arXiv:astro-ph/9904007v1 1 Apr 1999

Measuring Cosmological Parameters with the JVAS and CLASS Gravitational Lens Surveys

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Abstract. The JVAS (Jodrell Bank-VLA Astrometric Survey) and CLASS (Cosmic Lens All-Sky Survey) are well-defined surveys containing about ten thousand flat-spectrum radio sources. For many reasons, flat-spectrum radio sources are particularly well-suited as a population from which one can obtain unbiased samples of gravitational lenses. These are by far the largest gravitational (macro)lens surveys, and particular attention was paid to constructing a cleanly-defined sample for the survey itself and for the underlying luminosity function. Here we present the constraints on cosmological parameters, particularly the cosmological constant, derived from JVAS and combine them with constraints from optical gravitational lens surveys, 'direct' measurements of Ω_0, H_0 and the age of the universe, and constraints derived from CMB anisotropies, before putting this final result into the context of the latest results from other, independent cosmological tests.

1. Cosmological constraints from JVAS...

The Jodrell Bank-VLA Astrometric Survey (JVAS) is a survey for flat-spectrum radio sources with a flux density greater than 200 mJy at 5 GHz. Flat-spectrum radio sources are likely to be compact, thus making it easy to recognise the lensing morphology. In addition, they are likely to be variable, making it possible to determine H_0 by measuring the time delay between the lensed images. (See [1] for the description of a time delay measurement in a JVAS gravitational lens system.) JVAS is also a survey for MERLIN phase-reference sources and as such is described in [2], [3] and [4]. JVAS as a gravitational lens survey, the lens candidate selection, followup process, confirmation criteria and a discussion of the JVAS gravitational lenses is described in detail in [5] (see also [6]).

In order to have a parent sample which is as large as possible and as cleanly defined as practical, our 'JVAS gravitational lens survey sample' is slightly different than the 'JVAS phase-reference calibrator sample'. For the former, the source must be a point source and must have a good starting position (so that the observation was correctly pointed) while its precise spectral index is not important. For the latter, only the spectral index is important, as the source can be slightly resolved or the observation can be less than perfectly pointed. Thus, the JVAS astrometric sample [2, 3, 4] contains 2144 sources. To these must be added 103 sources which were too resolved to be used as phase calibrators and 61 sources which had bad starting positions (thus the observations were too badly pointed to be useful for the astrometric sample), bringing the total to 2308. This formed our gravitational lens sample, since these additional sources were also searched for gravitational lenses [5] (none were found meeting the JVAS selection criteria: multiple flat-spectrum point-source components with a separation between 300 mas and 6 arcsec with a flux ratio of $\leq$20).

We have used the gravitational lens systems in Table 1 in this analysis. The

Name	# images	$\Delta\theta[''']$	$z_{\rm l}$	$z_{\rm s}$	lens galaxy
B0218+357	2 + ring	0.334	0.6847	0.96	spiral
MG0414+054	4	2.09	0.9584	2.639	elliptical
B1030+074	2	1.56	0.599	1.535	spiral
B1422+231	4	1.28	0.337	3.62	**?**

Table 1. JVAS lenses used in this analysis. Of the information in the table, for this analysis we use only the source redshift $z_{\rm s}$, and the image separation $\Delta\theta$.

JVAS lens B1938+666 [7] was not included because it is not formally a part of the sample, having a too steep spectral index and having been recognised on the basis of a lensed extended source as opposed to lensed compact components. Also, the JVAS lens B2114+022 [8] was not included because it is not a single-galaxy lens system.

For this analysis, due to the paucity of the observational data, we have made rather stark assumptions: the redshift distribution of the sample is assumed to be identical to that of the CJF (Caltech-Jodrell Bank Flat-spectrum) sample [9], independent of flux density, and the number-magnitude relation is assumed to be identical to that of CLASS the Cosmic Lens All-Sky Survey, [10], independent of redshift. Otherwise, we have calculated the likelihood as a function of λ_0 and Ω_0 as described in [11]. That is, we use a non-singular isothermal sphere as a lens model, model the lens galaxy population with a Schechter function and use the Faber-Jackson relation to convert between luminosity and velocity dispersion, considering only elliptical galaxies. The results are presented in Fig. 1. At 95% confidence, our lower and upper limits on $\lambda_0 - \Omega_0$, using the JVAS lensing statistics information alone, are respectively -2.69 and 0.68. For a flat universe, these correspond to lower and upper limits on λ_0 of respectively -0.85 and 0.84. (Reducing the constraints in the λ_0-Ω_0 plane to $\lambda_0 - \Omega_0$ is, of course, just an approximation, but a reasonably good one when considering upper limits on λ_0 for small Ω_0 values. These numbers were derived from the corresponding confidence limits on λ_0 for fixed Ω_0 and are thus of course different than the intersection of lines of constant $\lambda_0 - \Omega_0$ with the corresponding contour in Fig. 1.)

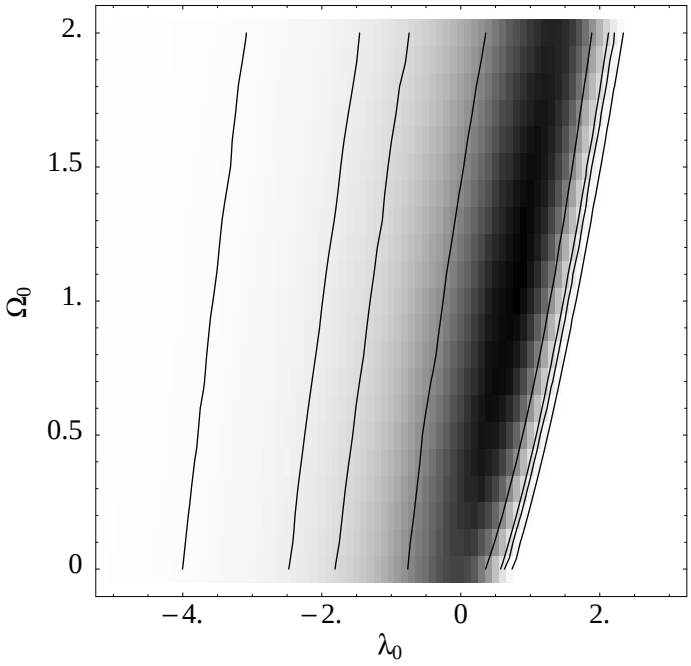

Figure 1. The likelihood function $p(\lambda_0, \Omega_0)$ based on the JVAS lens sample. The pixel grey level is directly proportional to the likelihood: darker pixels reflect higher likelihoods. The pixel size reflects the resolution of our numerical computations. The contours mark the boundaries of the minimum 0.68, 0.90, 0.95 and 0.99 confidence regions for the parameters λ_0 and Ω_0.

2. . . . and optical gravitational lens surveys. . .

One can improve these constraints by adding those from optical gravitational lens surveys, though one should keep in mind that the systematic errors—for example, lens systems which are missed due to extinction in the lens galaxy or to the fact that the typical seeing is not much better than the typical image separation—are probably less well understood than is the case in the radio (though the statistical properties of the unlensed parent population are better understood). Not only does one have more objects and thus better statistics, but a different redshift range is sampled as well. Essentially repeating the analysis in [11] (but with λ_0 and Ω_0 as free parameters, of course) and combining the resulting constraints with those from Fig. 1, one obtains the better constraints shown in Fig. 2. Using the combination of JVAS lensing statistics and lensing statistics from the literature as in [11], the corresponding $\lambda_0 - \Omega_0$ values are -1.78 and 0.27. For a flat universe, these correspond to lower and upper limits on λ_0 of respectively -0.39 and 0.64.

3. . . . and 'reasonably well-accepted wisdom'. . .

Gravitational lensings statistics alone cannot usefully constrain Ω_0. Thus, it seems sensible to combine the constraints shown in Fig. 2 with measurements of Ω_0. Fortunately, there seems to be a consensus developing that $\Omega_0 \approx 0.3$ e.g. [12, 13,

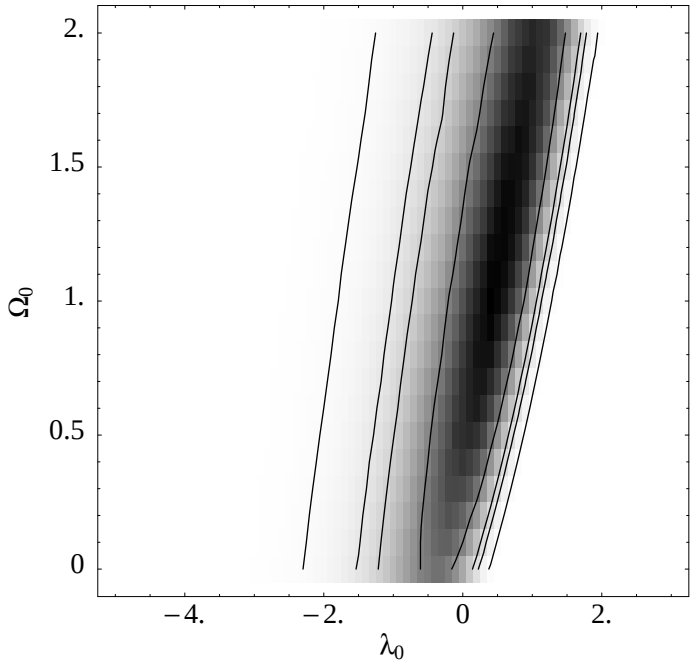

Figure 2. The same as Fig. 1 but combining JVAS with optical gravitational lens surveys from the literature.

14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. Conservatively, these results can be summarised as

$$p(\lambda_0, \Omega_0) = L(\Omega_0 | 0.4, 0.2). \tag{1}$$

where the two arguments of L represent the mean and standard deviation of a lognormal distribution.

In a similar vein, lensing statistics determines a lower limit on λ_0 much less strongly than an upper limit, so it seems sensible to include some prior information which can give a lower limit on λ_0. To be conservative, we take relatively undisputed estimates for the age of the universe and the Hubble constant, their product setting a (slightly Ω_0-dependent) lower limit on λ_0. The best estimate of the absolute age of the oldest galactic globular clusters currently is $t_{\rm gc} = 11.5 \pm 1.3\,{\rm Gyr}$ [26]. We choose to formulate this prior information in the form of a lognormal distribution that meets these statistics

$$p(t_{\rm gc}) = L(t_{\rm gc} | 11.5\,{\rm Gyr}, 1.3\,{\rm Gyr}). \tag{2}$$

Similarly, we roughly estimate $H_0 = 65 \pm 10\,{\rm km\,s^{-1}\,Mpc^{-1}}$ and choose to formulate this prior information in form of a normal distribution

$$p(H_0) = N(H_0 | 65\,{\rm km\,s^{-1}\,Mpc^{-1}}, 10\,{\rm km\,s^{-1}\,Mpc^{-1}}), \tag{3}$$

where, again, the notation for L (and N) is such that the two arguments correspond to the mean and standard deviation.

Fig. 3 shows how inclusion of this prior information, representing a conservative estimate of what we know about the values of the cosmological parameters, tightens

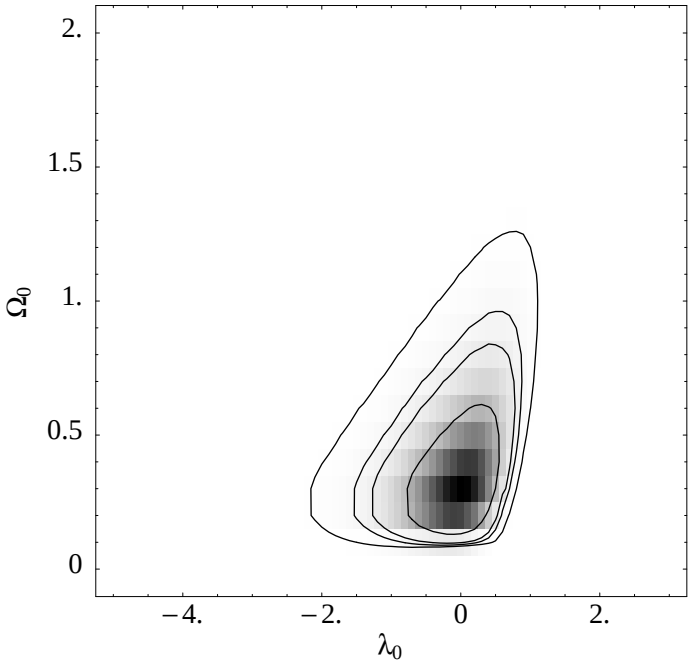

Figure 3. The same as Fig. 2 but combining JVAS and optical gravitational lens surveys from the literature with prior information on the value of Ω_0, H_0 and the age of the universe. This figure thus represents the combination of constraints from lensing statistics and from relatively undisputed knowledge about values of the cosmological parameters.

the constraints on λ_0 and Ω_0 as compared to the constraints from lens statistics alone (Figs. 2 and 1).

4. ...and the CMB...

It has long been realised, e.g. [27], that the direction of degeneracy of constraints from cosmic microwave background anisotropies is roughly orthogonal to that of most other tests, including lensing statistics. Thus, combining the constraints from CMB anisotropies with those from other cosmological tests can give much tighter constraints than either alone. We have performed an analysis similar to that done in [23], though including an updated Tenerife data point and calculating two-dimensional joint likelihood constraints as in the calculations done previously in this poster rather than employing Lineweaver's statistical method. Adding the constraints on λ_0 and Ω_0 so derived to the previous ones narrows down the region of parameter space further, as is shown in Fig. 4.

The power spectrum for the best-fit model using the CMB data alone ($\lambda_0 = 0.6$, $\Omega_0 = 0.3$, otherwise not shown here) along with various data points from the literature (see the collection of Max Tegmark at `http://www.sns.ias.edu/~max/cmb/experiments.html`) is shown in Fig. 5.

(Note added for the proceedings. The likelihood based on CMB observations which (combined with other tests) is shown in Fig. 4 is, due to a numerical error,

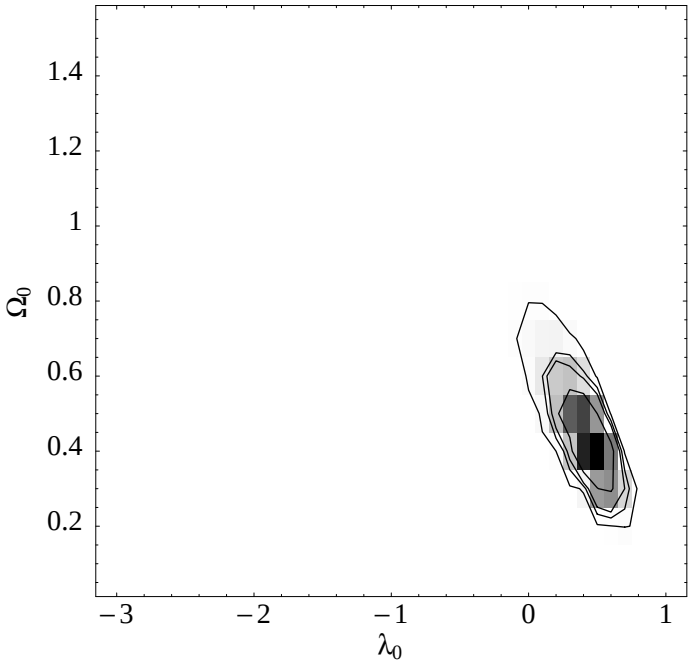

Figure 4. The same as Fig. 3 but combining JVAS optical gravitational lens surveys from the literature and prior information on the value of Ω_0, H_0 and the age of the universe with constraints derived from CMB anisotropies. Since the CMB constraints are more or less orthogonal to the lensing statistics constraints, this reduces the allowed area of the λ_0-Ω_0 parameter space significantly. Note that the scale of this plot differs from the previous ones. For technical reasons no models with $k = \mathrm{sign}(\lambda_0 + \Omega_0 - 1) = +1$ were calculated; this slightly distorts the contours near the $k = 0$ line, which otherwise would extend a bit more into the $k = +1$ region.

qualitatively but not quantitatively correct. We have since performed the correct computation, which will be presented elsewhere. However, the difference creates a smaller error than that caused by many other approximations made use of in these calculations, so we present the figure as shown in the original poster, in keeping with the concept of providing a record of the conference as opposed to an updated paper on the same subject.)

5. . . . and how this compares to other cosmological tests

Fig. 4 combines constraints based on optical and radio gravitational lensing statistics, 'direct' measurements of H_0, Ω_0 and the age of the universe and constraints derived from CMB anisotropies. This restricts λ_0 to a narrow range. If one believes that $\Omega_0 \approx 0.3$, then it follows that $\lambda_0 \approx 0.5$. This should be compared to the result of Perlmutter et al. [28]: $0.8\Omega_0 - 0.6\lambda_0 \approx -0.2$: inserting 0.3 for Ω_0 one obtains $\lambda_0 \approx 0.43$. Taking the errors into consideration (which are not large enough in either case to allow, for example, $\lambda_0 = 0$) one obtains perfectly consistent measurements of λ_0 from completely independent methods.

Taken together, present measurements of cosmological parameters *definitely* rule out the Einstein-de Sitter universe ($\lambda_0 = 0$, $\Omega_0 = 1$), *very probably* rule out a universe

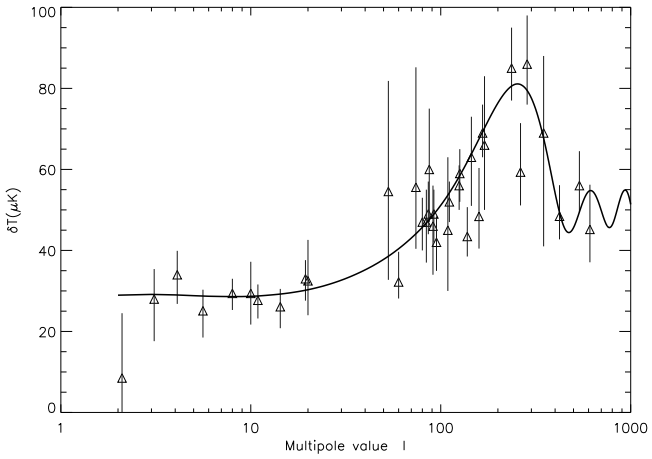

Figure 5. Power spectrum shown with data points from the literature for our best-fit cosmological model, fitting to the CMB data alone (and keeping parameters other than λ_0 and Ω_0 fixed at predetermined fiducial values).

without a cosmological constant ($\lambda_0 = 0$) and *tentatively* rule out a flat ($\lambda_0 + \Omega_0 = 1$) universe as well. A universe with $\lambda_0 \approx 0.4$ and $\Omega_0 \approx 0.3$ seems to be consistent with all observational data, including measurements of the Hubble constant and age of the universe.

6. The future

CLASS is similar to JVAS but contains about 4 times as many sources. The definition of both is flat-spectrum between L-band and C-band, i.e. $\alpha > -0.5$ where $s_f \sim f^\alpha$, the essential difference being the lower flux density limit of 200 mJy for JVAS and 30 mJy for CLASS. However, since CLASS is defined based on the newer GB6 and NVSS catalogues [29, 30] than JVAS, there will be some essentially random differences due to differing quality of observations and variability of the sources. All the JVAS lenses mentioned in Table 1 are in the new CLASS sample, which, having no upper flux density limit, subsumes JVAS. The previous samples CLASS-I and CLASS-II will be similarly subsumed in the same sense as JVAS, though the differences here will be slightly larger since bands other than L and C were used in the preliminary definition of these samples.

The initial phase of observations is complete; currently lens candidates are being followed up. At present, we have confirmed as gravitational lenses the systems listed in Table 2 (which for completeness also includes the two JVAS lens systems not used in the statistical analysis presented here).

We hope that the larger size of CLASS will allow the constraints on cosmological parameters from gravitational lensing statistics to improve. At present, the greatest uncertainty is the redshift-dependent luminosity function (or equivalently the flux-dependent redshift distribution) of the unlensed population (which of course, due to the amplification bias, extends to fainter flux-densities than the survey itself). We are currently taking steps to decrease this uncertainty.

Name	# images	$\Delta\theta''$	$z_{\rm l}$	$z_{\rm s}$	lens galaxy
B0712+472	4	1.27	0.406	1.34	spiral
B1127+385	2	0.70	?	?	?
B1600+434	2	1.39	0.414	1.589	spiral
B1608+656	4	2.08	0.63	1.39	spiral
B1933+507	$4+4+2$	1.17	0.755	?	?
B1938+666	$4+2$	0.93	?	?	?
B2045+265	4	1.86	0.867	1.28	?
B2114+022	2 or 4	2.57	0.32 & 0.59	?	?

Table 2. CLASS gravitational lenses and the two JVAS lens systems (1938+666 and 2114+022) not listed in Table 1.

Acknowledgements

This research was supported in part by the European Commission, TMR Programme, Research Network Contract ERBFMRXCT96-0034 'CERES'. CERES, standing for the Consortium for European Research on Extragalactic Surveys, is an EU TMR Network, coordinated by Ian Browne at Jodrell Bank, and involving the Nuffield Radio Astronomy Laboratories of the Universtity of Manchester at Jodrell Bank, the Institute of Astronomy of the University of Cambridge, The Kapteyn Astronomical Institute of the University of Groningen, the Netherlands Foundation for Research in Astronomy at Dwingeloo, the University of Bologna and the University of Portugal. One of the main goals of CERES is the use of the JVAS and CLASS surveys for research in gravitational lensing.

We thank our collaborators in the JVAS, CJF and CLASS surveys for useful discussions and for providing data in advance of publication and many colleagues at Jodrell Bank for helpful comments and suggestions. We also thank John Meaburn and Anthony Holloway at the Department of Astronomy in Manchester and the staff at Manchester Computing for providing us with additional computational resources. RQ is grateful to the CERES collaboration for making possible a visit to Jodrell Bank where part of this work was done.

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