

Limits on the Cosmological Abundance of Supermassive Compact Objects from a Search for Multiple Imaging in Compact Radio Sources

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Using very long baseline interferometry we have searched a sample of 300 compact radio sources for examples of multiple imaging produced by gravitational lensing; no multiple images were found with separations in the angular range 1.5–50 milliarcsec. This null result allows us to place a limit on the cosmological abundance of intergalactic supermassive compact objects in the mass range $\sim 10^6 M_\odot$ to $\sim 10^8 M_\odot$; such objects cannot make up more than $\sim 1\%$ of the closure density (95% confidence). A uniformly distributed population of supermassive black holes forming soon after the big bang does not, therefore, contribute significantly to the dark matter content of the Universe.

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Introduction.—The possibility that a first generation of objects with masses comparable to those of globular clusters formed prior to galaxies has long been recognized [1,2]. Such Jeans-mass ($\sim 10^{6.5} M_\odot$) objects forming shortly after the decoupling of matter and radiation in the early universe could have evolved to black holes and it is possible that some of the dark matter could be in this, difficult to detect, form [3,4]. Building on these ideas Gnedin and Ostriker [5] and Gnedin *et al.* [6] explored a cosmogonic model in which the baryonic density ($\Omega_b \sim 0.15$) is up to an order of magnitude higher than that inferred from primordial nucleosynthesis with the “excess” baryons being lost in the collapse of such Jeans-mass objects. It has also been conjectured that relic massive black holes might provide the seeds for quasars [7].

Press and Gunn [8] developed the idea of detecting supermassive compact objects (CO) by their gravitational lensing effects well before the actual discovery of gravitational lenses in 1979. They showed that in a universe filled with a mass density $\Omega_{CO} \sim 1$, the probability of a distant source being detectably lensed by a supermassive CO is of order unity, while for $\Omega_{CO} < 1$, the probability

decreases in direct proportion to the mass density. From this they drew the important conclusion that the fraction of distant galaxies that is lensed by CO directly measures Ω_{CO} and, ignoring angular resolution effects, is independent of the mass M_{CO} of the lenses. The latter property is simply understood. A given value of Ω_{CO} can be made up of a large number of low-mass objects or a small number of high-mass objects; hence the number density n of CO of a particular mass is proportional to $1/M_{CO}$. For point masses the gravitational lensing cross section $\sigma \propto M_{CO}$ [9], and hence the path length to lensing ($1/n\sigma$), is independent of the lens mass. However, the average image separation measures M_{CO} directly and is approximately independent of Ω_{CO} . These ideas were further developed by Nemiroff [10] and by Nemiroff and Bistolos [11].

Since for a lens at a cosmologically significant distance the image separation is $\sim 2 \times 10^{-6} (M_{CO}/M_\odot)^{1/2}$ arcsec, searching for Jeans-mass CO requires the milliarcsec (mas) resolution of very long baseline interferometry (VLBI). Kasiola *et al.* ([12]; hereafter KKB) used the lack of “millilensed” images in published VLBI maps of 48 compact radio sources to place an upper limit $\Omega_{CO} < 0.4$

(99.7% confidence) in the mass range 10^7 – $10^9 M_\odot$. In a closely related search Nemiroff *et al.* [13] used the lack of secondary “echoes” of gamma ray bursts, which would also arise from millilensing, to rule out a closure density of supermassive CO. In this paper we describe a millilensing search based on high-quality VLBI maps of 300 sources which extends KKB’s lower mass range to $\sim 10^6 M_\odot$ and enables us to push their limit on Ω_{CO} for Jeans-mass objects down by a factor 15. This is the most stringent limit to date on Ω_{CO} for uniformly distributed Jeans-mass objects and we discuss some cosmological implications of this result.

Selection of lens candidates.—The parent sample was drawn from catalogs of compact radio sources which have been systematically observed by us with intercontinental VLBI arrays at a frequency of 5 GHz and a resolution ~ 1 mas; a significant fraction of these sources was also observed at 1.6 GHz. The catalogs, radio images, and full description of the observations can be found in the following papers: the Pearson and Readhead VLBI Survey (PR; [14]); the first Caltech-Jodrell Bank VLBI Survey (CJ1; [15–17]); the second Caltech-Jodrell Bank VLBI Survey (CJ2; [18,19]). From these samples a large subset of 300 sources was selected on the basis of a “flat” integrated radio spectrum between 1.4 and 5 GHz. In this context, “flat” implies a source whose spectral index $\alpha \geq -0.5$, where the flux density at a frequency ν is proportional to ν^α . The sample thus selected contains nearly all of the strongest flat-spectrum radio sources in the sky above declination 35° .

Flat-spectrum radio sources are best suited to a millilensing search because they tend to be dominated by a single compact (sub-mas) “core,” which originates close to the massive central black hole in the nucleus of the background galaxy. The presence of *two* compact components (putative images) then provides a simple diagnostic of gravitational lensing by a pointlike mass, and genuine images will have well-understood, simply related, properties [9]. However, great care has to be taken in choosing lens candidates since compact radio sources have a range of intrinsic structures which can confuse the selection process. Guided by a series of simulations we decided to look only for cases of multiple imaging of the compact core. It is much harder to be certain of recognizing lensing effects on lower-brightness emission regions. We adopted the following quantitative selection criteria based on the Gaussian models listed in the original VLBI survey papers:

A candidate has to have two or more compact (< 1 mas) components and the secondary component should be smaller than the primary. Because of the surface-brightness conserving property of lensing, weaker images are smaller images. However, conservative allowance was made for Gaussian model-fitting uncertainties by accepting some candidates in which the secondary had an area up to two and, in a few cases, three times that of the primary. *The separation of the primary and secondary*

components, $1.5 \leq \Delta\theta \leq 50$ mas. This is set by the VLBI resolution and field-of-view limitations and determines the mass range to which the search is sensitive. The upper limit on the separation was set by the practicalities of map making at the time the VLBI surveys were made. *The ratio of the flux densities of the core of the primary component and the secondary component is $\leq 40:1$.* At this level, secondaries are detected with high signal-to-noise ratio.

Fifty lens candidates were selected, of which six could immediately be ruled out from other published VLBI data.

Scrutiny of lens candidates.—Since the brightness contrast between the core and all other emission regions in a radio source increases with increasing frequency, the simplest way to determine whether two or more of the components are compact, and have properties appropriate for lensed images, is to observe at a higher frequency and higher resolution than the original 5 GHz survey maps. The candidates were therefore all observed at 15 GHz using the very long baseline array (VLBA). A minority of the candidates was also observed at one or more of the frequencies 1.6, 8.4, and 22 GHz. The observations and the radio maps will be described elsewhere.

Many of the candidates turned out to be core-jet sources in which the jet is faint but contains a “hot spot.” The VLBA 15- and 22-GHz maps reveal the bright core and resolve the lower-brightness hot spot. An example of such a candidate is shown in Fig. 1. The 5-GHz map of 0740 + 768 shows a simple unresolved double source but the higher resolution 22-GHz map clearly shows that the compact core lies at the eastern (left) end with the other “jetlike” emission having markedly lower brightness. Other candidates turned out to be compact symmetric objects (CSOs)—an early ($< 10^4$ yr) high-luminosity phase of large double radio sources [20]. At high resolution, CSOs often show a single central core straddled by a pair of outer “lobes” of significantly lower surface brightness; not only is there no detailed correspondence between substructures in the lobes but also their parities are incorrect for lensed images.

Component spectra can also be used to rule out candidates. For lensing on the present scales the time delay between the light paths ranges from a few seconds to a few hours, which is much shorter than the time scales between sets of VLBI observations. Lensed images must, therefore, brighten and fade together. A strong corollary is that lensed images must have identical radio spectra or, equivalently, their flux ratio must not be frequency dependent. This argument should be used with care if one or both of the components is well resolved but we ruled out candidates with compact components if the flux ratios at different frequencies were inconsistent by $\geq 30\%$.

Component motion is also an excellent discriminant. If the lens moves across the line of sight the relative separation of the images will change. For example, a lens at $z \sim 0.5$, moving transversely with $v \sim 1000$ km s $^{-1}$, will produce a relative image motion $\sim 1 \times 10^{-5}$ mas yr $^{-1}$.

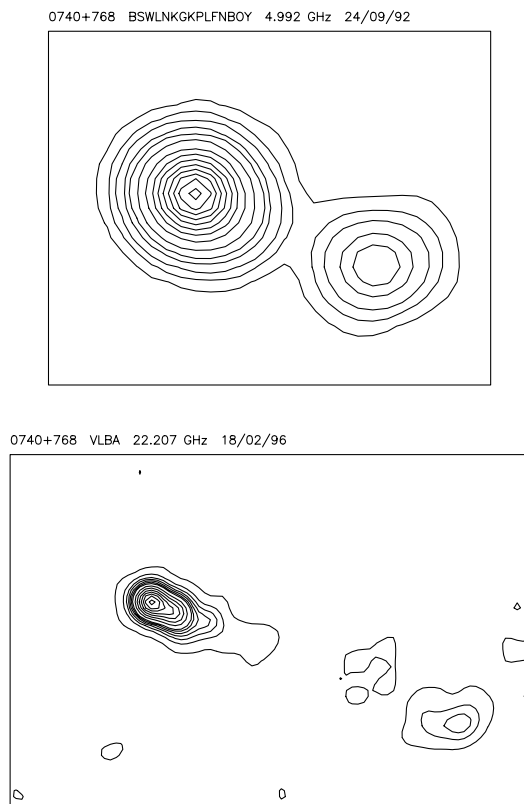


FIG. 1. (Upper) VLBI map of a millilens candidate 0740 + 768 at 5 GHz and 1 mas resolution; the separation between the two components is 3.2 mas. (Lower) VLBI map of 0740 + 768 at 22 GHz and 0.3 mas resolution; the two components, barely resolved at 5 GHz, have markedly different surface brightnesses. Rather than a characteristic lensing morphology 0740 + 768 displays the asymmetric “core-jet” structure commonly found in flat-spectrum radio sources.

This is much too small to be measurable with VLBI and thus, if relative motion is detected, the secondary cannot be a lensed image. In a separate follow-up program for the PR and CJ VLBI surveys most of the sources have been observed more than twice over a period of several years [21]. Currently over 30 of our 50 candidates are known to show component motions greater than $\sim 0.1 \text{ mas yr}^{-1}$ and hence can be ruled out by this means as well.

All 50 candidates were ruled out, often for a combination of the reasons cited above, and we now use this null result to set quantitative limits on supermassive Ω_{CO} for objects *uniformly distributed* throughout the universe.

Limits on Ω_{CO} .—We used the detection volume method introduced by Nemiroff [10] and developed in detail for the specific case of a VLBI search for point masses by KKB. We will, therefore, only make a few points specific to our search. The most important observational limit is the flux ratio $R (< 40:1)$ which sets the maximum source-lens impact parameter and hence defines the basic detection volume. The usual definition of “strong” lensing [9] refers to images with a flux ratio of $< 7:1$; our $< 40:1$ flux ratio therefore corresponds to a configuration with a larger

lens-to-source “impact parameter” and hence the cross section for lensing is almost 5 times that normally assumed for lensing calculations. Each source is observed with an approximately fixed angular resolution and hence minimum image separation, $\delta (= 1.5 \text{ mas})$, and limited field of view, $\Delta (= 50 \text{ mas})$, both of which act to truncate the detection volume. In effect δ and Δ define the lower and upper limits of a mass range for which the truncation is small. Our search is sensitive to the mass range $\sim 10^6 M_{\odot}$ to $\sim 10^8 M_{\odot}$. For observations of a number of sources the individual detection volumes for each source can be summed to give a total detection volume. In the calculation of these volumes, one needs to know the source redshifts and these are available for 270 out of the 300 sources in our sample; the mean redshift is 1.30, and 20% of the sources have redshifts ≥ 2 . For the remaining 30 sources we have assumed a distribution in redshift similar to that exhibited by the other 270. For the calculation of the angular size distances we took $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and, for direct comparison with KKB’s result, we assumed an Einstein–de Sitter Universe ($\Omega_M = 1; \Omega_{\Lambda} = 0$).

Our null result allows an upper limit to be placed on Ω_{CO} , and Fig. 2 shows the limit at the 95% confidence level as a function of CO mass. The limit is approximately constant from $\sim 10^6 M_{\odot}$ to $\sim 10^8 M_{\odot}$ and in this mass range $\Omega_{\text{CO}} \leq 0.013$. If Ω_{CO} was equal to 0.013 the “expected” number of lenses in the total detection volume associated with our 300 sources would be three and the fact that none are detected allows us to reject this hypothesis with 95% confidence. If Ω_{CO} was equal to 0.026 then ~ 6 lenses would be expected and we can reject this higher-mass density with 99.7% confidence.

These limits are conservative because gravitational lensing increases the observed flux density of a background source and hence lensed sources are drawn from a fainter source population than the unlensed sources; a flux-limited survey will contain more lenses than expected. Our null

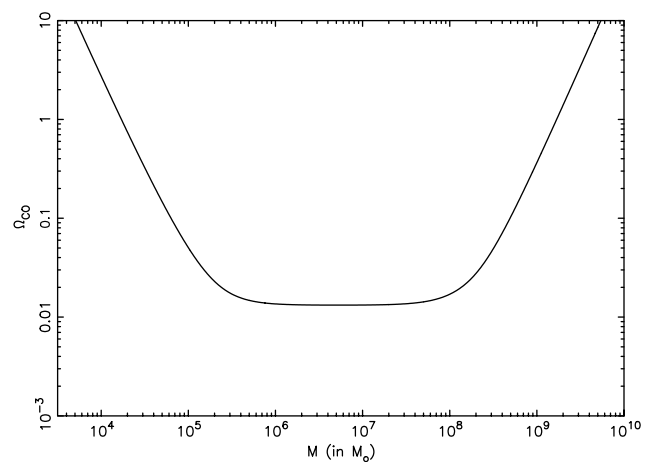


FIG. 2. Limit on Ω_{CO} at the 95% confidence level from the failure to detect gravitational lensing among 300 compact sources with image separations in the range 1.5–50 mas.

result therefore corresponds formally to a stronger limit on Ω_{CO} but the “magnification bias” associated with flat spectrum radio sources, especially for lens systems with high flux ratios, is of order unity [22] and we have therefore ignored this effect.

Discussion.—KKB derived a limit on Ω_{CO} [$(10^7-10^9)M_{\odot}$] < 0.4 (99.7% confidence); this corresponds to $\Omega_{\text{CO}} < 0.2$ (95% confidence). The lower mass limit is larger than ours since they took $\delta \sim 4$ mas compared with our 1.5 mas. The upper mass limit derived by KKB is high since it is based on $\Delta = 500$ mas which is, in our view, optimistic; we used $\Delta = 50$ mas. Our null result implies $\Omega_{\text{CO}} \lesssim 0.013$ (95% confidence) in the mass range $\sim 10^6 M_{\odot}$ to $\sim 10^8 M_{\odot}$ which is about 15 times more stringent than KKB’s. The improvement arises from a combination of more sources (300, cf. 48), larger R ($< 40:1$, cf. $< 20:1$), and hence larger lensing cross section and a higher mean redshift for the parent sample (1.30, cf. 0.89). Our result allows the following conclusions to be drawn.

Uniformly distributed CO in the mass range $\sim 10^6 M_{\odot}$ to $\sim 10^8 M_{\odot}$ do not make up more than $\sim 1\%$ of the closure density $\Omega_{\text{total}} = 1$ which is strongly supported by the latest measurements of the angular spectrum of the cosmic microwave background [23]. Similarly such CO do not make up more than $\sim 3\%$ of the dark matter density $\Omega_{\text{DM}} \sim 0.3$ favored by current observations. The favored value of the baryon density from big-bang nucleosynthesis is $\Omega_b h^2 = 0.019 \pm 0.002$ [24]. Taking a plausible value for h (0.65) implies $\Omega_b = 0.045 \pm 0.005$, thus our 95% confidence limit implies that uniformly distributed Jeans-mass CO do not make up more than about one-third of Ω_b .

A large population of uniformly distributed $\sim 10^{6.5} M_{\odot}$ black holes is required by the cosmogonic model developed by Gnedin and Ostriker [5] and Gnedin *et al.* [6]. This model predicts that up to 5% of high redshift sources should be detectably lensed by such a population, i.e., there should be up to 15 lenses in our sample. They are not observed and hence the model can be ruled out.

Perhaps the next interesting limit is $\Omega_{\text{CO}} \lesssim 0.005$ which would constrain the contribution of supermassive CO to be no more than the baryonic contribution of presently observable stars and galaxies. To reach this limit, about 1000 sources, with the same redshift distribution as the present sample, would have to be studied; this would be a time-consuming, but relatively straightforward, task.

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Note added.—When this work was almost completed we became aware of the millilensing results of Nemiroff *et al.* [25] using gamma ray bursts. Their work has produced limits on the CO abundance which are similar to ours.

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