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Lenses of small angular scales from Jodrell Bank survey

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Abstract. The Jodrell Bank 5 GHz sky survey provides a complete flux-limited sample of radio sources at latitude greater than 2°.5 which are brighter than 200 mJy and have a spectrum flatter than 0.5. From the analysis of nearly 100 sources from this survey, three cases of multiply imaged lens systems have been detected, all of which have scales in the range of 0.3 to 1.3 arcseconds. The most extensively studied object among these, B0218+357, consists of the fainter source, probably lensed by a spiral galaxy of redshift 0.68. The lens models indicate that the radio ring is likely to be multiple images of two or three extended blobs forming an Einstein ring. Another system, B1422+231 is probably a quintuply imaged point source at a redshift of 3.62. Two bright images of almost equal intensity and the third image of half their intensity are indicative of the source being located near a naked cusp of the lens. The third candidate, 1938 + 666 is very faint but has extended arc-like features. The lens configurations deduced from this complete flux-limited sample indicate one of the following scenario : (i) The number density of compact but faint galaxies with mass distribution having high quadruple moment increase rapidly at high redshifts. (ii) The number density of compact flat spectrum sources probably decreases rapidly at redshift greater than around 3. These conclusions are necessarily preliminary in the absence of measurement of the redshift of lens galaxies.

Key words : lens systems—spiral galaxy—radio observations

1. Description of the radio survey

The Jodrell Bank 5 GHz sky survey (Patnaik *et al.* 1992a) was intended to obtain a grid of phase calibration sources for long-baseline arrays like VLA or MERLIN. However, it could provide a complete flux-limited sample of radio sources at latitude greater than 2°.5 which are brighter than 200 mJy and have a spectrum flatter than 0.5 between 5 and 22 GHz. The sources are believed to be almost entirely quasars and AGNs, because of the selection procedure, thereby ensuring homogeneity of the sources. An unbiased analysis of nearly 1000 sources from this survey was carried out to search for possible gravitational lens candidates. All objects which have a companion of the same class within a separation of 0″.25 to ten arcseconds and flux ratio of less than about 10 are examined for similarity of

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spectral index or other possible lens characteristics. From the analysis, only three cases of multiply imaged lens systems have been detected, though a few are still being monitored. All the selected candidates turn out to have angular scales in the range of 0.3 to 1.3 arcseconds.

2. The gravitational lens candidates

The most extensively studied among the three systems is B0218+357 (Patnaik *et al.* 1991). It consists of two bright nearly point like objects at flux levels of 0.73 and 0.24 Jy separated by 0.335 arcsec and faint structures forming a near-complete sub-arcsecond radio ring of diameter 0.33 arcsec around the weaker source. The redshift of the lens galaxy, indicated by the radio absorption lines, is 0.68 and the extent of Faraday rotation is suggestive of the lens being a spiral galaxy.

The source B1422+231 consists of two 0.2 Jy point objects separated by half an arcsecond and a similar third component having half the brightness situated at one arcsecond away. Their redshift has been detected at $z = 3.62$ (Patnaik *et al.* 1992b). Another source at 1.3 arcsecond away from the main components detected at the level of 4 mJy/beam could be part of the lens configuration. Polarisation measurements of the three bright components is consistent with the lens hypothesis. Probably the spectral index of all the four sources is very similar.

The faint system of an arcsecond extent, 1938 + 666 has arc-like features in addition to three compact components. All the components have flux of a few mJy. However, no compact object in this system has 5 GHz flux near 200 mJy, the level down to which the sample is complete.

3. Quick reference to the gravitational lens theory

The morphology of the images in gravitational lens systems can be understood in terms of the caustics in the image plane (where the intensity of the images become infinity) and the corresponding critical curves in the source plane for a given lens and distance to the source. The image multiplicity changes across the critical curves and sources crossing them form extended merging arc-like features.

A galaxy or cluster of galaxies can generally produce multiple images of a background source near its line of sight if its projected surface mass density, Σ is above a critical limit,

$$\Sigma_{\rm cr} = \frac{c^2}{4\pi G D_{\rm eff}} \qquad \ldots (1)$$

where c is the velocity of light, G, gravitational constant and the distance measure,

$$D_{\rm eff} = \frac{D_{\rm ls} D_{\rm l}}{D_{\rm s}} \qquad \ldots (2)$$

depends on the distance from the source to the observer, $D_{\rm s}$, distance from the lens $D_{\rm l}$ and the distance from the source to the lens $D_{\rm ls}$. The properties of the image plane can be described in terms of the function $\alpha = \Sigma/\Sigma_{\rm cr}$. For elliptical symmetry, which is a good approximation for most galaxies and galaxy-clusters, the central value of α, the scale-length at which it varies and its eccentricity determine the image properties. If $\alpha(0)$ is near unity but its scale-

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length is large, an extended diamond shaped critical curve will be formed, the sources lying near which will be magnified substantially. On the other hand the size of the region producing two-image configuration will increase with increasing $\alpha(0)$. It is apparent from the above equation that, when the lens is close to the source α will be small. A small α indicates shear-induced lensing as against the focussing action of the lens when α is large.

4. Gravitational lens models

The gravitational lens models were numerically computed using the formalism described by Narasimha, Subramanian & Chitre (1982). However, the following discussion is to a good extent independent of specific lens models.

The configuration of the system B0218+357 can be due to the lensing action of any ordinary galaxy but in the absence of redshift measurements of the radio source very little more can be said about the lens models. However, the models indicate that the radio ring is likely to be multiple images of two or three extended blobs. The prediction of the model, namely, tangential magnification of the bright component of this system has since been verified.

The high redshift object B1422+231 appears to be a case of background source imaged essentially by the shear of the lens as against its focussing. The equality of brightness of the bright components and the location of the three images are the outcome of the background source being located very near to, but inside the cusp of the lens. The morphology of the source plane will depend on whether the faint source in the field is part of the system; if the faint object is the fourth image of the background source, the critical curve of the lens should consist of a cusp and a dumb-bell shaped figure while if the faint source is independent of the main images, the critical curve in the source plane is likely to be a lip. The models suggest that the lens very likely consists of an extended galaxy or a galactic halo and probably a compact luminous object of size similar to the bulges of normal galaxies, located at redshift of around 2. The detection of the lens will indeed have implications regarding the structure of galaxies at high redshifts.

It is tempting to assume that the system 1938 + 666 is made up of two images of a faint point-like source and four images of an extended radio blob. Two of the merging images form an arc-like feature extending over nearly an arcsecond. In spite of the weakness of the sources, this interpretation is mildly supported by the observed polarisation angles and degree for the extended images as well as the profile of surface brightness of the extended images. In such a scenario the lens galaxy should probably have redshift nearly comparable to that of the lensed sources.

5. Cosmological implications of the radio survey

The survey is important for statistical analysis of lensing because a homogeneous volume limited sample of objects can be obtained from a survey which was originally not intended to be for lensing. Any reliable conclusions could be arrived at from this survey only after detailed analysis of the maps. However, even after the preliminary analysis of the lens candidates one notices the apparent paucity of two-image configurations in the sample. And the models of observed lenses are suggestive of the configuration composed mainly of extended cusp or lip shaped critical curve. Assuming the completeness of the sample and

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unbiased analysis of the sources, the lens morphology deduced from this complete flux-limited survey extending down to 200 mJy level indicates one of the following scenario :

1. The number density of compact but faint galaxies with mass distribution having high quadruple moment increases at high redshifts.
2. The number density of compact flat spectrum sources probably decreases rapidly at redshift greater than around 3.

In either of the above scenarios, the lensing action of the distant galaxies is more likely to be due to shear as against focussing due to their mass. These conclusions are necessarily tentative in the absence of measurement of the redshift of lens galaxies. However, the major problem for a trustworthy analysis is that, at present only objects having peculiar geometry appear to have been noticed even when their flux is low. In the absence of accompanying bright radio blobs some of the compact flat spectrum sources might form uninteresting two-image configurations in which the morphology of the image closer to the lens galaxy could be modified to the extent its identification may not be easy. In this context the detection of the very faint system 1938+666 having noticeable geometric features probably renders statistical analysis of the sources in the survey slightly suspect.

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