A Search for Wide-Separation Lenses in the JVAS SURVEY and Implications for the Standard CDM Model of Structure Formation

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Introduction

Gravitational lensing directly measures fluctuations in the gravitational potential along paths to distant objects. Currently, there are no firm examples of radio selected lens systems with image separations >7", but many with separations <7".

We have made use of the ~2500 flat-spectrum radio sources that make up JVAS (the Jodrell Bank VLA Astrometric Survey)(Patnaik et al. 1992 and papers in preparation) to select wide-separation (>6") gravitational lens candidates. Lensing of flat-spectrum radio sources is relatively easy to recognise since the source structures are point-dominated. In the original JVAS analysis, no attempt was made to look for lenses with separations >6", so this is a new search. The secondary components will be lensed images or part of the source structure or less probably, simply chance sources nearby.

We have remapped and reanalysed the original JVAS data to look for candidates up to separations of one arcminute. The search covered all 2500 fields to look for all aditional components in the data at the 6σ level with a flux ratio less than 50:1 of the primary JVAS source flux density. Finally, only candidates with an 8.4GHz flux density ≥10mJy were considered since only secondary components of this strength could be reliably followed-up. Ten promising large-separation lens candidates satisfying these criteria were found.

One simple test to tell if the secondaries are independent sources or part of the primary source's structure rather than lensed images is to see if they have different morphologies and radio spectra to those of the primaries. MERLIN observations at 5GHz (50mas resolution) as well as VLA observations at L,C,U and K bands in BnC configuration have recently been made and the data reduced. The results of these observations and their implications are presented here.

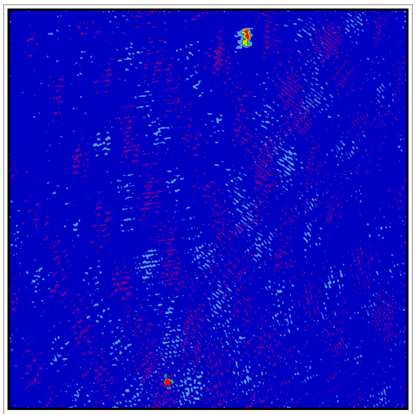

Figure 1: MERLIN C-band map of the source 1438+385. In this case, the secondary component is 6.9" to the North of the primary and is weak and resolved. The components are not lensed images of a single compact core.

The Standard CDM Model of Structure Formation

Wambsganss et. al. (1995) computed the predicted distribution of magnifications for single and multiply imaged point sources as a function of z_s, multiplicity of images, and the distribution of angular splittings for the CDM scenario with $\Omega = 1$, $\lambda = 0$ and $H_0 = 50 \mathrm{kms}^{-1} Mpc^{-1}$. This is the simplest model that satisfies the requirement for a flat universe with $\Omega = 1$ (ie. no cosmological constant). Normalization from the COBE first year results of the density Fourier power spectrum was built into the calculations.

Probably the single most revealing statistic is the distribution of image separations predicted for lenses in the CDM scenario. In general, large separation lenses should be common in JVAS- hence the need for this search. The standard CDM model predicts that 0.0007 of all lines of sight to $z_s = 1$, 0.0014 of all lines of sight to $z_s = 2$ and 0.0020 of those to $z_s = 3$ will be multiply imaged with angular splittings ≥10" and with amplification ratios of less than 4. JVAS sources have a mean redshift of 1.3. In fact, amplification bias would increase these probabilities by a significant factor. Splittings >6" should be common in the JVAS sample if this cosmogonic model is correct.

Recently Flores and Primack (1996) showed that if clusters have large cores then the number of large-separation splittings would be greatly reduced, even for cosmological models that predict excessive large-scale structure (eg. standard CDM). They have argued that large-splitting lensing is not a sensitive probe of large-scale structure. Bartelmann (1996) demonstrated that clusters with a core can produce radial arcs which has renewed confidence that such clusters can be efficient splitters of background quasars and hence useful probes of large-scale structure and its evolution.

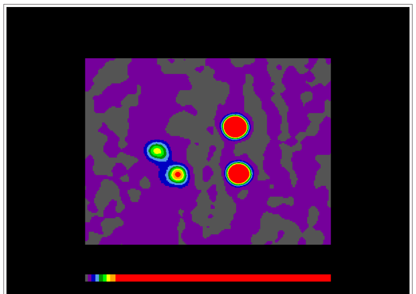

Figure 2: VLA L-band map of 1149+234. This source has two distinct components separated by 52". There is weak extended emission probably associated with a jet. The presence of multiple compact compoents means this source remains a candidate.

Sample and Observations of Candidates

It became clear that it would be possible to mount a search for wide separation lensing in the JVAS data for secondaries within one arcminute. We would not be limited by bandwidth smearing due to the observing frequency, the synthesised beam and the bandwidths that were used. Further, we would only expect of order ~ 6 compact "confusing" sources in the JVAS ±1 arcminute "big fields" with flux densities ≥ 10mJy from the statistics of the GB6 catalogue (Gregory et al. 1995).

We have a large enough search area and enough sources to be capable of impacting on the Wambsganss et. al. (1995) predictions for the standard CDM model of structure formation.

The JVAS sources all satisfy the following selection criteria:

- $\alpha \geq -0.5$
- $S_{GB6} \geq 200$ mJy
- $|b| > 2.5^{\circ}$

A total of 66 arcsecond-scale lens candidates in JVAS have been followed-up with the VLA, MERLIN and the VLBA (King et al. 1997) and to-date, six lenses have been discovered. This wide separation search is the first systematic search for strong lensing at these angular separations.

1 MERLIN Observations

MERLIN observations at C-band (5GHz) were made between the 4th and the 10th of February 1997 and were reduced using the AIPS and DIFMAP software.

As with previous MERLIN clarification observations, the sources were observed in "snapshot mode". The sources were observed over 24 hours. This was a straightforward task since the primary components acted as phase calibrators for the weaker secondary components. The sources were self-calibrated using a Gaussian point-source model. A bandwidth of 50 MHz was used to reduce the effects of bandwidth smearing considering the observing frequency and resolution of the instrument.

2 VLA Observations

The ten candidates were observed at 1.5GHz (L-band), 5GHz (C-band), 15GHz (U-band) and 22.5GHz (K-band) at the VLA interferometer on 18th, 20th and 22nd June 1997 in BnC configuration.

The L-band data were analysed first. It was at this frequency that the sources were observed for longest so that radio maps could be made. The low resolution and high sensitivity of this frequency was expected to reveal low surface brightness structure to either confirm or rule out the lensing hypothesis. The observations at C, U and K band were designed to simply build additional spectral information on the candidates in addition to the X-band (8.4GHz) observations performed for JVAS.

Name	Separation ["]	$S_{8.4GHz}$ A	$S_{8.4GHz}$ B	$\alpha^5_{1.4}$A	$\alpha^5_{1.4}$B
0113+241	73.6	203	91.2	0.15	0.56
0200+304	70.1	241	131	−0.56	0.15
0748+582	56.6	93.4	16.4	−0.38	0.69
1142+446	16.1	172	11.6	−0.40	−0.09
1149+234	52.3	61	52.4	−0.56	−0.40
1305+804	17.0	120	13.9	−0.37	−1.11
1438+385	6.9	501	59.6	0.03	−0.48
1518+046	59.6	336	30.5	−0.83	−0.72
1713+218	59.5	103	29.2	−0.57	−0.31
2147+031	58.6	76.6	26.3	−0.35	0.36

Table 1: The ten wide-separation lens candidates from JVAS. The separation is shown in column 2. The X-band fluxes from the original JVAS survey are given for the primary (A) and secondary (B) components. Columns 5 and 6 show the two-point spectral indices from 1.4GHz to 5GHz for each component.

Observational Results

The low number of candidates illustrates that we are already close to reaching the expected number of unlensed doubles due to chance associations. This is significant since if standard CDM is correct we expect to have found lenses in addition to these sources.

A major problem with searching for large-separation quasar lensing is the lack of confidence in ruling out systems due to the related time delays that would be associated with such lenses. Our approach to ruling out arcsecond-scale systems has been based primarily on possible lensing morphologies and on comparing component spectra. In the case of large-splitting images, time delays of the order of hundreds or even thousands of years limit our confidence in this approach.

We feel confident in ruling out the system 1438+385 being multiple images of a compact core based on the MERLIN C-band data. The secondary component is resolved and extended.

Further observations are needed to follow-up the remaining candidates. VLBA observations to compare individual components and perhaps optical imaging of the fields would provide additional evidence to rule out the lensing hypothesis. None of the candidates have optical identifications associated with the radio positions on the POSS.

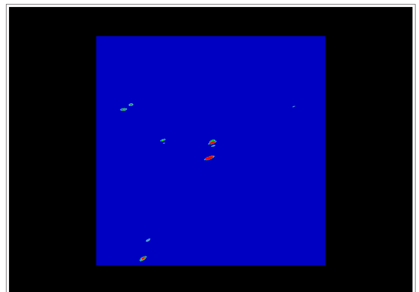

Figure 3: VLA L-band map of the source 0200+304. This is a 10' by 10' map about the primary and secondary components which are separated by 70" towards the centre. The source is therefore not formally in the sample. There is a collection of weak radio sources in the field, perhaps radio galaxies in a cluster.

Discussion and Conclusions

The predictions of the standard CDM model were already in serious conflict with observations. All confirmed QSO systems have image splittings less than 10" and most have splittings less than 5".

Our data sharply contradicts the predictions of standard CDM. This is significant, since we have mounted the first systematic and complete radio survey for lensing at separations >6". The large-splitting, modest flux ratio systems predicted by the model would be easier to detect than those arcsecond-scale systems already discovered.

The failing of the model tested is not presented as a new result, rather as a new robust confirmation of a previously recognised problem; namely the deep potential wells produced by the dark-matter component in COBE-normalised standard CDM. These deep potential wells would produce excess galactic pairwisw velocity dispersions and lead to the predicted excessive rate of wide-separation lensing. The lensing test is independent of other tests and are no caveats concerning bias of galaxies with respect to dark matter.

Could there be variant models that would not fail our test? Many alternative models have been considered or reconsidered in recent years. Extra parameters have been added to allow for a non-standard spectrum shape, for other components of matter (such as massive neutrinos), or for less matter than is assumed in the ($\Omega = 1$) models. Of course the simplest change would be to reduce the density of matter in the universe, since the large number of large mass concentrations produces an overabundance of large splittings. So, a lower value of Ω would be useful (increasing the computed age of the universe). It would however be premature to argue that our observations by themselves argue for $\Omega < 1$, since many other properties of the scenario (such as the temperature of the dark matter and the shape of the power spectrum) contribute to the lensing properties.

However, the directness of gravitational lensing as a test for the growth of homogeneities, coupled with the incresing speed of computers and numerical algorithms means testing and discriminating between competing cosmogonic scena rios should become a reality in the near future.

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References

Bartelmann, M., 1996. *A&A*, **313**, 697
Flores, R.A. & Primack, J.R., 1996. *ApJ*, **457**, L5
Gregory, P. C. and Scott, W. K. and Douglas, K. and Condon, J. J., 1995. *National Radio Astronomy Observatory (NRAO)* publication
King, L.J., et al. 1997. In preparation
Patnaik, A. R. & Browne, I. A. W. & Wilkinson, P. N. & Wrobel, J. M., 1992. *MNRAS*, **254**, 655
Wambsganss, J., Cen, R., Ostriker, J. P., Turner, E. L., 1995, *Science*, **268**, 274
CERES publications: http://multivac.jb.man.ac.uk:8000/ceres/papers/papers.html