GRAVITATIONAL LENSING STATISTICS BASED ON A LARGE SAMPLE OF HIGHLY LUMINOUS QUASARS OBSERVED WITH GROUND-BASED TELESCOPES AND HST[1]

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ABSTRACT

We present here some recent results on gravitational lensing statistics as applied to a sample of 470 highly luminous quasars. These objects were directly imaged, either from the ground (ESO, CFH) under optimal seeing conditions, or using the Hubble Space Telescope. We have derived values for the effectiveness parameter F of galaxies, modeled by means of singular isothermal spheres, to produce macro-lensed images of distant quasars, and upper limits on the density parameter Ω_L of compact objects with masses $\simeq 10^{10}$ - 10^{12} $M_{\odot}$. Adopting H_o = 50 km/sec/Mpc, $\Omega_o = 1$ and $\Lambda = 0$, we find that at the 99.7% confidence level, $0.005 \leq F \leq 0.527$ and that $\Omega_L \leq 0.02$.

Comparing the efficiencies of ground-based and space instruments used to search for gravitational lens systems among highly luminous quasars, we conclude that for the near future, ground-based direct imaging characterized by a good dynamical range still constitutes the best observational strategy. Replacement of the WFPC I camera by WFPC II will of course improve much the efficiency of HST to constrain Ω_L. This is particularly true in the mass range 10^8 - 10^{10} $M_{\odot}$. A more detailed account of this work will be reported soon in the Astronomical Journal.

1. INTRODUCTION

Since macro-gravitational lens systems provide us with equivalent optical benches having dimensions comparable to the size of the Universe, we may conveniently use them in order to infer various parameters of astrophysical (mass of deflecting galaxies, size of intervening gas clouds, etc.) and cosmological (H_o, Ω_o Λ, etc.) significance. We refer to Blandford and Narayan (1992) for a general review on this subject.

The possibility of using statistical gravitational lens studies as an astrophysical or cosmological tool has motivated the present work. Before recalling the basic concept underlying this method, we describe our database of 470 highly luminous quasars (hereafter HLQs) that have been used as probes of gravitational lensing. Results are finally presented as well as some general conclusions.

2. OBSERVATIONS

Following the successful outcomes of the survey for gravitational lens (GL) candidates among HLQs (typically $M_V \leq -27$)[2] initiated in November 1986 by the Liège/ESO/Hamburg group (Surdej et al. 1988a-c), four teams of observers have carried out independent, direct imaging searches for additional closely spaced gravitationally lensed QSO components.

The most important observational characteristics of these four samples of HLQs are summarized in Table 1 and are also partly illustrated in Fig. 1 (totalizing 660 observations; see Surdej et al. 1992, Crampton et al. 1992, Yee et al. 1992 and Bahcall et al. 1992, Maoz et al. 1992 for more details). Note that because of observational duplication, there only remains a total of 470 distinct quasars.

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[1] based upon observations collected at the European Southern Observatory (La Silla, Chile), with the Canada France Hawaii Telescope and with the Hubble Space Telescope.
[2] Unless quoted otherwise, we have adopted in the present work H_o = 50 km/sec/Mpc, $\Omega_o = 1$ and $\Lambda = 0$.

Considering the merged sample of HLQs, we adopt $3 \leq N_L \leq 15$ for the observed number N_L of lenses whose multiple images are characterized by an angular separation $\theta \leq 3''$ and a magnitude difference $\Delta m \leq$ 5 mag. (ground-based observations) or $\Delta m \leq 3$ mag. (HST observations). The lower limit corresponds to the most "pessimistic" estimate for the number of lenses (PG1115+080, UM673 and H1413+117) present in the merged sample, and the upper limit to the most "optimistic" one.

Defining the "angle selection function" (ASF) as being the maximum detectable magnitude difference Δm between two point-like images separated by an angle θ, we have illustrated in Fig. 2 these ASFs for each of the 4 HLQ samples and the various methods of image analysis that have been used: i.e. 'Type' = 1 (ESO-KP, visual examination), 2 (ESO-KP, PSF subtraction), 3 (Crampton et al.), 4 (Yee et al., visual examination), 5 (Yee et al., comparison with contour plots of nearby stars), 6 (HST, visual examination).

Table 1: Summary of the observational characteristics (number, average redshift, apparent and absolute visual magnitudes, and seeing) relevant to the four selected HLQ samples

Sample:	ESO-KP	Crampton et al.	Yee et al.	HST	Merged sample
N^{O} of HLQs:	188	101	104	267	470
<z>:	2.3	2.4	2.2	2.2	2.2
<V>:	17.5	18.1	17.7	17.6	17.7
$<M_V>$:	-28.0	-27.5	-27.8	-27.8	-27.7
<FWHM>:	1.05"	0.67"	0.76"	-	-
Pessimistic:	3	0	1	0	3
and Optimistic:	11	2	1	3	15
estimates of the					
N^{O} of GL candidates					

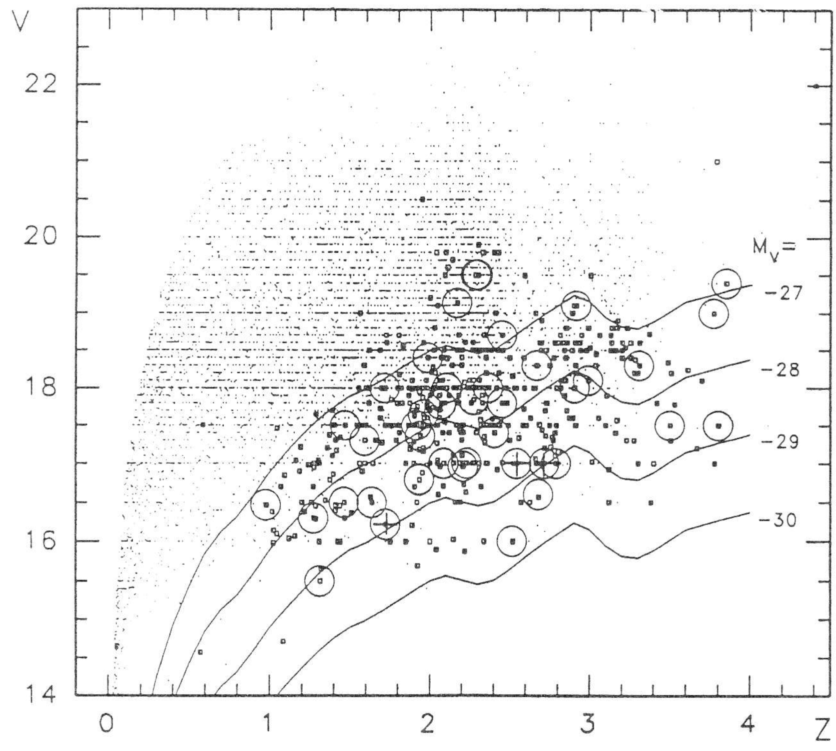

Figure 1: Apparent magnitude (V) versus redshift (z) diagram showing the locations of 6003 quasars (very small dots) extracted from the Véron-Cetty and Véron (1991) catalogue. Note that not all apparent magnitudes quoted for the quasars in the above catalogue are visual and that most of them are just estimates. The 470 selected HLQs are shown by small squares, the 28 (although only about half of these probably consist of) possible lens candidates by circles, and the 3 known lensed quasars identified in the merged sample by crosses. Several lines of constant absolute visual magnitudes are also shown.

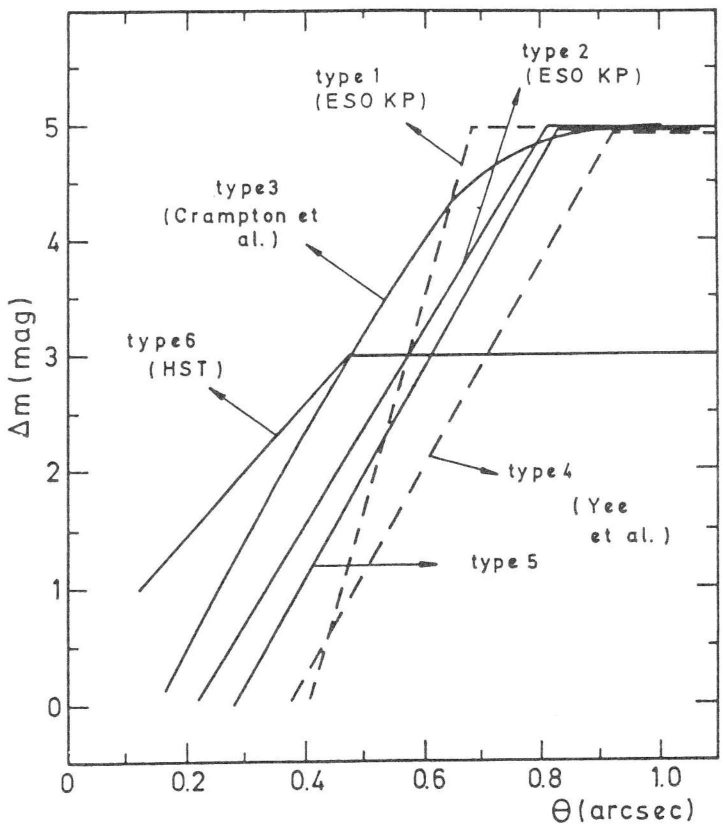

Figure 2: The "angle selection functions" (ASFs), derived under average seeing conditions (see <FWHM> in Table 1), for the various types of ground based (Type = 1-5) and HST (Type = 6) observations. The maximum detectable magnitude difference Δm between two images is plotted here as a function of their separation θ. Whereas the HST angle selection function is somewhat better for $\theta \leq 0.4''$ (equivalent to ground based seeing conditions near 0.7"), the better dynamical range of ground based CCDs accounts for better ASFs when $\theta \geq 0.4''$.

3. GRAVITATIONAL LENSING STATISTICS

Considering first a singular isothermal sphere lens model (SIS), useful to describe as a first approximation the lensing properties of galaxies in the Universe, we know that in case of a perfect alignment between the source, the lens and the observer, there will be formation of an Einstein ring whose angular radius θ_E just depends on the redshift of the source z_s, of the deflector z_d and on the one-component velocity dispersion σ of the galaxy. Of course, the same phenomenon occurs for the case of a point mass lens model (PM), characterized by its mass M.

In the absence of a perfect alignment, the Einstein ring breaks into two lensed images whose angular separation θ is still of the order of 2 θ_E, but whose brightness difference Δm increases with the value of the impact parameter b. For a fixed value of Δm, dictated for instance by the dynamical range of our instrument, one may thus define a cross section $\sigma(\Delta m)$ surrounding the lens such that if the light ray from a distant quasar crosses $\sigma(\Delta m)$, the two lensed images, which are characterized by a magnitude difference Δm, will be detectable by the observer. One may easily derive the expression of $\sigma(\Delta m)$ for the two different types of lensing model.

Now, for a given ASF, which depends of course on seeing conditions in the case of ground-based observations and, unfortunately, on spherical aberration in the case of HST observations, and also given a cosmological distribution of lenses in the Universe and a distant source, it is easy to evaluate the expression of the optical depth τ for lensing, i.e. the probability that a distant quasar will be multiply imaged: it is given by the number of lenses (usually << 1) enclosed in the volume between the observer and the source whose cross section, at a redshift z_d, is equal to $\sigma(\Delta m, \theta, z_d)$.

3.1 The effectiveness parameter F of galaxy lenses

For the case of the SIS model, one finds that the number of expected lenses N_L (= τ N_Q) may be expressed as

$$N_L = F\sum_{q=1}^{N_Q} f\left(z_q\right) H\left(b_q, Type, \theta_{\max}\right) S_{cat} \quad , \tag{1}$$

where :

- N_Q represents the number of quasars in the sample having a redshift z_q and a blue apparent magnitude b_q ,

- F $\div$ $n_o\sigma^4$ measures the effectiveness of cosmically distributed 'singular isothermal spherical' (SIS) galaxies to produce double QSO images (n_o being the local number density and σ the one-component velocity dispersion of those galaxies; see Turner, Ostriker and Gott, 1984, hereafter TOG). From observed parameters of local galaxies and adopting an SIS lens model, Fukugita and Turner (1991, hereafter FT), Kochanek (1991) and Mao (1991) have calculated that F$\simeq$ 0.047 $\pm$ 0.011, with 90% contributed by E and S0 galaxies. All those authors also report that 0.023 $\leq$ F $\leq$ 0.047 when the effects of a finite core radius are taken into account. Note that these estimates are independent of the value adopted for H_o and that FT actually confirm that the core radii of E and SO galaxies seem to be very small,

- $f(z_q)$ accounts for the redshift dependence of the optical depth τ for macro-lensing,

- $H(b_q,Type,\theta_{max})$ is a complex function which depends on the importance of the amplification - or more appropriately, the magnification - bias (increasing very much with decreasing values of b_q), on the probability distribution $p(\theta)$ for the angular separation between two source images produced by an SIS lens model to lie in the range $[\theta, \theta+d\theta]$, on the particular set of observations considered (see the ASFs in Fig. 2 for the different values of Type = 1-6) and, finally, on the maximum angular radius θ_{max} (set here to 3") of the field under consideration (see Surdej et al. 1992 for more details).

- finally, because of criteria imposed on the image morphology, color, proper motion, etc. while selecting quasar candidates, existing quasar catalogues are thought to be biased against the inclusion of gravitationally lensed objects. Indeed, quasar candidates might have been excluded from quasar catalogues because they appear either not to be stellar-like (e.g. made of multiple images), or somewhat redder than expected (because of a possible contamination by a deflecting galaxy) or even, possibly affected by an apparent proper motion (induced by light variability of one or more of its components). Taking into account the two first observational biases, Kochanek (1991) has estimated that losses of up to 30% of GL systems may result. Therefore, in order to correct for these biases, we have set $S_{cat} \simeq 0.7$ in Eq. (1).

3.1.1. Numerical applications and results

We consider together the ESO-KP, Crampton et al., Yee et al. and HST snapshot samples of 470 = (188 U 101 U 104 U 267) HLQs for which we have also listed in Table 1 the numbers N_L^O (optimistic estimate) and N_L^P (pessimistic estimate) of possible lens candidates and known cases of gravitational lensing, respectively. We have then derived by means of Eq. (1) lower and upper limits for the effectiveness parameter F, taking into account the dependence of the functions $f(z_q)$ and $H(b_q Type,\theta_{max})$ for each HLQ, assuming various types of cosmologies (cf. different values of the normalized cosmological parameter $\lambda_o = \Lambda / 3H_o^2$). Conversely, we have adopted the range of values 0.023 $\leq$ F $\leq$ 0.047, inferred by FT for the effectiveness parameter F of SIS galaxies, and we have derived upper (N_{up}^{exp}) and lower (N_{lo}^{exp}) estimates for the expected numbers of lenses. Our results are summarized in Table 2.

Table 2: Results on F and N^{exp} from our statistical GL studies (see Text)

Ω_o	λ_o	F_{lo} (99.7%)	F_{up} (99.7%)	N^{exp}_{lo}	N^{exp}_{up}
1	0	0.005	0.527	1.3	2.6
0.1	0.9	0.001	0.100	6.7	13.7
0	1	0.0004	0.041	16.7	33.4
0	0	0.003	0.292	2.3	4.7

3.1.2. Discussion

For the case of an Einstein-de Sitter cosmology ($\Omega_o = 1$, $\Lambda = 0$), we find that, at the 99.7% confidence level, $0.005 \leq F \leq 0.527$. This large interval of values encompasses the predicted value $F = 0.047 + 0.011$ for the case of a SIS lens model and $0.023 \leq F \leq 0.047$ when the effects of a finite core radius are taken into account (see FT, Kochanek 1991 and Mao 1991). Furthermore, our statistical results seem to confirm the claims by Turner (1990), Fukugita, Futamase and Kasai (1990, FFK), Fukugita, Futamase, Kasai and Turner (1991, FFKT), FT and others that flat universe models excessively dominated by the cosmological constant are not favored. However, due to a number of complications not discussed here, the possibility of estimating the cosmological parameter Λ from the observed rate of quasars being lensed by galaxies should be considered presently with great caution.

For a given instrumental configuration (i.e. fixed ASF and θ_{max}), it is obvious from Eq. (1) that in order to maximize the detection of GL systems among HLQs, one should select quasars such that the quantity $f(z_q)\ H(b_q, Type, \theta_{max})$ is as high as possible. Representing for instance this latter quantity as a function of the absolute magnitude M_V for each of the 470 HLQs in the merged sample, one immediately notices the very tight correlation existing between $f(z_q)\ H(b_q, Type, \theta_{max})$ and M_V (see Fig. 3). This clearly indicates why selecting a sample of quasars with an intrinsic brightness as high as possible constitutes the best approach to search for new lenses as well as to constrain most efficiently the value of the effectiveness parameter F.

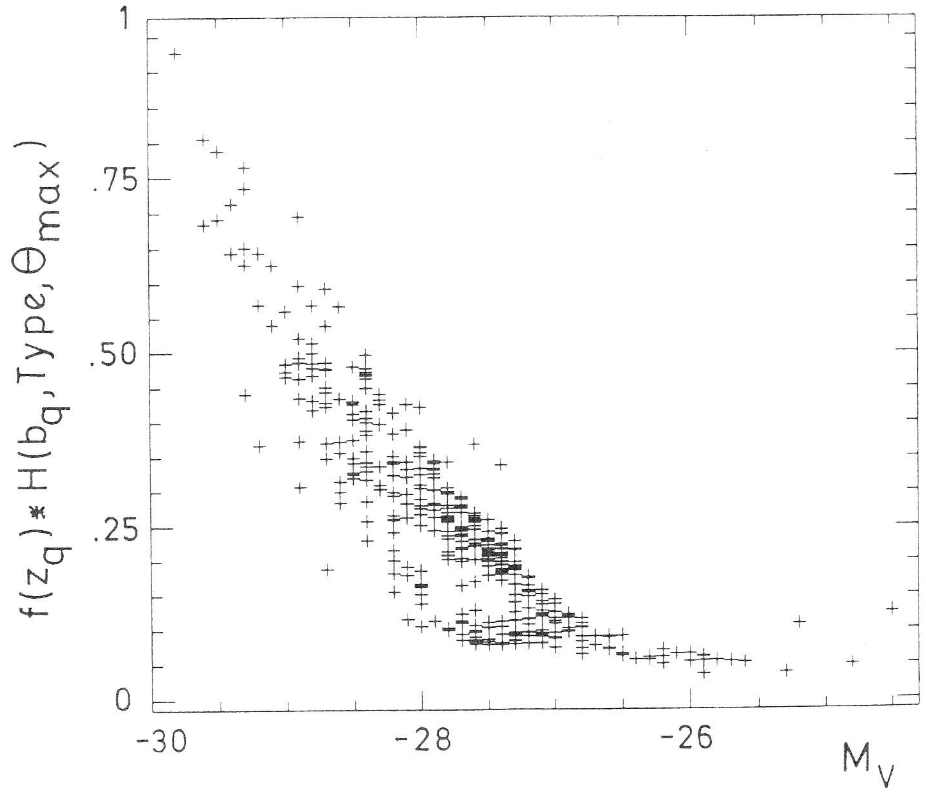

Figure 3: The quantity $f(z_q)\ H(b_q, Type, \theta_{max})$ is represented as a function of the absolute magnitude M_V for each of the 470 HLQs observed in the merged sample.

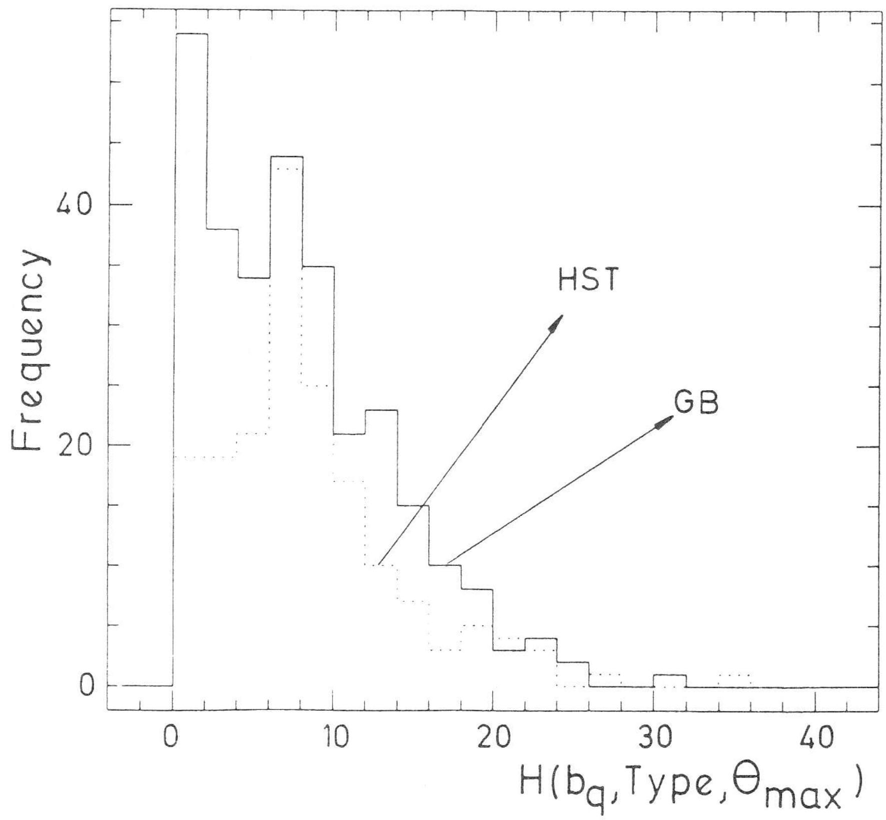

Figure 4: Histogram of the function $H(b_q, Type, \theta_{max})$ (see Eq. (1)) for the 660 observations of HLQs either obtained with ground-based (GB) telescopes or with HST.

Addressing now the observational strategy (cf. instrumental efficiency) to follow when searching for new GLs, we see from Eq. (1) that the function $H(b_q, Type, \theta_{max})$ should be maximized, i.e. one should make use of instruments characterized by the best resolving power (e.g. optimal seeing conditions for the ground based observations) with as large a dynamical range as possible. We have illustrated in Figure 4 the histogram of that quantity for the 660 observations of the 470 HLQs available so far, in accordance with the "angular selection functions" illustrated in Fig. 2. Although the angular resolution of the HST observations is substantially superior to that of the ground based data, the corresponding dynamical range is presently more limited, resulting in a very comparable efficiency for the detection of GL candidates. Given the much lower costs for operating instruments from the ground, there is no doubt that observations of HLQs obtained with a 2-4m ground-based telescope and characterized by a large dynamical range ($\Delta m \geq 5$) and high angular resolution (optimal seeing conditions or using a speckle camera) should still provide in the near future the best strategy to search for new GLs.

3.2. The cosmological density parameter Ω_L of point mass lenses

For the case of the PM lens model, we find that the number of expected lenses may be expressed as

$$N_L = \Omega_L \sum_{q=1}^{N_Q} G\left(z_q, b_q, Type, \theta_{\max}, M_L, \Omega_L\right) S_{cat} \quad , \qquad (2)$$

where Ω_L represents the local density of lensing points in units of the critical density of the Universe and where G is a complex function of z_q , b_q , Type, θ_{max}, M_L and Ω_L.

3.2.1. Numerical applications and results

Making use of the 470 quasars observed within the ESO-KP, Crampton et al., Yee et al. and HST snapshot samples, we have applied Eq. (2) in order to set upper limits on the parameter Ω_L for compact lenses in the mass range 10^{10} - 10^{12} $M_\odot$ (see Table 3). At the 99.7% confidence level and adopting H_o = 50

4. GENERAL CONCLUSIONS

Generally speaking, gravitational lensing effects may alter the observed number counts of distant quasars in various ways. Whereas we have considered in this work the phenomenon of multiply imaged quasars at $\simeq$ 0.1-3" angular scales, it should be noted that magnification of distant quasars may also result from microlensing effects due to stellar and/or planetary-like objects in intervening galaxies as well as by matter (galaxies, clusters, large sheets of dust and gas, other -unknown?- forms of dark matter, etc.) at various possible locations along the line-of-sight.

In the present paper, we have applied statistical gravitational lens studies to a sample of 470 highly luminous quasars (HLQs), either observed from the ground or with HST, in order to estimate the effectiveness parameter F of singular isothermal sphere (SIS) galaxies as well as upper bounds on the density parameter Ω_L of compact objects in the mass range 10^{10} - 10^{12} $M_{\odot}$. For the values of the cosmological parameters H_o = 50 km/sec/Mpc, $\Omega_o = 1$ and $\Lambda = 0$, we have found, at the significance level of 99.7%, that (i) $0.005 \leq F \leq 0.527$, a result which overlaps current expectations (FT) and that (ii) $\Omega_L \leq 0.02$, implying that less than 2% of the closure density of the Universe is in the form of compact objects with masses in the range $10^{10} < M_L/M_{\odot} \leq 10^{12}$.

Comparing the efficiencies of ground based and of HST observations carried out for the 470 selected HLQs in a search for new lenses, we have concluded that these efficiencies were presently very comparable. Note that observations of a medium size sample of HLQs with WFPC II should allow one to constrain the density parameter Ω_L to less than 0.01 in the mass range 10^8 - 10^{10} $M_{\odot}$; a search for massive compact objects near 10^9 $M_{\odot}$ being of course dictated by the possible existence of dark black holes with masses similar to AGN central engines.

REFERENCES

Bahcall, J.N., Maoz, D., Doxsey, R., Schneider, D.P., Bahcall, N.A., Lahav, O., Yanny, B.: 1992, Astrophys. J. 387, 56.

Blandford, R.D., Narayan, R.: 1992, preprint, to appear in Annual Review of Astron. and Astrophys.

Crampton, D., McClure, R.D., Fletcher, J.M.: 1992, Astron. J., in press.

Fukugita, M., Futamase, T., Kasai, M.: 1990, MNRAS 246, 24p-27p. (FFK)

Fukugita, M., Futamase, T., Kasai, M., Turner, E.L.: 1991, POP-422. (FFKT)

Fukugita, M., Turner, E.L.: 1991, Monthly Notices Roy. Astron. Soc. 253, 99. (FT)

Kochanek, C.S.: 1991, Astrophys. J. 379, 517-531.

Mao, S.: 1991, Astrophys. J. 380, 9

Maoz, D., Bahcall, J.N., Doxsey, R., Schneider, D.P., Bahcall, N.A., Lahav, O., Yanny, B.: 1992, preprint

Surdej, J., Magain, P., Swings, J.P., Borgeest, U., Courvoisier, T.J.-L., Kayser, R., Kellermann, K.I., Kühr, H., Refsdal, S.: 1988a, Astron. Astrophys. 198, 49-60.

Surdej, J., Magain, P., Swings, J.P., Remy, M., Borgeest, U., Kayser, R., Refsdal, S., Kühr, H.: 1988b, invited paper to the First D.A.E.C. workshop on "Large Scale Structures", proceedings edited by C. Balkowski and S. Gordon, 95-101.

Surdej, J., Swings, J.P., Magain, P., Borgeest, U., Kayser, R., Refsdal, S., Courvoisier, T.J.-L., Kellermann, K.I., Kühr, H.: 1988c, in the proceedings of a workshop on "Optical surveys for quasars", Astron. Soc. of the Pac. Conf. Series 2, 183-193.

Surdej, J. et al.: 1992, submitted to the Astron. J.

Turner, E.L., Ostriker, J.P., Gott III, J.R.: 1984, Astrophys. J. 284, 1-22. (TOG)

Turner, E.L.: 1990, Astrophys. J. 365, L43.

Véron-Cetty, M.P., Véron, P.: 1991, ESO Scientific Report No. 10.

Yee, H.K.C., Filippenko, A.V., Tang, D.: 1992, submitted to the Astron. J.