A SEARCH FOR GRAVITATIONAL MILLI–LENSES

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Abstract. We have searched for gravitational milli–lens systems by examining VLBI maps of ~ 300 flat–spectrum radio sources. So far we have followed up 7 candidates, with separations in the range 2–20 mas. None have been confirmed as lenses but several of them can not yet be definitively ruled out. If there are no milli-lenses in this sample then uniformly–distributed black holes of 10^6 to 10^8 $M_\odot$ cannot contribute more than ~ 1% of the closure density.

1. Introduction

A few lens systems have been found with sub–arcsecond image separations but lensing by mass concentrations below $\sim 10^9 M_\odot$ has not yet been investigated because the image separation has been below the resolution limit of the VLA and the HST. VLBI imaging is the only direct way to push the image separation limit below ~ 100 mas.

Searches for lensed systems with image separations in the range 1–100 mas (so–called "milli–lenses"), are of particular cosmological interest. Such separations correspond to lensing masses in the range $\sim 10^6$–$10^8 M_\odot$, comparable with the expected masses of pre–galactic compact objects (PCOs). PCOs arise in a wide range of cosmogonic scenarios with a natural mass scale, set by the Jeans mass, of order $10^6 M_\odot$ (e.g. Carr 1990). Uniformly

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distributed PCOs could provide a significant fraction of the closure density of the universe and can only be detected by their gravitational lensing effects. Press & Gunn (1973) first calculated the optical depth of the Universe to lensing by point masses and their calculations have been extended by Ostriker & Vietri (1986), Nemiroff and Bistolas (1990) and Kassiola, Kovner and Blandford (1991). Gnedin & Ostriker (1992) have recently suggested that radiation from an early generation of massive stars ($10^{6.5} M_{\odot}$), forming somewhat after decoupling, may have altered the light element abundances. Their hypothesis allows a larger amount of baryonic dark matter and does away with the need for non–baryonic forms. The massive stars collapse to black holes and with the required density, $\Omega \sim 0.15$, $\sim 5\%$ of high-redshift quasars should be milli–lensed.

2. The VLBI Surveys

A series of VLBI surveys have now been made with resolutions of ~ 1 milliarcsec (mas). The most recent was the second Caltech-Jodrell Bank (CJ2) VLBI survey—a global MkII snapshot VLBI survey of 193 flat–spectrum radio sources at $\lambda 6$ cm (Taylor et al. 1994; Henstock et al. 1995). The aims of the CJ2 survey were to extend the morphological classification of the PR (Pearson & Readhead 1988) and CJ1 (Polatidis et al. 1994; Thakkar et al. 1994; Xu et al. 1994) VLBI surveys and to address several new cosmological questions. Amongst these was whether or not there is evidence for gravitational lensing on scales 2–200 mas.

On the mas scale the great majority of flat–spectrum radio sources are asymmetric core–jets. Simulations of the lensing effect of a PCO show that the typical image configuration is likely to consist of the core-jet primary with the demagnified, hence fainter, secondary off to one side. When the images are convolved with a 1 mas restoring beam the secondary may appear unresolved even if the primary is well resolved. Any source with a compact companion component no larger than the strongest component was therefore treated as a lens candidate.

About 300 flat–spectrum radio sources have now been mapped in the PR, CJ1 and CJ2 VLBI surveys; the typical resolution is 1 mas and the dynamic range is $> 100 : 1$. We are confident of detecting compact lensed components 30 times weaker than the brightest component in the map out to ± 200 mas. However, for image separations < 1.5 mas, i.e. comparable with the beam size, we are only sensitive to compact components with flux ratios $< 10 : 1$.

3. The Redshift Distribution

The majority ($\sim 80\%$) of the ~ 300 flat–spectrum sources in the PR, CJ1 and CJ2 surveys now have measured redshifts. The redshift distribution is shown in Fig. 1. The fraction of high redshift sources is a strong function of the limiting flux density of the sample. In the combined PR sample ($S_{6cm} > 1.3$ Jy) and CJ1 sample (1.3 Jy $\leq S_{6cm} \leq 0.7$ Jy) only 3 objects ($\sim 3\%$) have $z > 2.5$ whereas in the CJ2 sample (0.7 Jy $\leq S_{6cm} \leq 0.31$ Jy) 18 objects ($\sim 9\%$) have $z > 2.5$. As yet we have redshifts for only $\sim 70\%$ of the CJ2 sample but expect to increase this to $\sim 90\%$ with further optical observations of the faint objects.

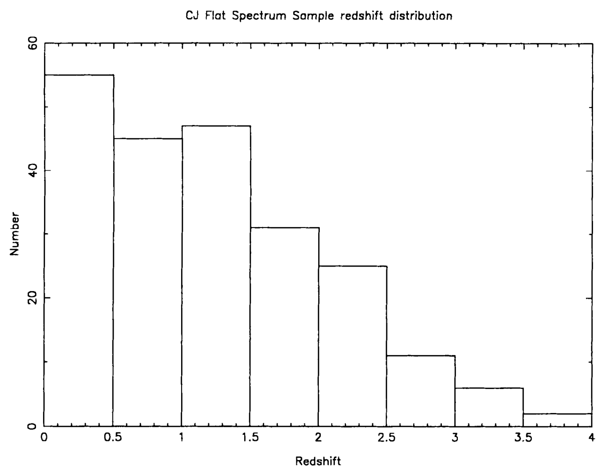

Figure 1. The redshift distribution of flat–spectrum sources in PR+CJ1+CJ2

4. Follow–up Observations

For the seven lens candidates we are made initial follow–up observations with 6 telescopes of the VLBA during February and March 1994. We made total intensity maps at λ 18cm, λ 3.6cm and λ 2cm to complement the existing λ 6cm maps. Lensed sources *must* contain two or more mas components which have simply–related structures and identical radio spectra. This multi–wavelength attack enabled us to show that about half of the candidates are conventional core–jet sources. For example Fig. 2 shows the CJ2 survey map of 0740+768; our higher resolution VLBA map at λ 2cm reveals the compact double source to be a core with a jet in p.a. $-100°$. A few candidates cannot yet be definitively ruled out. For these we must await the results of higher sensitivity VLBA observations at $\lambda 2$ cm scheduled for the Winter of 1994/5.

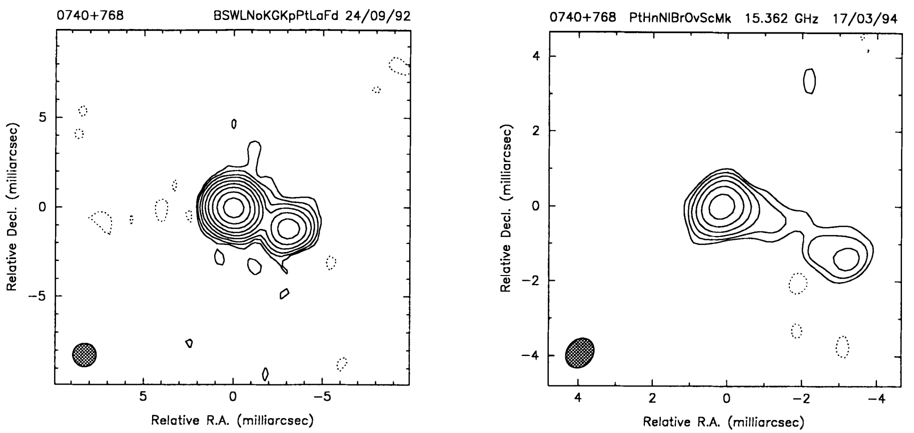

Figure 2. The lens candidate 0740+768: left) CJ2 map at λ6cm (resolution $\sim$ 1 mas) made with a "global" array; right) VLBA map at λ2 cm (resolution $\sim$ 0.5 mas)

It we fail to detect milli–lensing in $\sim$ 300 flat–spectrum radio sources then uniformly–distributed PCOs can only contribute $< 1\%$ to the closure density. In order to place tighter limits on the cosmological density of PCOs, and specifically to confront Gnedin and Ostriker's (1992) prediction that $\sim$ 5% of high redshift quasars might be lensed, at least 1000 radio–selected flat–spectrum sources must be searched. The VLBA is well–suited to this new surveying task.

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