JVAS, CLASS, **CERES** and gravitational lenses

CERES, standing for the **C**onsortium for **E**uropean **R**esearch on **E**xtragalactic **S**urveys, is a project funded by the European Commission's Training and Mobility of Researchers programme involving 6 institutes in 4 countries. One of the main objectives of the project is the determination of cosmological parameters from survey data; here we report some preliminary results in this area. There is much cooperation and some overlap with the CLASS (**C**osmic **L**ens **A**ll **S**ky **S**urvey) and JVAS (**J**odrell Bank **V**LA **A**strometric **S**urvey) teams, whose data form the starting point of our investigations. The institutes forming the CERES network are

- University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, UK
- University of Cambridge, Institute of Astronomy, UK
- University of Groningen, Kapteyn Institute, The Netherlands
- Netherlands Foundation for Research in Astronomy, Dwingeloo, The Netherlands
- University of Bologna, Institute for Radioastronomy, Italy
- University of Lisbon, Astronomical Observatory, Portugal

At present about 2500 JVAS and 5000 CLASS flat-spectrum sources have been observed with the VLA. Our goal is to increase the CLASS sample to ≈7500 sources, for a total of ≈10 000 sources with a total flux >20 mJy at 8.4 GHz. In the ≈5000 sources which have been carefully studied to date we have found 11 gravitational lenses. Candidates are followed up with progressively higher resolution—MERLIN, VLBA, VLBI—as long as necessary. Recently, the final remaining 75 candidates were observed with MERLIN. 15 of these are still 'live' candidates, not having been ruled out as gravitational lenses. Further VLA observations will complete the discovery phase of the initial 7500 sources and should form a good basis for one of our major goals, namely the statistical analysis of the survey with the aim of measuring λ_0 and Ω_0. It is conceivable that this could offer the best measurement of λ_0 in the near future.

It is important to note that the fraction of spiral galaxies is an important ingredient in a statistical analysis with the aim of measuring λ_0 and Ω_0. Should the present relatively large number of spirals prove to be representative (as opposed to being due to selection effects or a statistical fluke) then some 'standard' conclusions based on lensing statistics might have to be revised.

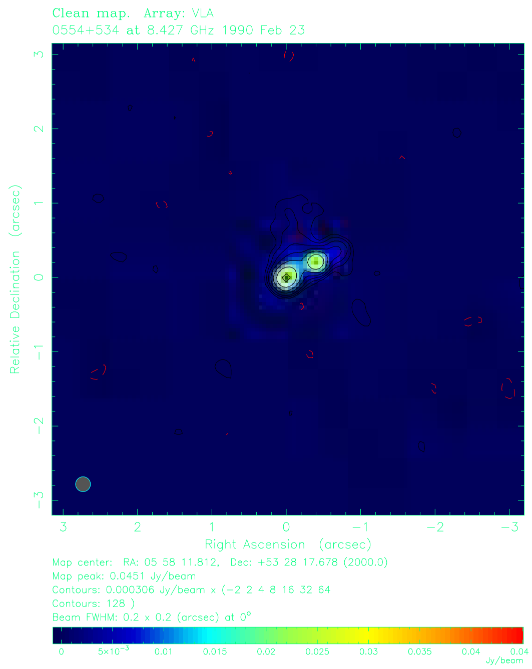

Figure 1: VLA 8.4 GHz map of 0554+534

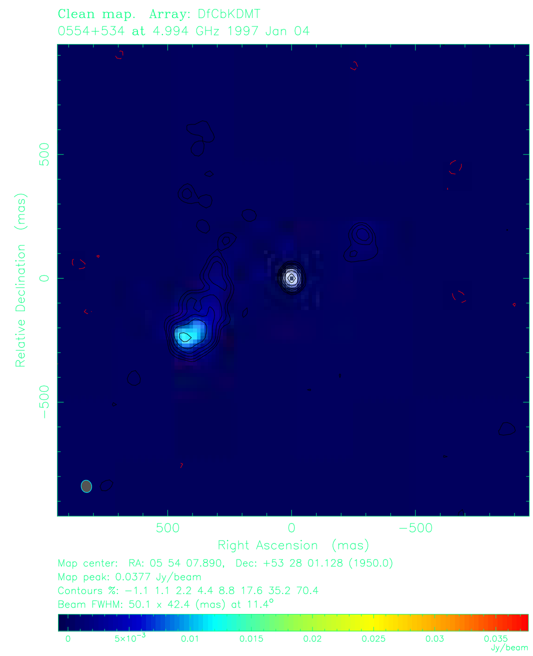

Figure 2: MERLIN 5 GHz map of 0554+534, ruling out a lens candidate

Spiral galaxies as gravitational lenses

HST observations of the lenses are beginning to reveal some interesting results. We detect all the lensing galaxies in the objects so far studied, at typical I magnitudes of ≈20–21. The nature of these lensing galaxies is also of considerable interest. Of the first five lens systems studied, two (B0218+357 and B1600+434) contain spiral lens galaxies; the B1600+434 lens is clearly an edge-on spiral and the B0218+357 lens shows absorption in both molecular and neutral gas (Carilli *et al.* 1993; Wiklind & Combes 1995). The lens of B1608+656 is also likely to be spiral-type, both because of its extreme elongation and because of its light profile. The other two galaxies (the lenses of B0712+472 and B1933+503) are more equivocal; although elongated ($b/a \approx 0.5$–0.6) the profile fits are suggestive of at least some contribution from a de Vaucouleurs-type profile.

The lensed images can also be studied in all objects except one, B1933+503, where they are exceedingly faint ($I > 24$). Further NICMOS observations are to be obtained to assess whether this is due to reddening. There is also evidence for variability in at least two of the

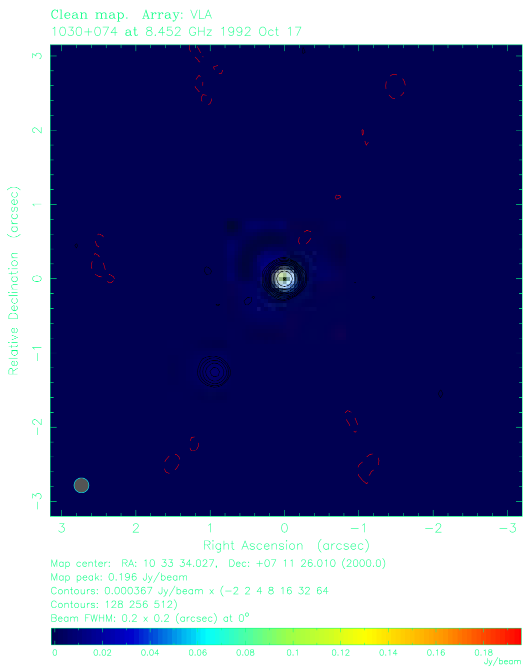

Figure 3: VLA 8.4 GHz map of 1030+074

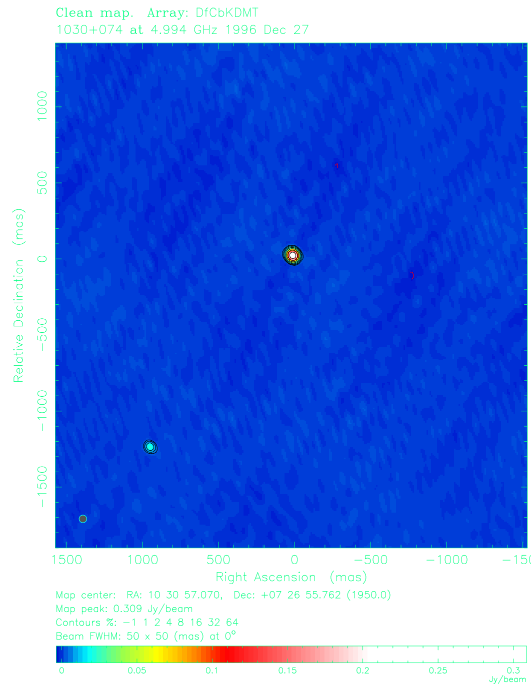

Figure 4: MERLIN 5 GHz map of 1030+074, confirming a good lens candidate

systems (B0712+472 and B1600+434) leading to hopes of using at least one lens for Hubble constant determination. Relative flux ratios between the lensed images in B1600+434 are different in the radio and the optical, almost certainly because of reddening in the lensing galaxy.

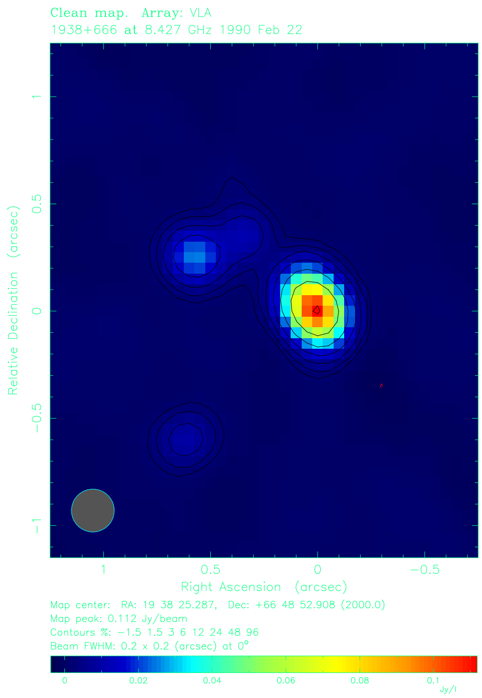

Figure 5: VLA 8.4 GHz map of 1938+666

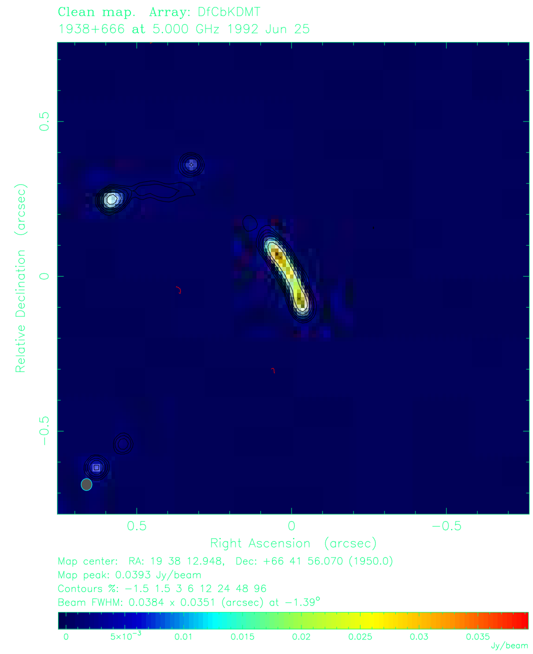

Figure 6: MERLIN 5 GHz map of 1938+666, in which the lensed nature of the object becomes obvious

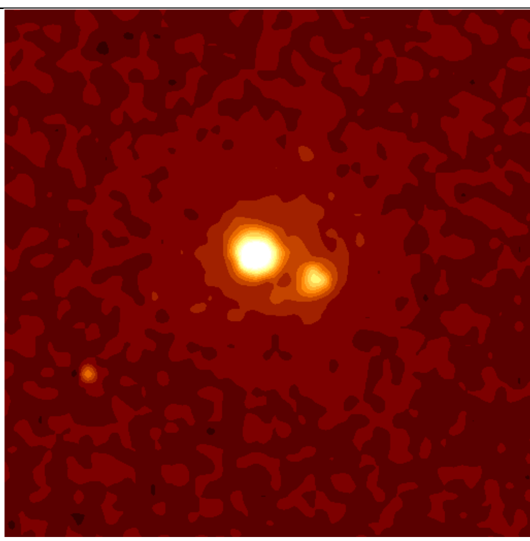

Figure 7: HST V band image of 0218+357

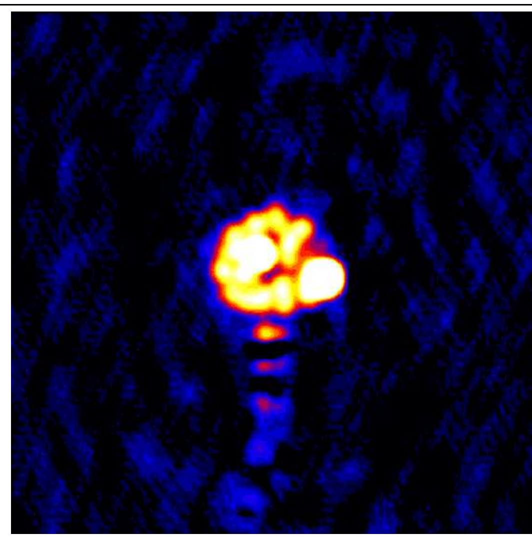

Figure 8: MERLIN 5 GHz map of 0218+357

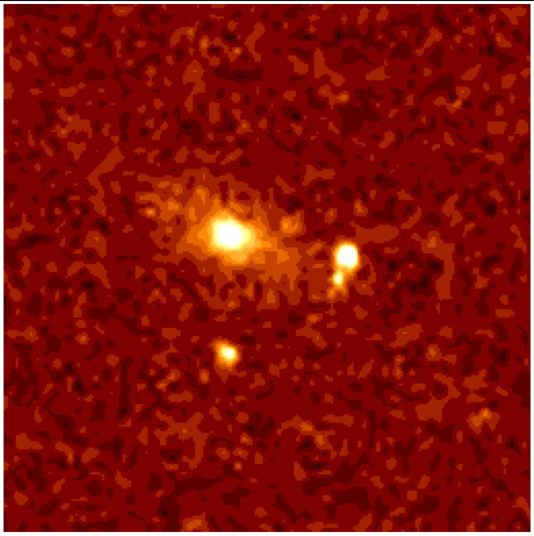

Figure 9: HST V band image of 0712+472

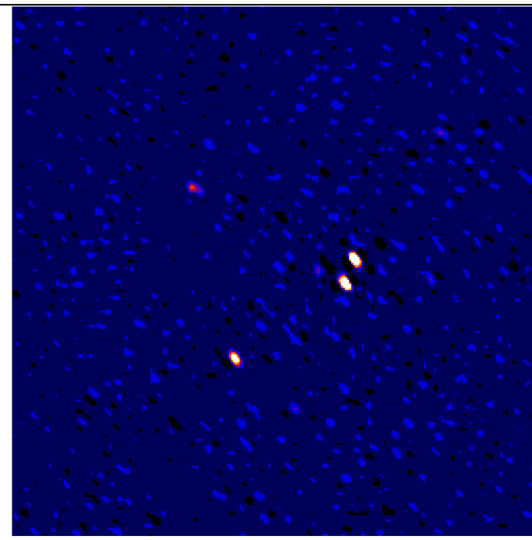

Figure 10: MERLIN 5 GHz map of 0712+472

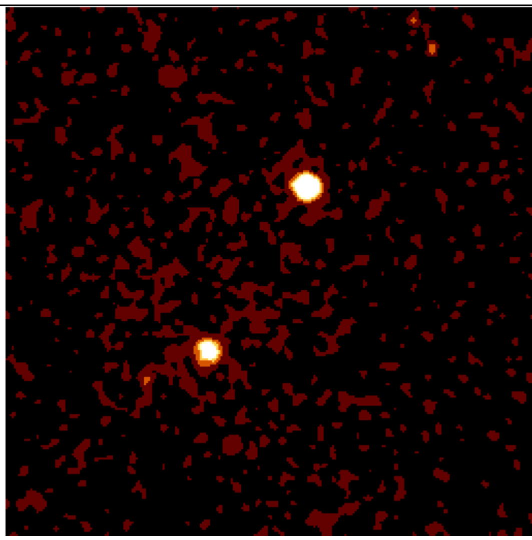

Figure 11: HST V band image of 1600+434

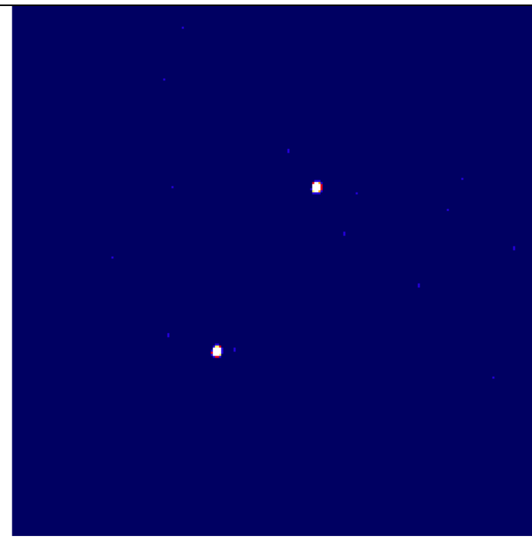

Figure 12: MERLIN 5 GHz map of 1600+434

Time delays

Introduction

Previous work on the gravitational lens 0218+357 (Corbett *et al.* 1996) derived a time delay of 12 ± 3 days from VLA observations of the percentage polarised flux at 8.4 and 15 GHz.

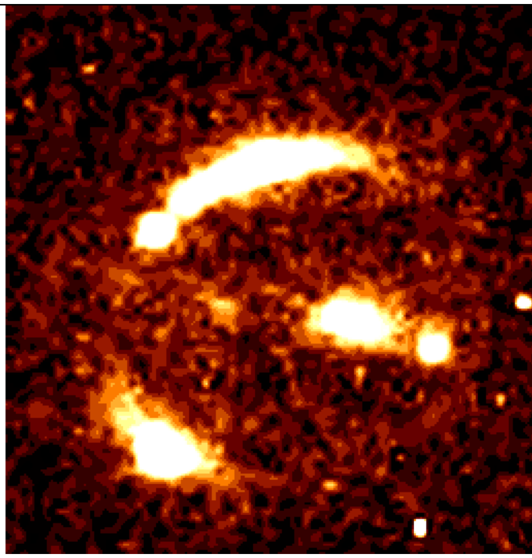

Figure 13: HST V band image of 1608+656

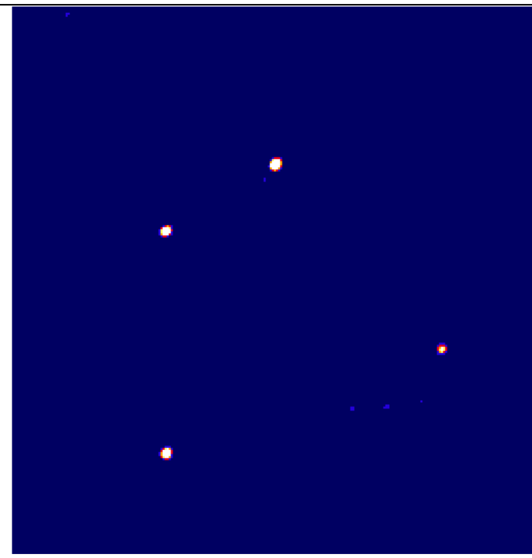

Figure 14: MERLIN 5 GHz map of 1608+656

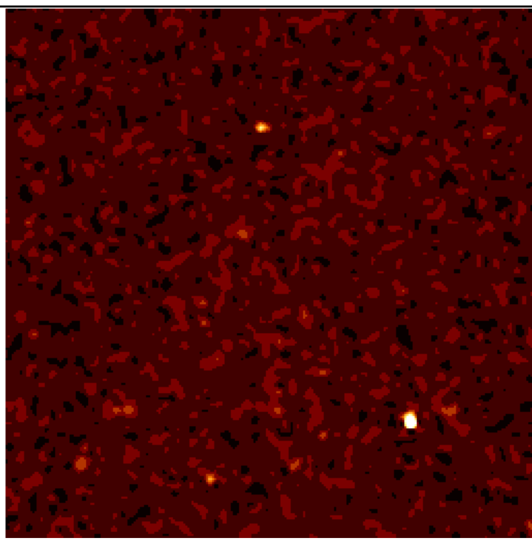

Figure 15: HST V band image of 1933+503

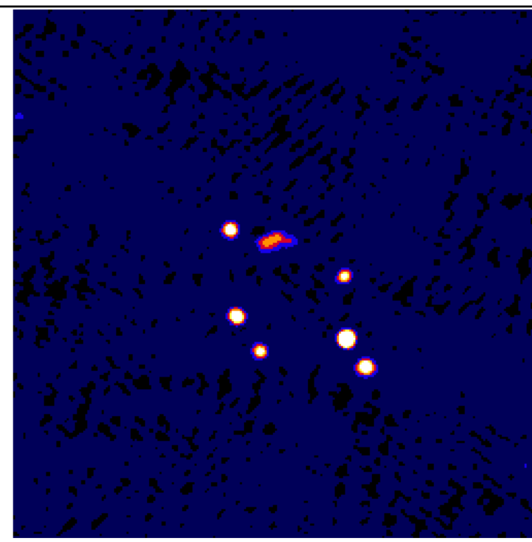

Figure 16: MERLIN 5 GHz map of 1933+503

This result leaves the time delay as the biggest source of error in the final determination of H_0 at this time.

Observations

- 0218+357 was observed with the VLA in A configuration from mid October 1996 to mid January 1997, once every 1–3 days. This resulted in 47 epochs of data, twice the amount used in the previous estimate of the time delay.
- Observed at 8.4 GHz and 15 GHz (resolution 0.2 arc seconds and 0.12 arc seconds respectively) the two components are easily separated and can be monitored for variations in total intensity, percentage polarised flux and polarisation position angle.
- Each observation consisted of scans of 3C84 for amplitude and phase calibrating purposes, and of 3C119 to check for variations in the flux of 3C84 over the course of the observations and to calibrate the position angle of 0218+357.
- At the same time as the VLA observations, 0218+357 was also being observed with MERLIN at 5 GHz. Observations were more frequent than with the VLA, resulting in $\sim$90 epochs.

Results

- So far only the VLA 15 GHz data have been reduced and analysed.
- The flux of 3C119 has varied minimally over the period of the observations. The scatter around a straight line of best fit is 23 mJy which corresponds to an error on the 3C119 fluxes of approximately 1%.
- A time delay is seen in all 3 light curves: total intensity, polarised flux and polarisation position angle. In each case the delay is of the order of 12 days.

Conclusions and future work

- Results from the 15 GHz VLA data have proved very promising so far. The data show clear variations and fluxes are being measured to a high degree of accuracy.
- Work is in progress to refine the time delay estimate and to derive the associated error.
- VLA 8.4 GHz and MERLIN 5 GHz data are still to be reduced.

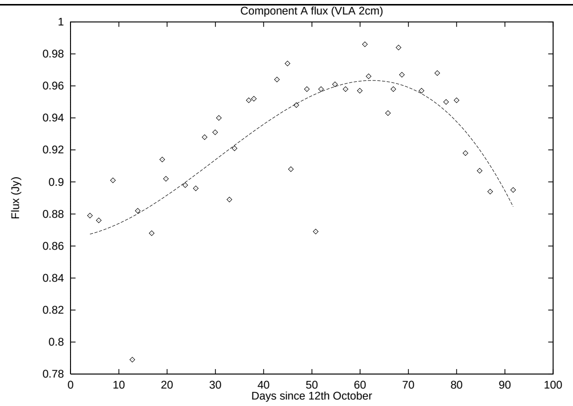

Figure 17: 0218+357A: total flux (VLA at 15 GHz)

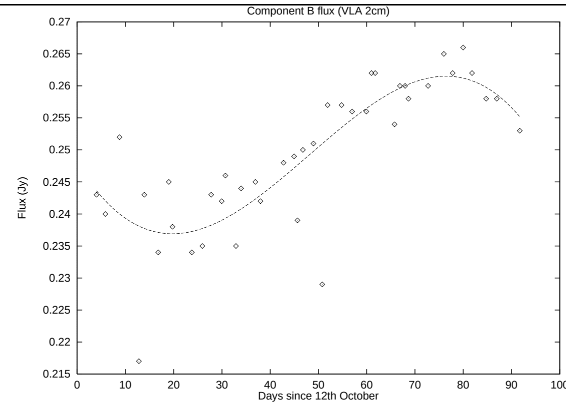

Figure 18: 0218+357B: total flux (VLA at 15 GHz)

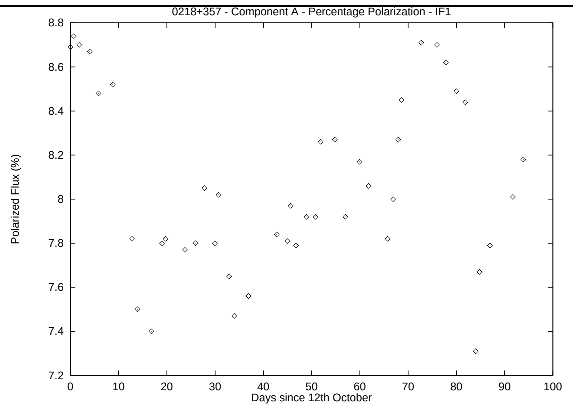

Figure 19: 0218+357A: percentage polarisation (VLA at 15 GHz)

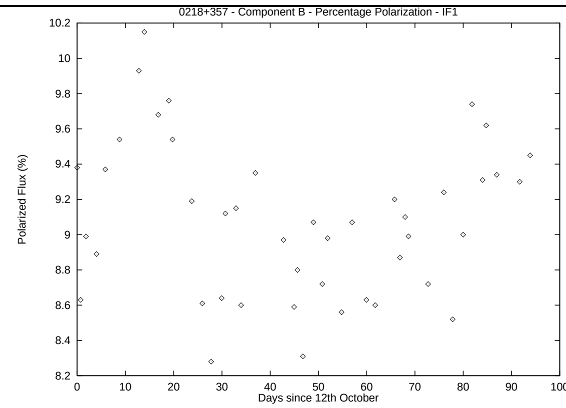

Figure 20: 0218+357B: percentage polarisation (VLA at 15 GHz)

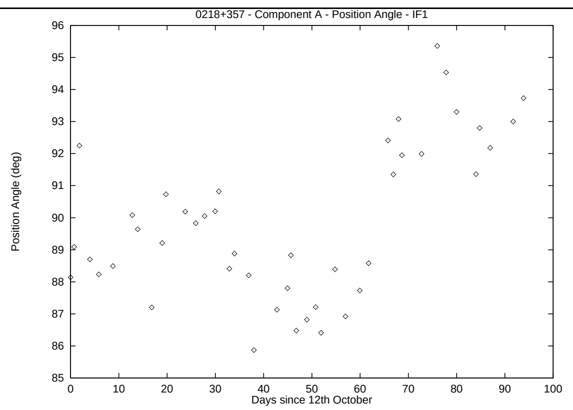

Figure 21: 0218+357A: polarisation position angle (VLA at 15 GHz)

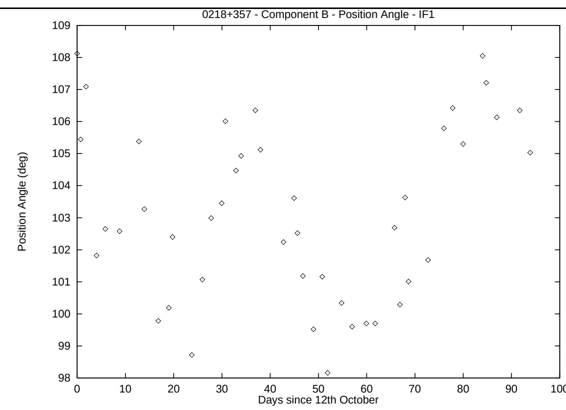

Figure 22: 0218+357B: polarisation position angle (VLA at 15 GHz)

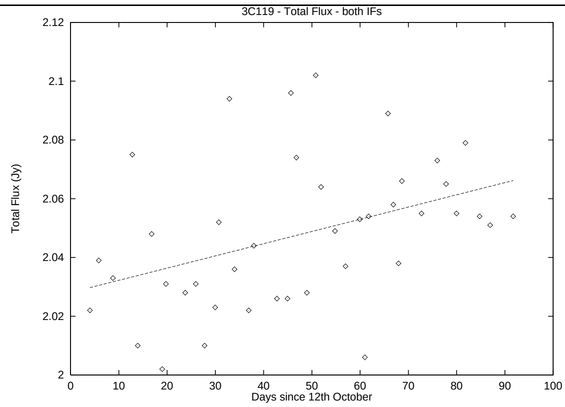

Figure 23: 3C119 (calibrator): total flux (VLA at 15 GHz)

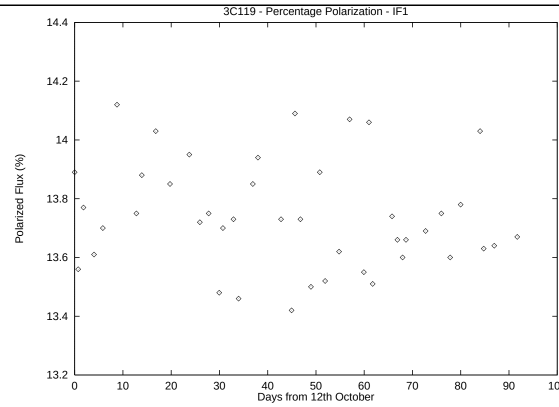

Figure 24: 3C119 (calibrator): percentage polarisation (VLA at 15 GHz)

The JVAS/CLASS gravitational lenses

With only 4 unknown, the redshift information on the JVAS/CLASS gravitational lenses is almost complete. Even where no redshift has yet been measured, the lens galaxy has been detected. The table presents a coarse overview of basic information on these lens systems; more detailed data will be published elsewhere.

Name	#images	$\Delta\theta$ [$''$]	lens galaxy type	$z_{\rm d}$	$z_{\rm s}$
0218+357	ring + 2	0.33	spiral	0.6847	0.96
0414+0534	4	2.0	elliptical	?	2.62
0712+472	4	1.2	?	0.406	1.34
1030+074	2	1.6	peculiar	0.599	1.53
1422+231	4	1.2	?	0.65	3.62
1600+434	2	1.4	spiral	0.415	1.57
1608+656	4	2.2	spiral?	0.64	1.39
1933+503	4+4+2	0.9	?	0.755	?
1938+666	4+2	0.9	?	?	?
2045+265	4+1?	2.0	?	0.87	1.28
2114+022	2+2?	2.4	?	0.316	0.588?

A search for multiple images from cluster-mass lenses: a progress report

Gravitational lensing has been used to put constraints on the distribution of clumpy matter over mass scales ranging from $\ll 1\ M_\odot$ to $\geq 10^{12}\ M_\odot$. Little attention has, however, been paid to systematic searches for multiple imaging by masses comparable to those of clusters of galaxies ($\sim 10^{14} M_\odot$), even though such searches are potentially important ways of testing cosmogonic models (Wambsganss *et al.* 1995). The simplest CDM models suggest that multiple imaging by clusters should occur approximately as frequently as imaging by single galaxies; i.e. $\sim$1 in 500 quasars should be imaged at this scale. The JVAS/CLASS surveys form an ideal starting point for such a search. We have selected the strongest 2500 flat spectrum sources and reprocessed the original VLA 8.4 GHz data picking out any (compact) companion source stronger than 10 mJy and lying within 1 minute of arc of the original target source. The secondary source so selected could either be there by chance or be a second image of the primary source. We find 10 candidates satisfying our selection criteria which is approximately the number expected by chance assuming a random distribution of 10 mJy sources on the sky.

We are in the process of following up the ten candidate pairs to try to test whether we are seeing multiple images. We have made MERLIN 5 GHz observations with a resolution of 50 mas and 1.4 GHz VLA observations with a resolution of 4×12 arc seconds. What we are searching for are gross differences of extended radio structure. We emphasise extended radio structure because real lens systems with the kind of separations we are following up will have time delays of $\sim$1000 years and compact features may be highly variable on this kind of timescale. Reduction of the data is still in progress. Up to now we have been able to rule out about 5 candidates with a reasonable degree of confidence and none of the candidates looks very promising. In the following two figures we illustrate a candidate that we believe we can rule out as not being a multiple imaging event, showing the VLA discovery map and the higher resolution MERLIN map. Further radio and optical follow up of surviving candidates is planned.

Based on the fact that the number of candidates we find is what we would expect by chance and that none of the surviving candidates looks very promising, the most likely outcome of our search is that none of the candidates will turn out to be lensed. If this is the case, the lensing rate would be ≤ 1 in 2500 compared with the roughly 1 in 500 predicted by the simplest CDM model of Wambsganss *et al.* (1995). Whatever the outcome, the search will produce a datum against which the predictions of cosmogonic models must be compared.

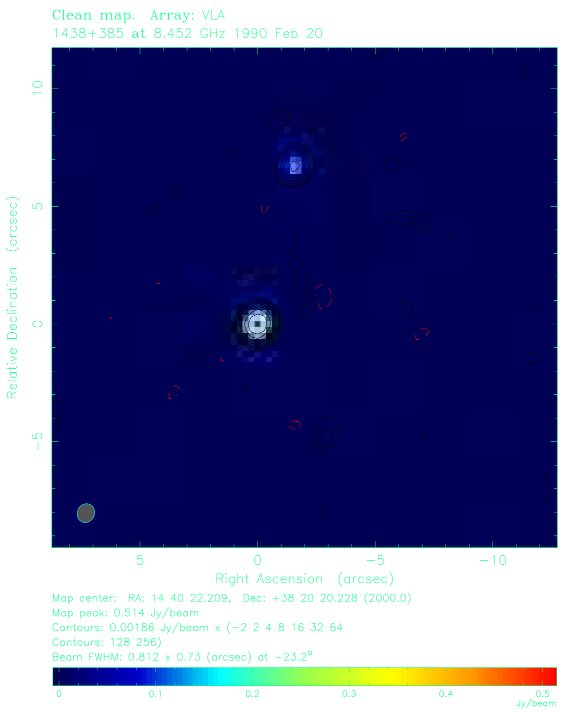

Figure 25: VLA 8.4 GHz map of 1438+385

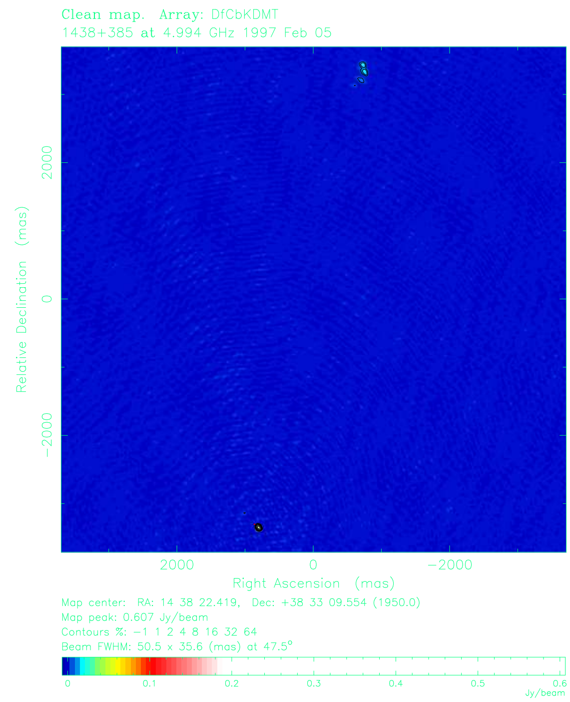

Figure 26: MERLIN 5 GHz map of 1438+385

Acknowledgements

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CERES publications: `http://multivac.jb.man.ac.uk:8000/ceres/papers/papers.html`