (i) reduce the statistical error on the average value of  $H_0$  inferred from different GL systems, which is dominated by the errors on the measured time delays, (ii) allow one to select only those GL systems for the determination of an average value of  $H_0$  that are relatively isolated (i.e. no strong perturbing mass distributions in the surrounding

field) and (iii) enable one to find systematic differences between GL systems for example due to differences in the slope of the radial mass profile or the mass-sheet degeneracy. Unfortunately, systematic uncertainties in the deflector potential (e.g. the slope of the radial mass profile) could potentially ‘skew’ values of  $H_0$ , determined from different GL systems, in the same direction. Hence, even though the resulting statistical scatter can be relatively small (e.g. Koopmans & Fassnacht 1999), a large systematic uncertainty (i.e. a scale-factor in  $H_0$ ) can remain undetected. This problem can only be solved with detailed modeling of each individual GL system, making use of all available information such as extended image structure (e.g. rings, arcs, jets), knowledge about the lens potential (e.g. the stellar velocity dispersion in the lens galaxy, rotation curves) or general ideas about the structure of galaxies (e.g. N-body simulations). Not all GL systems have this additional information readily available, however, which again stresses the need to increase the number of GL systems with measured time delays.

For this reason, the *Cosmic Lens All-Sky Survey* (CLASS) collaboration (e.g. Browne & Myers 2000) has started to monitor a number of GL systems over the past few years. In Section 2, I will review results from three systems with measured time delays. In Section 3, I briefly discuss the values of  $H_0$  estimated from these GL systems, under some very simple assumptions. In Section 4, I discuss future prospects, including two new programs with the *Very Large Array* (VLA) and *Multi Element Radio-Linked Interferometer Network* (MERLIN) to monitor a combined total of 14 CLASS GL systems.

## 2 Time Delays from CLASS Gravitational Lenses

**B0218+357** The GL system B0218+357 was discovered (e.g. Patnaik et al. 1993) as part of the *Jodrell Bank-VLA Astrometric Survey* (JVAS), which is the brighter

<sup>1</sup>The ‘deflector potential’ includes all gravitational effects by which a photon can deviate from its global geodesic, which assumes homogeneity and isotropy of the universe (i.e. a FRW universe).

subsample ( $S_{5\text{ GHz}} \geq 200\text{ mJy}$ ) of the CLASS survey. The system consists of two lensed images of a flat-spectrum radio core, separated by 0.335 arcsec, and an Einstein ring that results from a more extended steep-spectrum source structure. The redshift of the source is 0.96, whereas the deflector (a relatively isolated spiral galaxy) has a redshift of 0.68. Corbett, Browne, & Wilkinson (1996) reported a time delay of  $12 \pm 3\text{ d}$  ( $1\sigma$  error). More recently, Biggs et al. (1999) presented the results from a VLA A-array monitoring campaign. From the percentage linear polarisation, polarisation angle and 8.5 and 15 GHz flux-density light curves, a time delay of  $\Delta t_{B-A} = 10.5 \pm 0.4\text{ d}$  (95% confidence) was measured. This value was confirmed by Cohen et al. (2001), who find  $\Delta t_{B-A} = 10.1^{+1.5}_{-1.6}\text{ d}$  (95% confidence), using independent data obtained with the VLA during the same period as Biggs et al. (1999).

**B1600+434** The GL system B1600+434 (Jackson et al. 1995) consists of two compact flat-spectrum radio images, separated by 1.39 arcsec, of a quasar at a redshift of 1.59. The primary lens galaxy is an edge-on spiral galaxy at a redshift of 0.41 (Jaunsen & Hjorth 1997; Koopmans, de Bruyn & Jackson 1998). An A and B array VLA 8.5 GHz monitoring campaign gave a time delay of  $\Delta t_{B-A} = 47^{+12}_{-9}\text{ d}$  (95% confidence) (Koopmans et al. 2000). More recently, a value of  $\Delta t_{B-A} = 51 \pm 4\text{ d}$  (95% confidence) was found from an optical monitoring campaign with the *Nordic Optical Telescope* (NOT) (Burud et al. 2000). Preliminary results from a new multi-frequency monitoring campaign with the VLA seem to confirm these results.

**B1608+656** The GL system B1608+656 consists of four compact flat-spectrum radio images with a maximum image separation of 2.1 arcsec (Myers et al. 1995). The source has a redshift of 1.39 and is being lensed by two galaxies inside the Einstein radius, of which at least the brightest has a redshift of 0.63. In the optical and near-infrared the host galaxy of the radio source is lensed into prominent arcs (Jackson et al. 1998). Fassnacht et al. (1999) have measured all three time delays from radio light curves obtained in 1996–1997 at 8.5 GHz with the VLA in A and B-array. Combined with data from a similar campaign in 1998, their preliminary results are:  $\Delta t_{B-A} = 26\text{ d}$ ,  $\Delta t_{B-C} = 34\text{ d}$  and  $\Delta t_{B-D} = 73\text{ d}$ , with an error of 5 d (95% confidence) on each time delay (Fassnacht et al. 2001).

### 3 Estimates of the Hubble Constant

To estimate the value of  $H_0$  from these time delays requires a good model of the deflector potentials. In all three GL systems, it is *assumed* that these are dominated by the potential of the primary lens galaxies (two in the case of B1608+656) and that these galaxies have an *isothermal* mass distribution.

Under these assumptions (see the references for more details) one finds:  $H_0 = 69^{+13}_{-19}\text{ km s}^{-1}\text{ Mpc}^{-1}$  (95%) from B0218+357 (Biggs et al. 1999),  $H_0 = 60^{+15}_{-12}\text{ km s}^{-1}\text{ Mpc}^{-1}$  (95%) from B1600+434 (Koopmans et al. 2000) and  $H_0 = 63^{+7}_{-6}\text{ km s}^{-1}\text{ Mpc}^{-1}$  (95%) from

B1608+656 (Koopmans & Fassnacht 1999) with  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ . Burud et al. (2000) estimate a slightly lower value of  $H_0$  from B1600+434, using the mass models from Maller et al. (2000). In addition, Lehar et al. (2000) claim a larger systematic error on the value of  $H_0$  from B0218+357, due to the uncertainty in the position of the lens galaxy. Results from modelling the Einstein ring in B0218+357 (Wucknitz, private communication) seem to agree with the galaxy position used by Biggs et al. (1999), however. Although we stress that these are preliminary values, the interesting conclusion from a comparison of these values of  $H_0$  is their good agreement not only with determinations from other GL systems, but also with those from the HST Key-Project, S-Z measurements and determinations from high-redshift SNe Ia (e.g. Koopmans & Fassnacht 1999; Freedman et al. 2001).

Even so, the uncertainties are still considerable and not all possible mass models have been fully explored yet. In none of these cases for example does the error include the uncertainty in the slope of the radial mass profile or the center of the mass distribution, which dominate the systematic uncertainties in the value of  $H_0$ . To improve this situation, Wucknitz et al. (in preparation) are using the additional information in the structure of the radio Einstein ring in B0218+357 to constrain the position of the lens galaxy and its radial mass profile. Similarly, Surpi & Blandford (in preparation) are using the arcs in B1608+656 to further constrain its mass distribution, whereas Fassnacht et al. (in preparation) have obtained data to measure the central velocity dispersion of the primary lens galaxy. In the case of B1600+434, no clear extended source structure is present, although Keck observations will be done to try to measure the velocity dispersion and rotation velocity of the bulge and disk, respectively.

### 4 The Future of $H_0$ from Gravitational Lensing

For the three CLASS GL systems discussed above (Section 2), the time delays are or will soon be known with errors less than 10%. With the ongoing efforts to improve the determination of the lens potentials of each individual GL system, in particular those from B0218+357 and B1608+656 (Section 3), one might also expect the uncertainty on the inferred time delays to reduce to less than 10% in the near future, although as indicated this still requires a considerable effort. These systems will then give an average global value of  $H_0$  comparable in accuracy to the results from the HST Key-Project. Together with other GL systems that have measured time delays, this situation can only improve. Another example of a very promising CLASS GL system is B1933+503 (Sykes et al. 1998), for which the inferred time delay from mass modelling has an uncertainty  $\approx 20\%$ , with excellent opportunities for improvement (Cohn et al. 2000; see also Nair 1998). Although no time delay could be determined from a VLA monitoring campaign (Biggs et al. 2000), the source has in the past varied by as much as 33% at 15 GHz

and is currently being re-observed with both the VLA and MERLIN. To increase the number of GL systems with measured time delays, CLASS is now engaged in two new monitoring projects with the VLA (8 systems; PI: Fassnacht) and MERLIN (Key-Programme; 8–12 systems; PI: Koopmans). In total 14 different CLASS GL systems will be monitored (including two of those in Section 2). With ongoing optical monitoring programs, the total number of GL systems being monitored in 2001 will likely be 20–30! Although not every system will yield time delays, we expect that the number of GL systems with measured time delays is likely to double in the next few years.

However, in order to obtain a ‘competitive’ global measurement of  $H_0$  from gravitational lensing, *the focus in the coming years needs to be on improving the determination of the deflector potential of each individual GL system* from which time delays are being measured. From the work being done at present, this appears to be a difficult, but certainly not an unattainable goal. In light of the fact that the first GL system was discovered over twenty years ago, progress might appear slow. However, the first unambiguous measurement of a time delay was done only some five years ago and since then at least seven GL systems have been added to this list, some of them having much simpler deflector potentials than Q0957+561, which has received the most attention over the last two decades.

Finally, we can ask ourselves the question: is it still worthwhile to measure  $H_0$  from gravitational lensing, now that the HST Key-Project has determined the local value with an uncertainty of around 10%? Here, one should keep in mind that the value of  $H_0$  determined from gravitational lensing is a ‘global’ single-step determination, whereas that determined from the HST Key-Project is a ‘local’ (distance–ladder) value. The HST Key-Project has measured distances out to  $\approx 400$  Mpc ( $z \approx 0.1$ ; e.g. Freedman et al. 2001), whereas the typical gravitational lens/source (angular diameter) distances are 1500–2000 Mpc. Both methods are therefore in some sense complementary and do not necessarily have to result in the same value for the expansion speed of the universe (i.e. locally  $H_0$  could differ from its global average value). This is often implicitly assumed based on the idea that the universe is homogeneous and isotropic on very large scales (but not necessarily on smaller scales), although recent work has indicated that the ratio of the global over the local value of  $H_0$  probably does not deviate from unity by more than a few percent (see Freedman et al. 2001 for a discussion). Homogeneity implies the R–W metric and a set of global parameters describing the evolution of the universe (i.e. the Friedmann equations), which by definition implies the

same local and global value of  $H_0$ . Agreement or disagreement between values of  $H_0$  from two or more independent and different methods over a wide range of distances (i.e. redshifts) can therefore elucidate our understanding of the universe and in case of agreement put its determination on a much firmer basis.

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