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Determination of the Cosmological Density of Compact Objects using Gravitational Lensing and the HST

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Abstract. The observed frequency of mutiply imaged objects among Highly Luminous Quasars (HLQs) provides a very interesting way to constrain the cosmological density of putative compact lenses in the Universe. Assuming a population of dark compact objects uniformly distributed in space, and making use of the detailed analysis of direct images obtained for 1207 different quasars with HST and ground-based telescopes, we show that the cosmological density Ω_L has to be smaller than 0.01 in the mass range 10^{10}–$10^{12} M_\odot$. This presently constitutes the best constraint on Ω_L. Simulations show that a careful analysis of 500 new observations of HLQs acquired with the refurbished HST would allow us to extend the present constraint down to $10^9 M_\odot$, and to rule out a Universe closed by any kind of compact objects in the mass range $10^{7.5}$–$10^{13} M_\odot$.

1 Introduction

Identifying the real nature of dark matter in the Universe constitutes one of the most challenging goals in modern astrophysics (see Carr 1990 for a review). Gravitational lensing provides a very powerful tool to detect the various signatures of baryonic dark matter. Indeed, the distribution of dark matter associated with clusters of galaxies can be probed from the detailed analysis of giant luminous arcs and of the shear deformations of background sources (Fort & Mellier 1994); the effect of *local* compact dark matter, belonging to the disk or to the halo of our galaxy, can be detected in micro-lensing experiments such those being presently conducted by the DUO, EROS, MACHO and OGLE teams (see the recent review by Paczyński 1995). Finally, the *cosmological* density of *isolated* dark compact objects can be indirectly constrained by the (non) observation of 'micro-lensing induced' flux variations in background QSOs or by the (non) detection of multiply imaged sources in a flux limited sample of QSOs. The first technique is specially sensitive to the effects of compact objects in the mass range 10^{-4}–$10^{5} M_\odot$ (Canizares 1982, Schneider 1993).

The second technique consists in trying to resolve multiple macro-lensed QSO images using ground-based, radio telescopes and/or the HST with adequate high angular resolution imaging instruments. This class of techniques has a good sensitivity in the mass range 10^6–$10^{12} M_\odot$, depending on the instrument being used. The limits of this method are dictated by both the angular resolution *and* the dynamics of the instrument. Using the point-mass lens model, we show in this paper how statistical constraints can presently be derived in the above mass range; the contribution due to HST is emphasized. To be complete, let us mention here that by modelling the observed frequency of mutiply imaged Highly Luminous Quasars with galaxy lenses (some examples are

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well known), it has been possible to constrain the values of galactic parameters, the number counts of QSOs and the cosmological constant (Claeskens et al. 1995a).

In the next section, we present and discuss the expression of the probability for observing doubly imaged QSOs lensed by compact objects; we also emphasize the influence of the instrumental characteristics (angular resolution and dynamics). We present the data in section 3. The results and a discussion are given in section 4.

2 Lensing Probability

2.1 General Expression

The generic expression for the probability of observing a lensing event along the line-of-sight to a QSO at redshift z_q, due to a population of compact objects with mass M_L, uniformly distributed in space, is:

$$P(M_L, z_q, b_q) \sim \Omega_L \int_0^{z_q} (1+z)^3 \frac{cdt}{dz} \Sigma(M_L, z, z_q, Instr) Bias(z, b_q) dz, \qquad (1)$$

where Ω_L represents the cosmological density of compact objects with mass M_L, in units of the present closure density of the Universe. Of course, the probability P increases with z_q. In the above equation, $Bias(z, b_q)$ is the so called magnification bias: because macro-lensing amplifies the flux of a background source, observing *bright* sources *enhances* the chance to discover a lens in a flux limited sample of quasars. Because of these two latter effects, the probability to discover a new lens is of course optimal when observing HLQs (typically $M_V \leq -27$; see Turner 1984 & Surdej et al. 1988). Finally, $\Sigma(M_L, z, z_q, Instr)$ in Eq. (1) represents the lensing cross-section for a compact object with mass M_L at redshift z to produce double images from a QSO at redshift z_q, and be detected by the given instrument.

2.2 Lensing Cross-Section and Instrumental Efficiency

At a given redshift, the general cross-section for multiple imaging is a ring whose thickness depends on three competing criteria:

1. Because the angular separation $\Delta\theta$ between lensed images increases with the degree of misalignment between the source, the lens and the observer, and because $\Delta\theta$ must be larger than the angular resolution of the instrument, the angular distance between the lens and the source, measured at the observer, must be larger than a *lower* limit $\theta_{L,inf}(z, z_q, M_L, Instr)$.
2. The magnitude difference Δm between double lensed images also increases with the degree of misalignment θ_L between the source, the lens and the observer; therefore, the finite dynamics of the instrument implies an *upper* limit on the angular distance $\theta_{L,Sup1}(z, z_q, M_L, Instr)$ between the lens and the source. So, the higher the dynamics of the instrument, the larger the cross-section for lensing. Δm increases faster with θ_L when M_L gets smaller, so, if M_L is too small, then $\theta_{L,Sup1} < \theta_{L,inf}$: the instrument is unable to resolve the lensed images.
3. In order to avoid contamination by cluster lensing and also by other uncontrolled biases, we consider that $\Delta\theta$ must be smaller than $3''$. So θ_L has to be smaller than an *upper* limit $\theta_{L,Sup2}(z, z_q, M_L, Instr)$. This condition sets an upper limit ($\sim 10^{12} M_\odot$) on the mass range of the compact objects which can be probed.

The general expression for the lensing cross-section is the following:

$$\Sigma(M_L, z, z_q, Instr) = \pi([Min(\theta_{L,Sup1}, \theta_{L,Sup2})]^2 - \theta_{L,Inf}^2) D_{OD}^2, \qquad (2)$$

where D_{OD} is the angular distance between the observer and the deflector. More formal details on this expression for the lensing probability can be found in Surdej et al. (1993a).

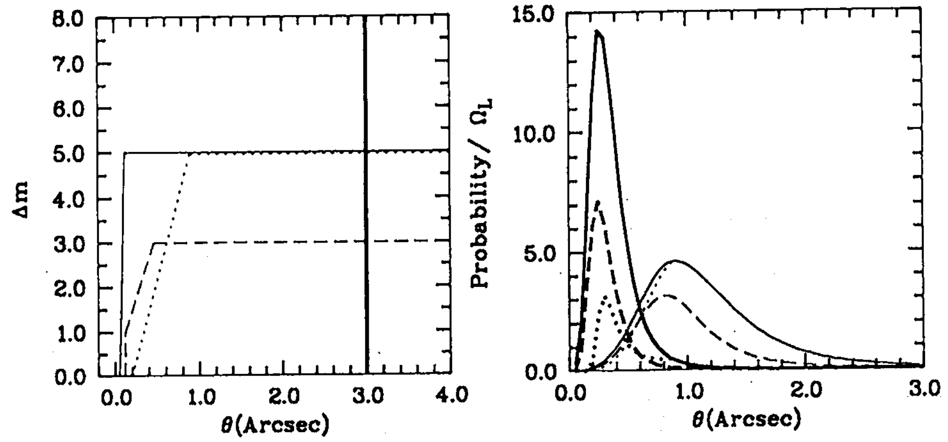

Figure 1. a) The ASF b) The lensing probability (see text).

Figure 1a displays the relation existing between the dynamics and the angular resolution (the Angular Selection Function (ASF)) for typical good seeing observations obtained with a ground-based telescope (dotted line) and for the pre- and post-refurbished HST (dashed and continuous lines). In some way, these curves represent the joined performance of the instrument and of the method of image analysis for resolving multiple images. The latter method usually consists in carefully subtracting a scaled PSF from the QSO image (see Surdej et al. 1995, Remy 1996). The thick vertical line represents the maximal angular separation between the images (criterion 3). Figure 1b illustrates the corresponding lensing probability versus the angular separation between the lensed images, for two different compact lens masses (heavy lines: $10^{10}M_\odot$; light lines: $10^{11}M_\odot$). The optical depth is expressed in Ω_L units. The better efficiency of HST to constrain the density of compact objects with $M \leq 10^{10}M_\odot$ is clearly seen from Fig. 1b.

3 Observing Material

3.1 The sample of HLQs

Sample	<z>	<V>	<Mv>	< FWHM(″)>	N_Q	$10^{11}M_\odot$ (%)	$10^{10}M_\odot$ (%)
HST (1)	2.1	17.6	−27.7	-	495	279 (56%)	442 (89%)
ESO (2)	2.2	17.6	−27.8	1.00	396	372 (94%)	287 (72%)
CFHT (3)	2.4	18.1	−27.4	0.66	101	81 (80%)	66 (65%)
CFHT (4)	2.2	17.7	−27.8	0.76	104	54 (52%)	31 (30%)
NOT (5)	2.0	17.5	−27.6	0.90	584	421 (72%)	381 (65%)
ALL	2.2	17.7	−27.6	0.90	1680	1207	1207

Table 1. Characteristics of HST and ground based imagery surveys of HLQs (1- Maoz et al. 1993; 2- Surdej et al. 1993a; 3- Crampton et al. 1992; 4- Yee et al. 1993; 5- Jaunsen et al. 1995)

The present sample contains 1680 observations of 1207 different HLQs. It has been compiled by merging the HST snapshot survey (before refurbishment) and four selected ground-based imagery

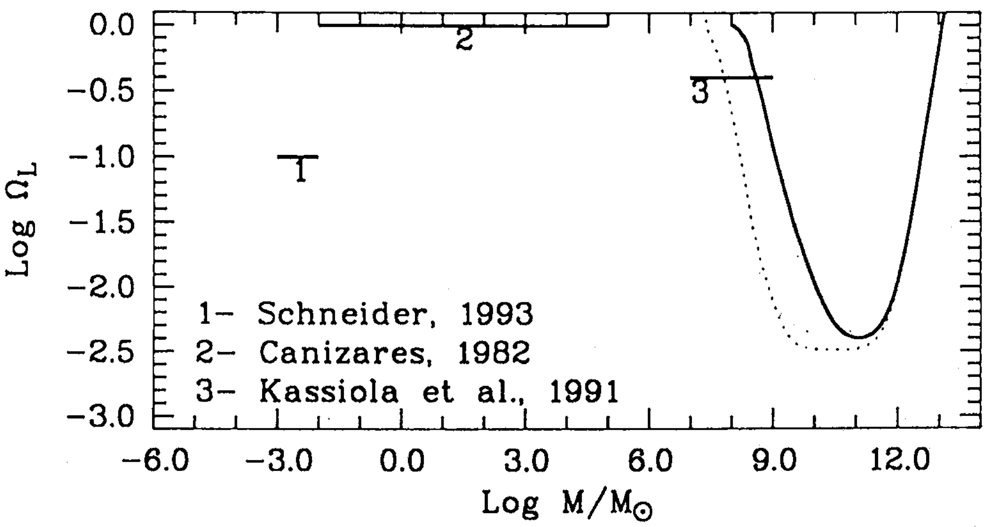

Figure 2. Upper limit on Ω_L versus M_L (with a 99.7 % confidence level).

surveys of HLQs. Table 1 summarizes the properties of each subsample. In the case of multiple observations of a same QSO, the most efficient one has been kept. But this choice depends on the assumed lens mass. The two last columns of Table 1 show how many observations per sample have been kept, for two different lens masses. The percentages represent the internal efficiency of each subsample.

3.2 Nature and Number of Lenses

The sample presented in Table 1 only contains three lens candidates which satisfy the hypothesis of being possibly lensed by a dark compact object (i.e., two lensed images and no already detected galaxy-type lens) and which present an angular separation between their images smaller than $3''$. These are Q1208+1011 (Magain et al. 1992, Maoz et al. 1992), Q1009-025 (Surdej et al. 1993b) and J03.13 (Claeskens et al. 1995b).

4 Results and Discussion

Comparing the observed and the predicted numbers of lenses in the sample, a firm upper limit on Ω_L can be derived. With a 99.7% confidence level, and adopting an Einstein-de Sitter Universe ($\Omega_o = 1, \lambda = 0$), we find that $\Omega_L \leq 0.01$ in the mass range 10^{10}–$10^{12} M_\odot$. The strongest constraint we have derived is $\Omega_L \leq 0.004$ for $10^{11} M_\odot$ compact objects. The use of other cosmological models or the identification of a yet unseen galaxy-type lens among the three candidates would reinforce the present constraints. As shown in Fig. 2, our results are the most constraining ones for masses larger than $10^{8.6} M_\odot$, and a closure density of the Universe by any kind of compact objects in the mass range 10^8–$10^{13} M_\odot$ is ruled out.

The dotted line in Fig. 2 corresponds to a simulation of the constraints on Ω_L if 500 additional observations of HLQs were obtained with the (presently refurbished) HST. This would drastically improve the constraint on Ω_L in the mass range 10^9–$10^{10} M_\odot$. This would even surpass the best presently existing constraints derived from VLBI radio observations for compact objects more massive than $10^{7.8} M_\odot$ (Kassiola et al. 1991). It is also important to note that the number counts of QSOs at radio wavelength is not known very accurately. So, the magnification bias for radio observations cannot be properly estimated and this makes optical observations presently more reliable in order to derive statistical values for the cosmological parameters. Therefore, HST can play a very important role in further constraining the cosmological density of compact dark matter. This goal could be achieved by carrying out a new snapshot survey.

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