Limits on Compact Dark Matter from Null Results of Searches for Lensing of Quasistellar Objects

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Recent searches for multiple quasistellar-object images created by gravitational lensing provide new limits on the density of massive compact objects in the Universe. These limits imply that the cosmological density of compact objects more massive than $10^{9.9}M_\odot$ must be less than closure density, and that the density of compact objects more massive than $10^{10.3}M_\odot$ must be less than 0.25 of the closure density.

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There is much evidence that dark matter composes a large fraction of the mass of the Universe.[1] There is no present consensus as to what form this dark matter takes. Assuming the dark matter is composed of individual components, there is little indication of the mass of these components. This dark matter may take the form of massive compact objects (COs) such as black holes which formed in the early Universe and dominate the Universe's mass.[2] The existence of these objects can be tested by their gravitational-lens effect on background quasistellar objects (QSOs).[3-7]

The most common lensing scenario to be expected with a spherical compact lens is a dim counterimage near a bright QSO image.[6] The previously most stringent limits on cosmological abundances of COs were based on radio observations of quasars taken at the Very Large Array[5] and showed that, conservatively, $\Omega_L<0.7$ for masses between $10^{11}M_\odot$ and $10^{12}M_\odot$, and $\Omega_L<0.9$ for masses between $10^{12}M_\odot$ and $10^{13}M_\odot$. A more detailed analysis[6,8] was subsequently applied to optical observations[9,10] and similarly ruled out a closure density for COs more massive than $10^{12}M_\odot$.

Recently, however, a high-angular-resolution, high-dynamic-range inspection of an optical QSO sample was carried out by Crampton, McClure, Fletcher, and Hutchings[11] (hereafter CMFH). In this work the CMFH data will be analyzed to determine the limits they place on a cosmological density of COs. It will be assumed that the total density of the Universe is the critical density ($\Omega=1$), that there is no cosmological constant, and that a fraction of this density, Ω_L, is composed of spherical dark compact components of mass M_L.

A compact lens placed between an observer and a source will create two bright images of the source.[12,13] Were the lens placed directly on the observer-source axis, a ring of light would be created.[14] Were the lens slightly displaced from this line, two bright images would be created, initially of comparable brightness. As the lens is moved perpendicular to the observer-source line, one image returns to the unlensed position and brightness, while the other image, nearest the lens, dims below detectability.

For the two images to be within a detectable magnitude difference Δm of each other the distance of the lens from the observer-source axis must be less than[8]

$$b_{\Delta m}=(4R_{\rm Sch}D^A_{OL}D^A_{LS}\Phi/D^A_{OS})^{1/2}, \tag{1}$$

where O, L, and S refer to the observer, lens, and source, respectively. Here $R_{\rm Sch}$ is the Schwarzschild radius of the lens $[\approx(3\text{ km})(M/M_\odot)]$, and Φ is related to the magnitude difference between images by[6,15]

$$\Phi=\tfrac{1}{2}(10^{\Delta m/5}+10^{-\Delta m/5})-1. \tag{2}$$

D^A refers to cosmological angular diameter distance, such that[16]

$$D^A_{LS}=\frac{2c}{\beta H_0(z_S+1)}[(z_L+1)^{-(\beta+1)/4}(z_S+1)^{(\beta-1)/4}-(z_S+1)^{-(\beta+1)/4}(z_L+1)^{(\beta-1)/4}], \tag{3}$$

where c is the speed of light, H_0 is the present value of the Hubble parameter, $\beta=\sqrt{25-24\alpha}$, and $\alpha=1-\Omega_L$. It is assumed that the rest of the mass in the Universe is distributed uniformly. The proper distance is given by

$$D^P_{OX}=(2c/3H_0)[1-(1+z_X)^{-3/2}], \tag{4}$$

where the superscript P designates proper distance and X refers to either L or S.

For the two images to be separated by an observed angle θ or greater the lens must be further from the observer-source axis than[8]

$$b_\theta=[(D^A_{OL}\theta)^2-8R_{\rm Sch}D^A_{OL}D^A_{LS}/D^A_{OS}]^{1/2}. \tag{5}$$

A specific detection procedure will define a limiting detectable dynamic range Δm between QSO images, and have a given angular resolution θ. For a lens of mass M_L at redshift z_L, the lens must be placed between $b_{\Delta m}$ and b_θ to ensure that both images are bright enough to be individually discernible and far enough apart to be individually resolvable to the observer. If $b_\theta > b_{\Delta m}$ at a given z_L, it is impossible for the observational procedure to detect the lens at this z_L. Considering these b as radii of circles centered on the observer-source line at each r, these circles collectively define a detection volume.[8] Were a lens to fall interior to this detection volume, a lensing detection would occur.

The probability P that a source at redshift z_L (equivalent proper distance D^P_{OS}) is lensed is

$$P = 1 - e^{-\lambda}, \tag{6}$$

where[8]

$$\lambda = \int_0^{D^P_{OS}} n_L \pi \max[(b^2_{\Delta m} - b^2_\theta), 0] dD^P_{OL}, \tag{7}$$

and the proper number density of lenses is given by

$$n_L = \frac{3H_0^2(1+z_L)^3\Omega_L}{4\pi R_{\rm Sch} c^2}. \tag{8}$$

Consider an ensemble of sources observed by a detection procedure that has an angular resolution limit θ and dynamic range threshold Δm. These sources are located in an $\Omega = 1$ universe filled to density Ω_L with compact lenses of mass M_L. From Eq. (6) the fraction of detectable split source images can be computed. If the observed fraction is well below the predicted fraction, it can be concluded that the Universe is not composed of compact lenses at the given density Ω_L and mass M_L.

The above analysis will now be applied to the results

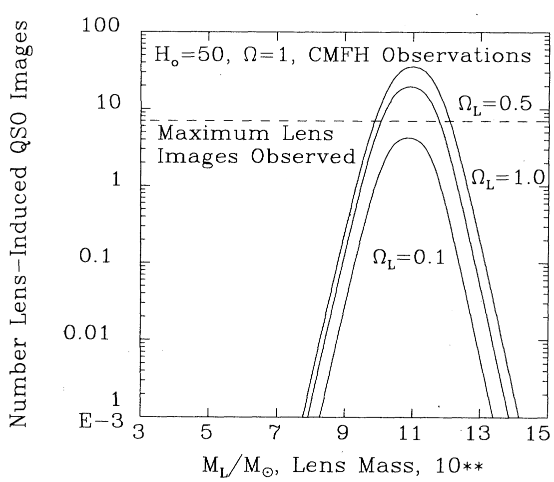

FIG. 1. A plot of the expected number of lens-induced counterimages from the CMFH observations of 32 QSOs vs the mass of the intervening lens. A fractional amount of QSO images has a corresponding probability of showing a single lens-induced image. A QSO lens-induced image number in excess of 32 demands that some QSOs show more than one counterimage. The Hubble parameter was taken to be 50 km $\sec^{-1}$ Mpc^{-1}. The dashed line indicates an upper limit on the actual amount of QSOs split as measured by CMFH. A critical universe ($\Omega = 1$) was assumed.

of the CMFH search for closely spaced QSO images. The parametrization of the CMFH detection function used in the present analysis is as follows: When the angle ξ between lensed images is less than 0.2″, the images will be considered unresolvable. When ξ is between 0.2″ and 0.6″, then both images are resolvable only when $\delta m \le \Delta m$ interpolated from Table 2 of CMFH, where δm is the magnitude difference between images. When $\xi \ge 0.6''$, both images will be resolvable only when $\delta m \le 4$. A maximum-angular-resolution-detection threshold was also included in the calculation. If the images are separated by more than 2″, there might exist a selection bias, and so these QSO pairs are excluded.

Of the 32 QSOs CMFH studied, they observed 7 candidate lens-induced QSO images. Probably several of these are not artifacts of gravitational lensing, but the result of coincidental superpositions of foreground or background sources onto the OSO field. To be conservative, it will be assumed that all the candidate systems are actually artifacts of gravitational lensing. From inspection of Fig. 1, it can be seen that about 40 lens-induced counterimages of the QSOs are to be expected (this number necessitates that some sources have more than one lens in the detection volume and thus have more than one dim lens-induced image created per source, which is possible even at low optical depth) if the Universe is filled to $\Omega_L = 1$ with compact objects of mass $10^{11} M_\odot$. But since at most 7 images were detected, this Universe is now excluded. In fact, from inspection of Fig. 1, it is clear that $\Omega_L > 0.5$ of compact objects of mass $10^{11} M_\odot$ is also excluded. It is not presently possible, however, to rule out $\Omega_L = 0.1$. A fractional amount of QSO images in Fig. 1 is to be interpreted as a probability of at least one lens-induced counterimage being detectable as computed from Eq. (6).

Figure 2 shows precisely the Ω_L-M_L range excluded

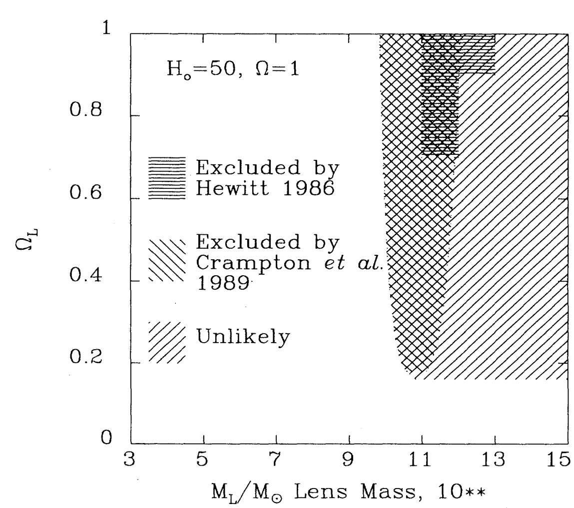

FIG. 2. The region of the Ω_L-M_L (lens mass) parameter space excluded by recent observations.

by recent observations. The area covered with lines of zero slope was previously excluded by the analysis and Very Large Array radio observations of Hewitt.[5] The region covered by lines of negative slope is derived here from the CMFH observations. The region covered by lines of positive slope was not rigidly excluded by any specific observations. Observations that would have uncovered lenses in this range are commonplace, however, and no cosmological density of lenses has ever been reported. Much of this region is also excluded when one considers less-conservative detection limits of the existing data.[5]

From inspection of Fig. 2, one can see that a closure density of compact lenses of $M > 10^{9.9} M_\odot$ is excluded, as is a cosmological density of $\Omega_L > 0.25$ for $M > 10^{10.3}$. A Hubble parameter of $H_0 = 50$ km sec^{-1} Mpc^{-1} was assumed. Were the Hubble parameter 100 km sec^{-1} Mpc^{-1}, an even lower mass would be excluded, with $\Omega > 1$ for $M > 10^{9.6} M_\odot$ and $\Omega_L > 0.25$ for $M > 10^{10.0}$.

One possible confounding factor is the potential existence of an opaque region surrounding the compact object. Were these COs surrounded by an opaque accretion disk, for example, one of the images might be absorbed and not seen, rendering the above arguments invalid. These systems, however, might also be expected to be quite luminous, as disk matter falling onto a CO should create a significant amount of light. Another possible confounding factor is any noncompactness of the lensing object. A CO in the gravitational lensing sense is any object with all of its mass between the images caused by lensing. A galaxy is typically *not* well represented by a compact mass.

Future observations will explore a larger range of (Ω_L, M) space by increasing the detectable dynamic range between images Δm and the angular resolution θ. Increasing the observational Δm limit has the effect of primarily lowering the maximum allowed cosmological abundance of these hypothetical COs. Improving θ has the effect of primarily reducing the maximum allowable mass. Both of these regimes are of interest in the near future. If the cosmological abundance could be reduced below $\Omega_L = 0.1$, then any dark CO component must be less significant than the currently known cosmological density of galaxies. If the maximum allowable mass limit could be reduced much further, then $10^9 M_\odot$ compact objects could be excluded, which is interesting as a hypothesized mass scale of active galactic nuclei. Inspecting QSOs of larger redshift should not have a large effect, however. This is because the probability is not a strong function of source redshift from $z_{\rm QSO} \approx 1$ through the maximum range exploitable by telescopes.[6]

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[1] For a review see, for example, *Dark Matter in the Universe,* IAU Symposium No. 117, edited by J. Kormendy and G. R. Knapp (Reidel, Dordrecht, 1987), and references within.

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