The JVAS/CLASS lens survey: review of the survey and results.

I.W.A. Browne and the CLASS collaboration

The University of Manchester. Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL, UK

Abstract.

To exploit gravitational lensing for cosmology large, reliable and statistically complete surveys are required. With JVAS/CLASS we have set out to achieve these goals. We pre-select targets to be flat spectrum radio sources as these have structures dominated by a single compact radio core. Initially we map every source with the VLA at 200mas resolution and then follow up all candidates having multiple compact components with high resolution MERLIN and VLBA observations, eliminating those candidates which do not match strictly defined surface brightness and morphological criteria. More than 15,000 sources have been observed with the VLA and the radio follow up of the candidates is nearly complete. At least 17 lens systems have been found so far.

Optical follow up of the radio-selected lens systems with HST reveal the lensing galaxy in all but one (questionable) case, indicating that dark lenses are rare. Even though the survey is complete for image separations in the range 0.2 to 6 arcsec, the observed separations are closely peaked around 1 arcsec.

The frequency of lensing in JVAS/CLASS constrains the cosmological constant (λ_0) and the density parameter (Ω_0). At 95% confidence, our upper limit on $\lambda_0 - \Omega_0$, based on a preliminary analysis of JVAS, is 0.68. For a flat universe, this corresponds to $\lambda_0 \leq 0.84$. This is broadly consistent with the results from the *m-z* relation for type Ia supernovae. We have measured time delays for 3 lens systems and obtain values for H_o in the range 59 to 70 km/sec/Mpc with formal errors of about 10%.

1. Introduction

Finding multiple image gravitational lens systems is not easy; creating a reliable and complete sample of such lens systems is even harder. The aims of JVAS/CLASS are to create a large, reliable and statistically complete survey for galaxy mass lens systems, to find ones that are suitable for time delay measurements and to identify lensing galaxies and study their properties. To achieve these goals we look for lensed images of compact radio cores amongst a sample of radio sources pre-selected to have flat radio spectra. This approach has several advantages:

- Flat spectrum radio sources have structures dominated by a single compact radio core and thus multiple imaging events are relatively easy to recognize.
- Being compact the probability of multiple imaging of radio cores depends only on the lens cross-section and not on the angular extent of the lensed object.
- Most flat spectrum radio sources are quasars and therefore at high redshift, thus maximizing the lensing cross section.
- Most flat spectrum radio sources are time variable and, if multiply imaged, are suitable for time delay measurements and Hubble constant determination.
- The targets are free from any bias arising from extinction in the lensing galaxy, something that affects the completeness of optical lens searches.
- High resolution radio follow up with MERLIN and VLBI is possible to provide extra constraints on the lens model from extended radio structure.

The work on lens surveys started in 1990 with the Jodrell VLA Astrometric Survey (JVAS) which had the dual purpose of identifying and measuring accurate positions for radio sources suitable as phase calibrators for interferometer arrays, and to find gravitational lens systems (Patnaik et al. 1993, Browne et al. 1998, Wilkinson et al. 1998). JVAS was successful on both counts; some 2500 targets were observed and five new lens systems identified.

In order to extend the work to a much larger sample of objects a wider collaboration was formed between the Jodrell Bank group and groups at Caltech and in the Netherlands (Dwingeloo and Leiden). The Cosmic Lens All-Sky Survey (CLASS) team now comprises groups at Jodrell Bank, Caltech, the University of Pennsylvania, Dwingeloo and the University of Groningen.

In this contribution we will describe the CLASS project. We will give details of the candidate selection and follow up procedures. Since one of the major uses of JVAS/CLASS lens statistics will be to constrain cosmological models, it is important to know the sample selection function before embarking on any analysis. We will then summarize the current status of the project and highlight the best results, some of which are discussed in more detail in other contributions.

2. Primary Sample Selection.

In order to pick a sample of flat spectrum radio sources, observations of radio sources at 2 or more frequencies are required. The most straightforward way to realize this is to use two source surveys, one at a high frequency and one at a low frequency. A big advantage of using such a simple selection method is that it makes it easier to get reliable information on the statistical properties of the unlensed objects (see Section 5). Currently the best two surveys for this purpose are the 5 GHz GB6 survey (Gregory et al. 1996) and the NVSS 1.4 GHz (Condon et al. 1998). Our final complete sample was selected from these two surveys; starting with GB6 we picked sources stronger than 30 mJy and looked

for their counterparts in NVSS rejecting all those with two point spectral indices steeper than -0.5 ($S \propto \nu^{\alpha}$)[1]. The area covered by GB6 is from declination 0° to 75°. To avoid difficulties with galactic extinction only sources with $|b| \geq 10°$ were included. A total of 11,685 GB6 sources meet these selection criteria[2].

Each source selected was observed with the VLA in its A-configuration at a frequency 8.4GHz resulting in a map with a resolution of 200 mas and a dynamic range of $\geq 50:1$. More details of the VLA observations and their analysis are given in the contribution by Myers et al.

3. Lens Candidate Selection and follow up.

A critical step in the whole survey process is the selection of candidates to follow up with further higher resolution observations. The CLASS philosophy has been to err on the side of caution and follow up objects meeting the well defined selection criteria listed below, even when our initial conclusion from the VLA maps was that they were very unlikely to be multiply imaged systems. It is because of this meticulous follow up procedure that we believe that our lens sample is complete within the well-defined selection criteria we set out below. We reiterate that for our statistically complete sample we are searching only for multiply imaged compact radio cores[3]. Complete sample candidates must meet the following criteria:

- The source must have multiple compact components with size $\leq$170 mas.
- The component separation must be $\geq$300 mas. The search is currently complete to 6 arcsec but is being extended to 15 arcsec from the strongest component in the map.
- The component flux density ratio must be $\leq$10:1.
- The total 8.4 GHz flux density in the components must be $\geq$ 20 mJy.

Candidates are selected visually and checked against an automatically generated list based on the results of modelling each source in DIFMAP. Even

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[1] A complication arises because the GB6 survey was made with a beam of 3.5 arcmin compared with the 45 arcsec of NVSS. This means that some entries cataloged as a single source in GB6 can sometimes be resolved into more than one brightness peak in NVSS. Also, because the GB6 positions of weak sources have rms errors of typically ∼15 arcsec, there can be an additional uncertainty about which, if any, NVSS peak to identify with the GB6 entry. No approach to this problem is perfect. We have adopted the procedure of adding up all the 1.4 GHz flux density from sources within 70 arcsec of the GB6 position before computing the spectral indices. This is a compromise which allows us to pick up true NVSS identifications with GB6 sources with large position errors but avoids spurious identifications with unrelated NVSS sources.

[2] Since the GB6 and NVSS surveys did not exist at the outset of the CLASS project, the first target sources were selected using slightly different criteria. This means that during the different stages of CLASS a significant number of sources not in the final complete sample were observed. A total of more than 15,000 sources have been mapped with the VLA.

[3] We do not of course ignore obvious lens systems in which lensed extended emission dominates; e.g 1938+666. Such objects should not, however, be used in a statistical analysis.

though the data have been collected over many years all have been recently been re-calibrated and mapped to ensure uniformity.

We follow up candidates with various stages of filtering, systematically increasing the radio resolution as we proceed. Since we expect lensed images to have the same surface brightness, spectra and percentage polarization, candidates are rejected if:

- The surface brightness of the putative images are different.
- The structure revealed by the high resolution maps is inconsistent with lensing; e.g. the radio map shows a core plus a knot in a jet.
- The spectral index of of the putative images and or their percentage polarizations are very different.

We are conscious that in variable source the effects of time delays can make the spectral indices and polarizations of two images appear different. In addition depolarization in the the lens can affect images differently. Thus we treat these quantities with caution. Only if one component has an obviously steep spectrum, and is therefore very unlikely to be variable, do we reject a candidate on this basis. Likewise we disregard percentage polarizations at frequencies $\leq$8.4 GHz where Faraday depolarization may be important. Even at 8.4 GHz and above we only reject on the basis of percentage polarizations if the component polarizations differ by more than a factor $\sim$4.

The first step in the follow up path for all candidates is a snapshot observation with MERLIN at 5 GHz. These observations give a map with a resolution of 50 mas and in about 80% of the cases the results are good enough to reject the candidate. In the majority of these cases the extra resolution is sufficient to distinguish between the components on the grounds of different surface brightness. Surviving candidates are then observed with the VLBA at 5 GHz – resolution $\sim$3 mas – again in snapshot mode. By this stage all but a hand-full of objects can be classified unambiguously. The remaining candidates yield to further radio observations at different frequencies and/or optical observations mostly with the HST.

4. The Current Status of JVAS/CLASS; Statistical Results.

The initial VLA observations of the 11,685 sources in the complete sample have been taken and analysed. The MERLIN follow up observations of candidates from all but the last $\sim$1000 sources have been completed, as have most of the VLBA observations. All the radio follow up, including candidates in the separation range 6 to 15 arcsec (see contribution by Phillips et al.), should be complete by August 2000.

Up to the present 17 confirmed lens systems have been found (see Table 1). We expect that when the follow up programme is complete this total will rise to $\sim$20 resulting in an overall lensing rate of approximately 1 per 500 to 600 targets. The lensing galaxy is seen in 15 of the systems and redshifts already measured in 12 cases. Redshifts for 11 of the lensed objects are available.

A somewhat neglected statistic is the ratio of the number of 4-image systems to the number of 2 image systems. In the sample of confirmed lens systems the ratio is 9 quads to 7 doubles. We believe that there are no more quads to be found in the survey and guess that there may be only about 3 more doubles. Our conclusion is that to within the accuracy of $\sqrt{n}$ statistics there are equal numbers of quads and doubles in JVAS/CLASS. This is a higher fraction of quads than one would expect on the basis of simple models (King & Browne, 1996; Kochanek, 1996). Though there is no clear consensus, possible explanations are a higher than expected ellipticity for the mass distributions (King & Browne, 1996) or a large component of external shear (Keeton et al., 1997). In the context of the use of lens statistics to constrain cosmological parameters, it is a concern that the lack of a clear explanation quad/double ratio suggests that our knowledge of the statistical properties of the lensing masses is still far from perfect.

The detection of the lensing galaxy (Jackson et al. 1998) in systems in which there is overwhelming evidence for lensing purely on the basis of the radio data is a strong argument against the existence of a significant number of dark lenses as suggested by (Hawkins, 1998). In only one case, that of the lens candidate 0827+525, is there possible evidence for a dark lens (Koopmans et al. 1999). In this case MERLIN and VLBA data show two compact components with a separation of 2.85 arcsec. The weaker radio object is probably slightly resolved in the VLBA observations and, moreover, the radio spectral indices of the two components are significantly different. Thus the radio evidence for lensing is not overwhelming. Optical/infrared emission is detected from the region of both radio components but with a very different flux density ratio from the 2.8:1 observed at 8.4 GHz. The difference in radio and infrared flux ratio might be caused by extinction in a hypothetical lensing galaxy. However, here is no lensing galaxy visible at the expected position in a one orbit H-band NICMOS image. The accumulated evidence suggests that 0827+525 is not a lens system and what we are seeing is two independent (but possibly related) radio sources. We have the redshift for the brighter optical counterpart but not the weaker.

A histogram of image separations is shown in Figure 1. The separations peak at $\sim$1 arcsec with none $\geq$3 arcsec. We are confident that we are not missing systems in the range 0.3 to 6 arcsec. The search from 6 to 15 arcsec using the JVAS/CLASS database (as described in the contribution by Phillips et al.) is only at a relatively early stage, but no systems have so far been found.

5. Lens Statistics and Cosmology.

The aim is to use lens statistics, the frequency of lensing and the redshift distribution of lenses, to constrain the value of the cosmological constant. To do this we need a complete sample of lens systems and their properties. We also need to know the properties of the lensing population and the distribution in the flux density/redshift plane of the parent population of lensed objects. Currently we do not yet know enough about the parent population of the weakest lens systems to exploit the lens statistics to the full (Falco et al., 1998; Helbig et al., 1999). The survey flux density limit is 30 mJy at 5 GHz and therefore, since lensing

Table 1. Radio loud lensed systems found in JVAS/CLASS. The image separation is given in arcsec.

Source	Survey	Source redshift z_s	Lens redshift z_l	Maximum image separation	Multiplicity
0218+357	JVAS	0.96	0.68	0.334	double
0414+054	MIT/JVAS	2.62	0.96	2.09	quad
0712+472	CLASS	1.34	0.41	1.27	quad
0742+366	CLASS	-	-	0.53	double
1030+074	JVAS	1.53	0.599	1.56	double
1127+385	CLASS	-	-	0.701	double
1152+199	CLASS	1.013	0.435	1.5	double
1352+154	CLASS	3.214	-	1.65	quad
1422+231	JVAS	3.62	0.34	1.28	quad
1555+375	CLASS	-	-	0.43	quad
1600+434	CLASS	1.57	0.415	1.39	double
1608+656	CLASS	1.39	0.64	2.08	quad
1933+507	CLASS	2.62	0.755	1.17	quad
1938+666	JVAS	-	-	0.93	quad
2045+265	CLASS	1.28	0.87	1.86	quad
2114+022	JVAS	-	0.32/0.59	2.57	double?
2319+051	CLASS	-	0.624	1.7	double

magnifies typically by factors of a few, we need to know about the properties of sources of $\sim$5 mJy.

We have a programme underway to study a small representative sample of 5 to 12 mJy sources selected in an equivalent way to the JVAS/CLASS sample. Unfortunately the GB6 survey does not go down to these flux density levels. We have, therefore, created our own "pseudo" 5 GHz survey in a small area of sky by taking $\sim$ 1000 NVSS sources down to a 1.4 GHz flux density of 2.5 mJy and measuring their flux densities with the VLA at 5 GHz. With these data we then select a complete sample of flat spectrum sources stronger than 5 mJy at 5 GHz. Finally, we have observed all the flat spectrum sources with the VLA at 8.4 GHz in A-configuration just as we have done for the lens survey. This step has been taken because approximately 7% of the JVAS/CLASS targets meeting the selection criteria of the complete sample are not clearly detected when observed in this manner and including such non-detections in our parent sample analysis might bias the redshift distribution.

The pseudo survey has been completed and we are now trying to obtain redshifts for the sample. Our approach is to try and get spectroscopic redshifts for the "easy" objects and photometric redshifts for the difficult faint objects using a combination of optical and infrared colours.

Knowledge of the statistics of the parent population is not such a problem for the strongest (JVAS) sources. In these proceedings Phillip Helbig presents results for the strongest $\sim$2000 sources (see also Falco et al. 1998; Corray 1999).

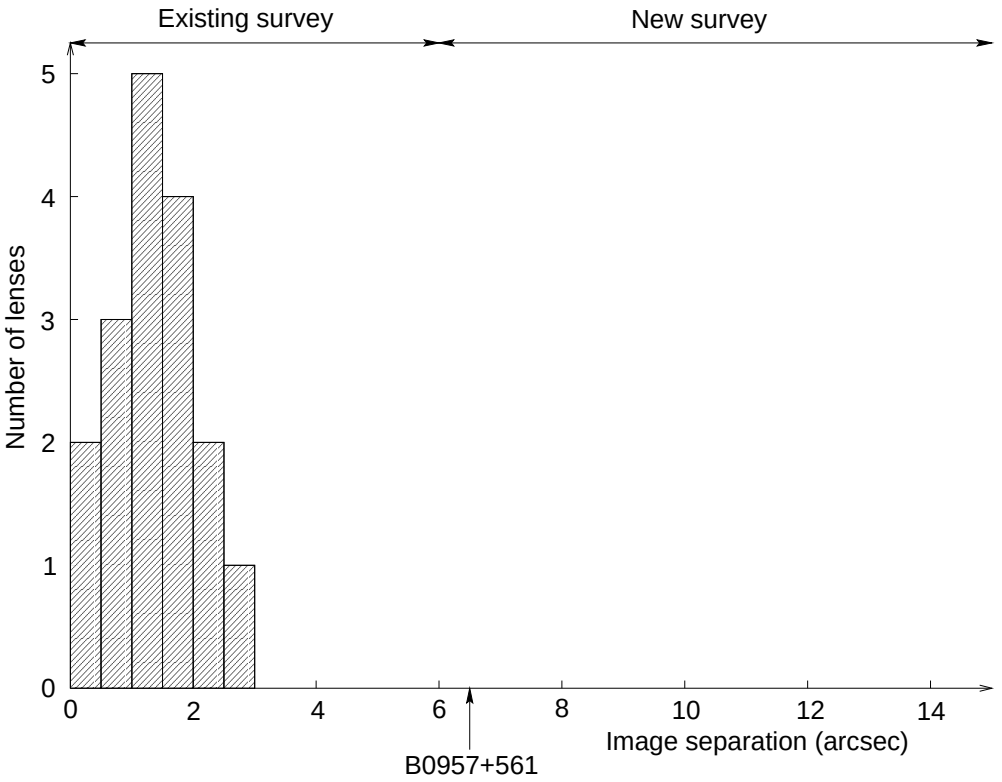

Figure 1. Separation histogram for the 17 confirmed lens systems.

At 95% confidence, our upper limit on $\lambda_0 - \Omega_0$, based on a preliminary analysis of JVAS, is 0.68. For a flat universe, this corresponds to $\lambda_0 \leq 0.84$ (Helbig et al., 1999). This is broadly consistent with the results from the m-z relation for type Ia supernovae (Riess et al., 1998).

6. Time Delays and the Hubble Constant.

A significant fraction of the CLASS collaboration effort has gone into the monitoring of lens systems for time delays in order to determine the Hubble constant. Serious VLA monitoring campaigns have been mounted for the systems 0218+357, 1030+074, 1600+434, 1608+656 and 1933+503 and others are being checked to see if they are variable and therefore worth monitoring regularly. No time delays have been obtained for 1030+074 and for 1933+503 (Xanthopoulos et al.; Browne et al., these proceedings) but we have had successes for 0218+357, for 1600+434 and for 1608+656 (Biggs et al. Cohen et al. Koopmans et al. and Fassnacht et al., these proceedings.) Adopting a singular isothermal ellipsoid for the mass model gives a value of H_0 between 59 and 70 $km^{-1}Mpc^{-1}$ for all three. These values are shown in Figure 2 along with values obtained from other methods. It is clear that most methods seem to be converging and that gravitational lenses, with the caveat that reliable mass models are still a major uncertainty, are making a significant contribution to the debate. The urgent task is to provide more observational constraints for these lens systems with measured time delays so as to reduce the modelling uncertainties.

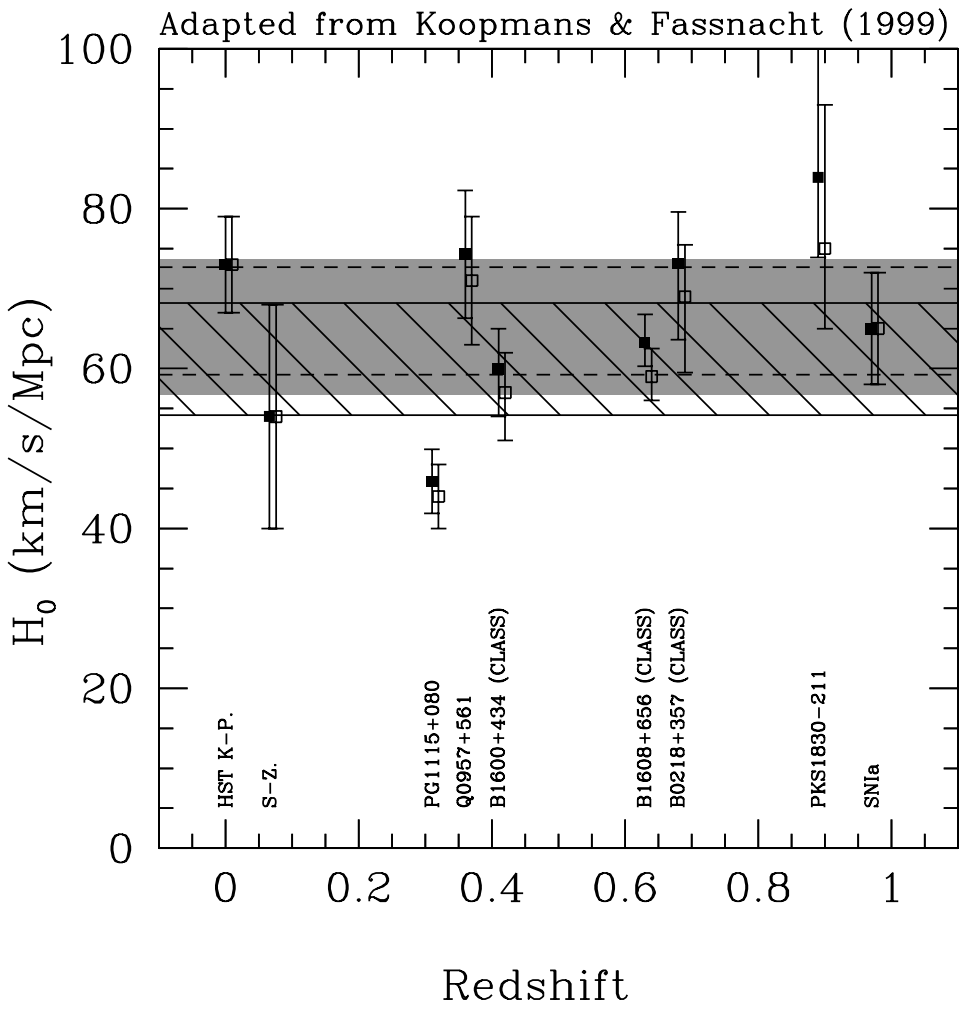

Figure 2. The Hubble parameter determined on cosmological scales plotted as function of redshift. The average local value, presented by Madore et al. (1999; HST Key Project for the Extra-galactic Distance Scale) has a redshift $z = 0$. The SNIa determination has been placed on the highest redshift SNIa in the sample (Riess et al. 1998). The redshift for the S-Z determination of H_0 is the average cluster redshift in the sample (Myers et al. 1997). The gravitational lenses have been placed at the primary lens redshift. The open symbols are the values of H_0 for $\Omega_m = 1$ and $\Omega_\Lambda = 0$, the closed symbols for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The local, S-Z and SNIa determinations are almost independent of Ω_m and Ω_Λ. The densely shaded region indicates the ± 2–σ region around the average of H_0 determined from the lens sample (excluding PG1115+080) for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The dashed horizontal lines indicate the ± 2–σ region around the average of H_0 determinated from the lens sample (excluding PG1115+080) plus the S-Z, SNIa and local determinations. The lower shaded region indicates the ± 2–σ region around the average of the lens sample (excluding PG1115+080) for $\Omega_m = 1.0$ and $\Omega_\Lambda = 0.0$. The 1–σ error-bars indicate the statistical errors.

7. Conclusions

The JVAS/CLASS methodology of using high resolution radio observations of flat spectrum radio sources to define reliable and complete samples of gravitational lens systems, works efficiently. Many of the lens systems turn out to be suitable for time delay measurements; time delays have been measured using radio monitoring for three lens systems found in the survey and more will follow. The biggest barrier to a confident claim that we have determined the value of the Hubble constant remains the uncertainty about the reliability of the adopted mass models. More observational constraints both from better high resolution radio mapping and from optical observations are required. Lens statistics for the stronger sources are already providing useful constraints on the maximum value for the cosmological constant. The full statistics will be available within a year. Here perhaps the biggest limitation is our relative ignorance of the distribution in the redshift/flux density plane of the objects that get lensed into the complete sample. We have programmes underway to try and overcome this problem.

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