Gravitational lens studies with a LMT

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Abstract: Given the very small number ($\simeq 25$) of known multiply imaged quasars, almost randomly distributed over the sky, the probability to observe even only one of these within the $\simeq 30'$ zenithal field of view of a Liquid Mirror Telescope (LMT) is virtually zero. Therefore, the observational strategy for studies of gravitational lensing effects with a LMT rather consists in first surveying a sky area as deep and as wide as possible for interesting targets (cf. quasar candidates using color or variability criteria) and then select gravitational lens candidates among them. The extent of the field of view is of course primarily dictated by the number and/or the size of the thin CCDs placed at the LMT prime focus. For the case of multiply imaged quasars, we find that direct imagery with a 4m LMT would lead, after less than six weeks of effective operation, to the detection of approximately 50 new gravitational lens systems ($\Omega_0 = 1$, $\Lambda_0 = 0$). The natural possibility to photometrically monitor these at daily intervals offers a unique opportunity to define a sub-sample of interesting lenses with reliable geometrical parameters, time delay measurements and/or micro-lensing signatures for further astrophysical and cosmological applications. For several obvious reasons (access to the south galactic pole, galactic center, good image quality, ...), a best site location for such a LMT is somewhere in the Atacama desert. At a latitude near −29.5 degrees, a deep LMT survey would cover $\simeq 90$ square degrees at high galactic latitude, specially useful for the GL studies proposed here, for the identification of various classes of interesting extragalactic objects (cf. galaxies, clusters, supernovae, etc. at high redshift) and subsequent follow-up observations with the VLT. Such a survey would in addition provide unique data for studies of the galactic structure and stellar populations, including the detection of micro-lensed galactic objects, accurate measurements of stellar proper motions useful for the detection of faint red, white and brown dwarfs, halo stars, etc.

1 Introduction

We address in this paper the unique scientific features of gravitational lensing (GL) studies using a LMT. We first summarize in section 2 known astrophysical and cosmological applications of gravitational lensing (GL) using multiply imaged quasars as extragalactic probes. However, given the fixed (constant declination) and limited ($\simeq 30'$) zenithal field of view of current LMTs and the distribution in equatorial declination of all presently known cases of multiply imaged quasars (a compilation of these is accessible on the GL homepage: http://vela.astro.-ulg.ac.be/grav_lens/grav_lens.html), it may seem ridiculous to operate such a telescope for GL studies. We therefore adopt a different conceptual approach. A deep multi-color LMT

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survey at high galactic latitude will lead to the detection of a very large number of quasars, among which numerous new cases of multiply imaged sources. In section 3, we make use of a simple expression for the GL optical depth to estimate the expected number of gravitational lenses as a function of the limiting magnitude and sky coverage of a 4m LMT survey. Daily photometric measurements of several tens of multiply imaged quasars will render possible, in a statistical sense, determinations of the Hubble parameter via the measurement of photometric time delays between the multiple images of the lensed quasars. Unprecedented studies of micro-lensing effects taking place in some of the macro-lensed images will also become feasible, and 2-D spectroscopic follow-up VLT observations of the most interesting cases will help in setting constraints on the size and structure of the various QSO emitting regions. Location of the optimal site to conduct such a survey as well as additional expected by-products are discussed in section 4.

2 Astrophysical and cosmological applications of gravitational lensing

We recall here some of the well known effects caused by macro- and micro- lensing as well as several related applications of great astrophysical and cosmological importance.

Because of the deformation of the space time near a massive object (e.g. a galaxy lens), we know that a spherical wavefront originating from a distant source (cf. a quasar) will get distorted in the vicinity of the deflector and that if an observer happens to lie very close to the line connecting the source and the lens, the former will see multiple images (e.g. images A, B and C in Figures 1a-c) of the background quasar (S). For a typical galaxy deflector and cosmological redshifts for the source and the lens, angular separations between the lensed images are typically of the order of one or several arcsec (see Blandford and Narayan 1992, Refsdal and Surdej 1994, Narayan and Bartelmann 1996 for reviews on *gravitational lensing*). We also know that because the light trajectories have different geometrical lengths, and also because time retardation varies along the different paths, a time delay Δt will become measurable between the lensed images by the observer, provided of course that the quasar source undergoes photometric light variations. We know from the work of Refsdal (1964) that Δt is inversely proportional to H_0 (see Figures 1a-c), and it is therefore straightforward (at least in principle) to derive H_0 from Δt if we dispose of a good model for the lens. Such a good lens model may be derived if we are able to measure the source redshift, the lens redshift, the angular positions of the lensed images with respect to that of the deflector, their flux ratio(s) (via the ratio(s) of emission-line fluxes, see below), the velocity dispersion of the deflector and, if possible, the mapping of that velocity dispersion across the deflector. From astrometric, spectroscopic as well as photometric observations of gravitational lens systems, it then becomes straightforward to trace the mass distribution of the luminous and dark matter in the deflector.

There is however one more difficulty. When a foreground galaxy (the "macro-lens") produces multiple images of a background quasar, these images are seen through rather dense parts of the galaxy and there is a good chance that one or several "macro-images" (cf. macro-image C in Fig. 1a) are affected by micro-lensing (Chang and Refsdal 1979). The "micro-lens" is a star (or several stars) of the galaxy, acting as a magnifiying lens with a very small "field of view" (typically of the order of one micro-arcsec), which produces a more or less intricated network of micro-caustics (cf. Kayser 1992 and Wambsganss 1993 for reviews on *micro-lensing*). When the light beams coming from different regions of the source cross this network, they get differently amplified, according to their sizes and locations. There will thus result a differential

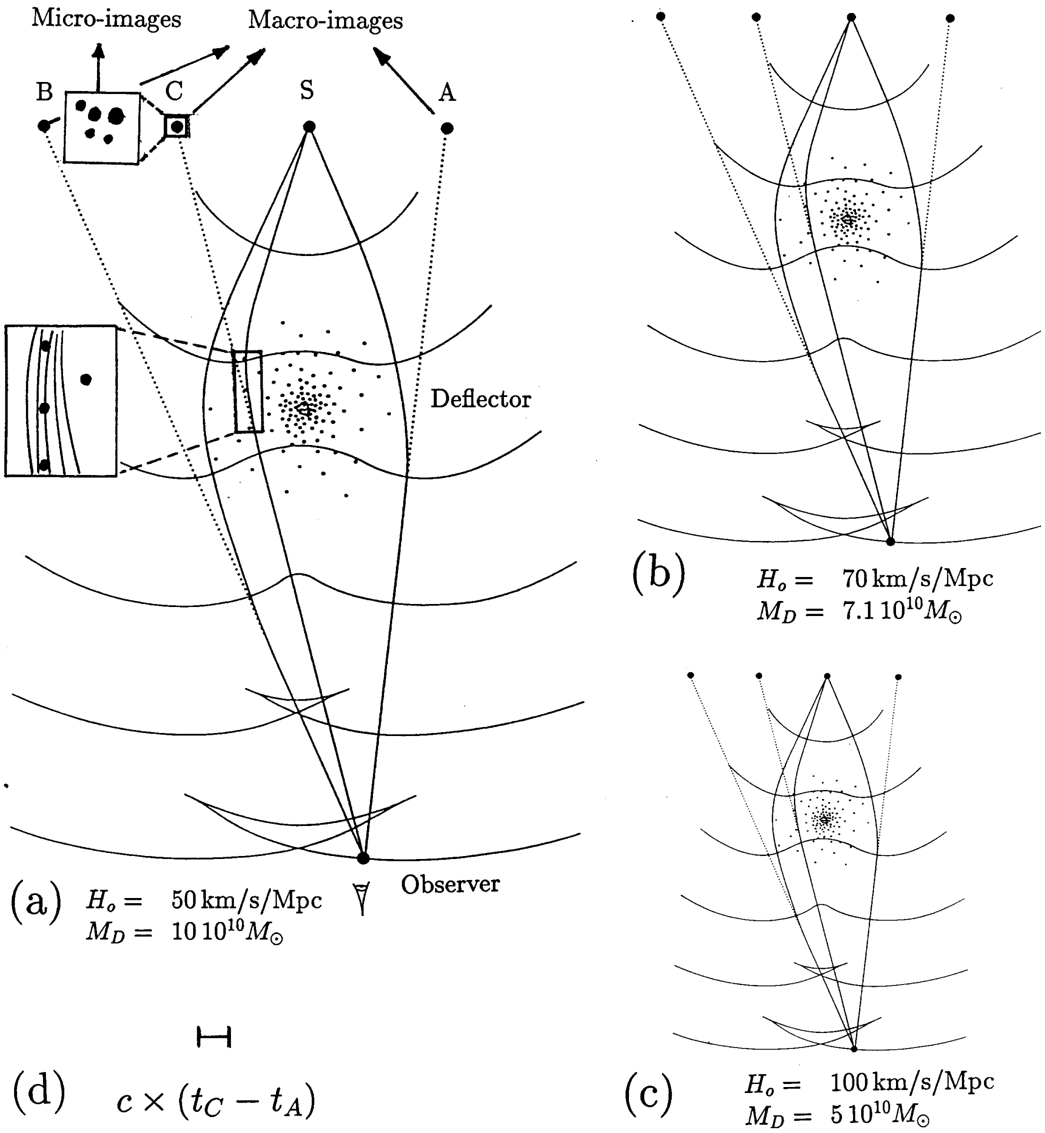

Figure 1: Adopting different values (50, 70 and 100 km/s/Mpc) for the Hubble parameter H_0 and corresponding values for the deflecting mass M (such as $M \times H_0 = C^{te}$), we have represented in (a), (b) and (c) the scaled versions of a gravitational lens system seen by an observer under a similar angular configuration (i.e. all angles measured by the observer on the plane of the sky between the macro-lensed images and the deflector are the same). Given the length of the segment $c \times (t_C - t_A)$ represented in (d), where c stands for the velocity of light and $t_C - t_A$ for the observed time delay between the lensed images C and A, it is straightforward to conclude that only one of the proposed models (namely model (b)) is compatible with the measured delay $t_C - t_A$ between the arrival times of the corresponding wavefronts at the observer (compare the length of the segment in (d) with the path difference in (a), (b) and (c) between the wavefronts for images A and C). This is the principle of the method first proposed by Refsdal (1964) to determine the value of H_0 from the measurement of the time delay Δt. In (a), we have also represented the splitting of macro-image C into several micro-images, with typical angular separations of approximately one micro-arcsec, due to gravitational lensing by individual stars located along its line-of-sight.

amplification of the different components of the quasar. For instance, in the spectrum of a micro-lensed quasar image, the optical continuum will be more amplified than the Broad Line Region (BLR) which has a larger extension (see Angonin et al. 1990, Hutsemékers 1993 and Hutsemékers et al. 1992, 1994 for the case of H1413+117). Due to relative proper motions, this phenomenon varies on a time scale of a few months or years and produces characteristic light curves (and very likely variable spectroscopic line profiles for the broad emission-lines). Of course, the shape of these curves depends on the size of the source. A spectroscopic monitoring of such micro-lensed QSO images, first identified on the basis of a LMT imaging survey, with VLT-like telescopes will thus allow to probe the structure and size of the continuum source, as well as the distribution in size (with an angular resolution of the order of 10^{-6}") and velocity of the BLR clouds.

In addition, high resolution spectroscopy of the multiple (2-4) lensed images of a background quasar should also allow one to set interesting constraints on the size and structure of the Ly-α and/or heavy absorbing element clouds located along their lines-of-sight (cf. Smette et al. 1992, 1995; see Figure 2). It should even be possible from such observations to set constraints on the value of the deceleration parameter q_0 of the Universe.

We therefore conclude that gravitational lens systems, consisting of several variable macro-lensed images and of a deflector with angular separations of the order of one arcsecond, constitute unique laboratories to probe very important astrophysical and cosmological parameters. As we shall see in the next section, a large number of interesting gravitational lenses ought to be identified within a LMT survey. Two-dimensional spectroscopic follow-up observations with a VLT-like telescope should lead to fundamental information on the various QSO emitting regions as well as on intergalactic dark and luminous matter distributed along their lines-of-sight.

3 Requirements for a GL imaging LMT survey

Keeping in mind the astrophysical and cosmological applications of GL discussed in section 2 and from previously published statistical GL studies, it is easy to derive the observational requirements to identify within a LMT direct imagery survey a large number (e.g. 50) of multiply imaged quasars. Given a flux limited sample of quasars down to the limiting magnitude B_{lim} and following Surdej et al. 1993 (see also Claeskens et al. 1996), we may write that the expected number of multiply imaged quasars $N_{lens}(S, B_{lim})$ over a sky area S (expressed in square degree) is:

$$N_{lens}(S, B_{lim}) = \tau_q \; Bias(< B_{lim}) \; N_q(< B_{lim}) \; S, \tag{1}$$

where τ_q represents the expression of the geometrical optical depth for intervening galaxies to produce multiple images of a background quasar with redshift z_q (Turner et al. 1984), $Bias(< B_{lim})$ the magnification bias correction factor (Fukugita and Turner 1991, Surdej et al. 1993) and $N_q(< B_{lim})$ the number counts of quasars per square degree brighter than B_{lim} (Hartwick and Schade 1990; we have adopted the fit by Narayan 1989). Let us remind here that the magnification bias merely accounts for the correction to be applied when dealing with flux limited samples of quasars as opposed to volume limited ones. This correction only gets significant (i.e. $>> 1$) for values of $B_{lim} < 19.2$. For the fainter values of B_{lim} (typically > 20) considered here, we can show that the magnification bias correction factor $Bias(< B_{lim})$ tends towards a constant value of 2.5.

For a quasar with redshift z_q, a cosmological density $\Omega_0 = 1$ and a cosmological constant $\Lambda_0 = 0$, the expression for the optical depth τ_q is

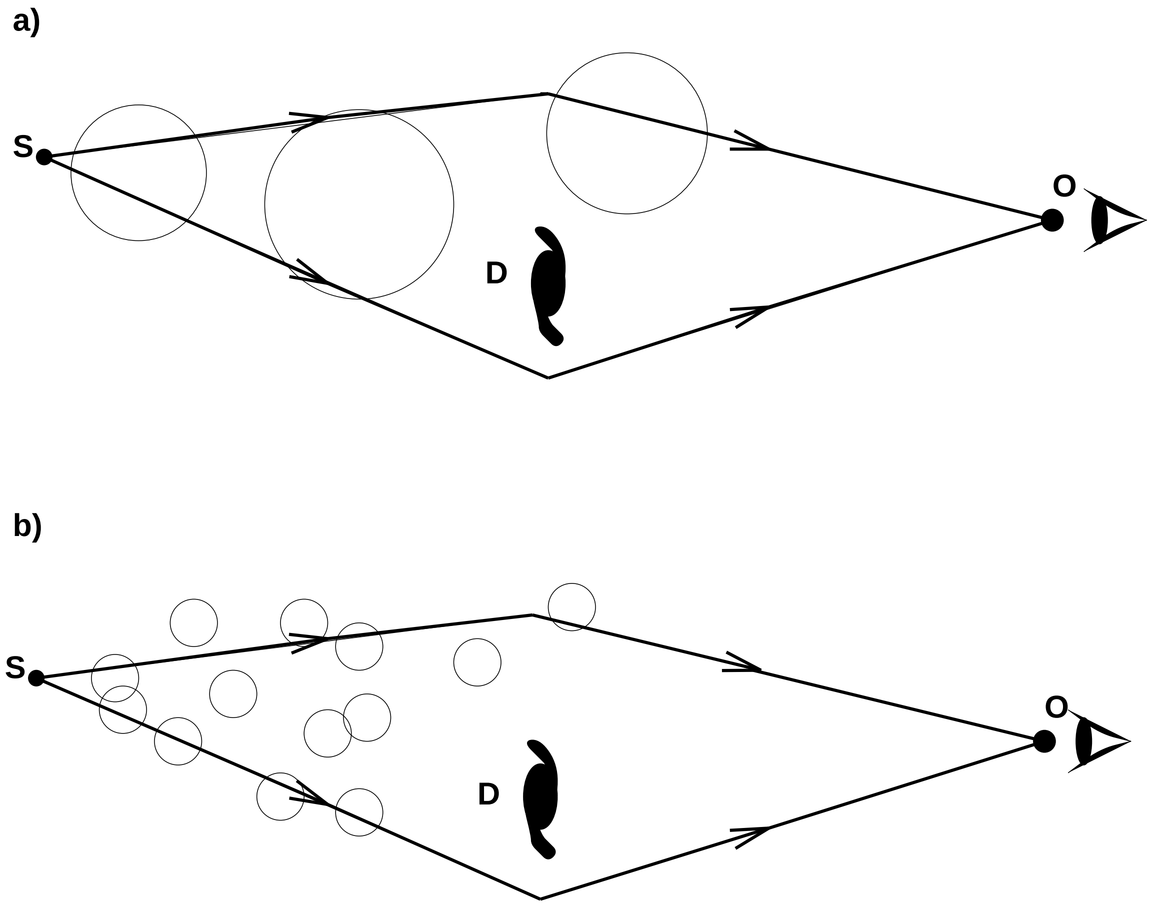

Figure 2: If an observer O takes high resolution spectra of the two lensed images of the distant source S, produced by the deflector D, the former will detect more *coincident* narrow absorption lines due to the intervening absorbing gas clouds in case (a) than in case (b), because the size of these clouds is more comparable in the former case with the distance separating the two lines-of-sight. In (b), the size of the gas clouds is significantly smaller than the typical separation between the lines-of-sight, resulting in a larger number of *anti-coincidences* in redshift between the narrow absorption lines observed in the two spectra. Smette et al. (1992, 1995) have used this method to set interesting constraints on the size of Ly-α clouds at high redshift.

$$\tau_q = \frac{4}{15}\, F\, \left(1 - (1+z_q)^{-0.5}\right)^3, \tag{2}$$

where the parameter F ($\propto n_0\sigma^4$) measures the effectiveness of cosmologically distributed "singular isothermal spherical" galaxies to produce multiple QSO images (n_0 being the local number density and σ the one-component velocity dispersion of those galaxies; see Surdej et al. 1993 and Claeskens et al. 1996 for applications of this formalism to real observations).

From observed parameters of local galaxies, Fukugita and Turner (1991) have calculated that $F \simeq 0.047$ from which we derive that $\tau_q \simeq 3.15\ 10^{-4}$, $6.22\ 10^{-4}$ and $9.46\ 10^{-4}$ for $z_q = 1$, 1.5 and 2, respectively.

Imposing $N_{lens}(S, B_{lim}) = 50$ in Eq. (1) and adopting, for sake of simplicity, a representative value of $z_q = 2$, we have illustrated in Figure 3 the resulting sky area S to be surveyed as a function of B_{lim}. Also shown in this figure are the results for the values of the cosmological parameters $\Omega_0 = 0$, $\Lambda_0 = 0$ and $\Omega_0 = 0$, $\Lambda_0 = 1$ and, finally, the results expected for $\Omega_0 = 1$, $\Lambda_0 = 0$, assuming that the number counts of quasars at faint magnitudes does not flatten out, as suggested by Hawkins and Véron (1995). Similarly, we have illustrated in Figure 4 the total number of quasars (N_q^{Total}) expected in the surveyed sky area S over which 50 new cases of GL ought to be identified.

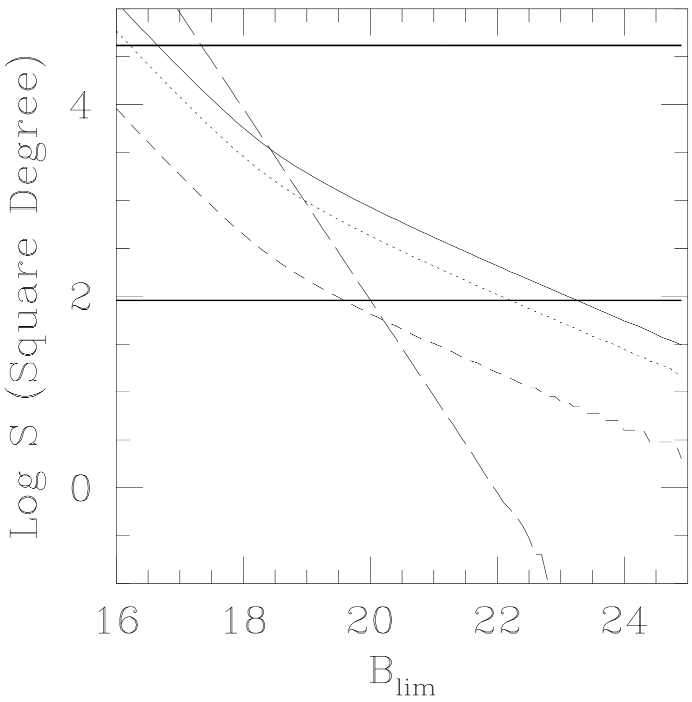

Figure 3: Sky area S to be surveyed as a function of the limiting magnitude B_{lim} to identify 50 multiply imaged quasars. The two horizontal lines refer to limits set by the whole sky area and a field of 90 square degrees (see text). For simplicity, a representative value of $z_q = 2$ was adopted for the quasar redshift and, unless stated otherwise, the number counts of quasars are taken from Hartwick and Schade (1990). The different curves refer to $\Omega_0 = 1$, $\Lambda_0 = 0$ (full), $\Omega_0 = 0$, $\Lambda_0 = 0$ (dotted), $\Omega_0 = 0$, $\Lambda_0 = 1$ (dashed) and, finally, $\Omega_0 = 1$, $\Lambda_0 = 0$ (long-dashed) with the number counts of quasars from Hawkins and Véron (1995). Note that for $B > 22$ (resp. $B > 21$), these curves are extrapolations from the Hartwick and Schade (resp. Hawkins and Véron) number counts of QSOs. Conversely, the LMT survey will help in defining more precisely the number counts of quasars at very faint magnitudes, resulting in a better defined and complete sample of QSOs.

We conclude that, even under the most unfavourable conditions (i.e. $\Omega_0 = 1$, $\Lambda_0 = 0$), a realistic sky area S to be surveyed in order to identify 50 new lenses down to limiting magnitudes $B_{lim} < 24$ can be easily probed with a 4m LMT (typically $S < 60$ square degrees at high galactic latitude). In this case, a total of approximately 20,000 quasars will also be identified. From the observed numbers of detected lenses and quasars in such a deep and complete survey, we should be able to independently infer the most realistic values for the cosmological parameters Ω_0 and Λ_0, as well as precisely characterize the luminosity function and number counts of quasars as a function of redshift and magnitude, respectively. Note that observational searches for multiply imaged quasars among highly luminous ones have prevented in the past to use a complete QSO reference sample and introduced many other ill-defined biases in the statistical estimates of the various physical (cf. F) and cosmological parameters (Ω_0, Λ_0).

Assuming that the observations would be carried out using a 4m LMT in the drift-scan

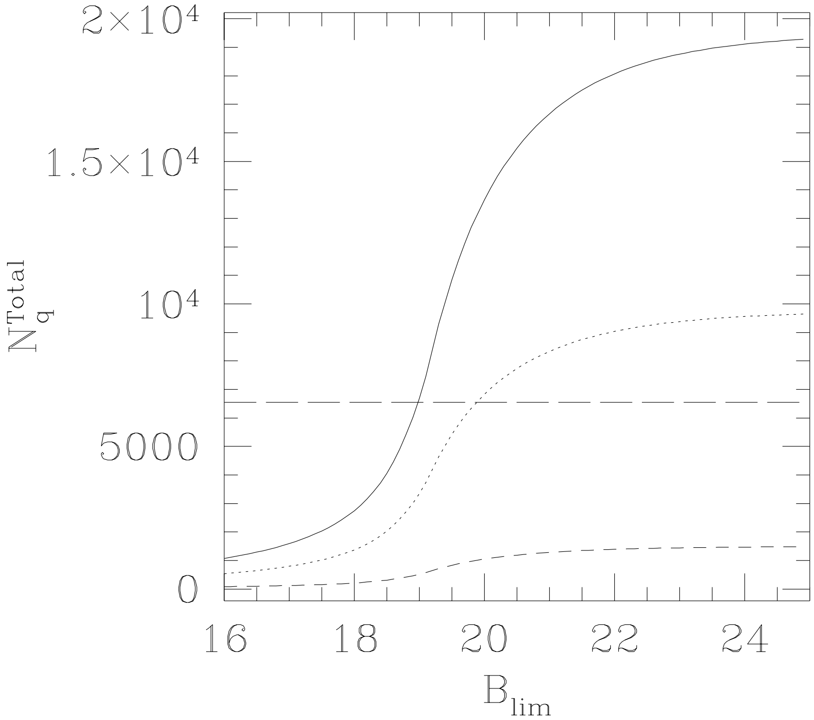

Figure 4: Total number of quasars (N_q^{Total}) versus the limiting magnitude B_{lim}, expected in the surveyed sky area S over which 50 new cases of GL ought to be identified. For simplicity, a representative value of $z_q = 2$ was adopted for the quasar redshift and, unless stated otherwise, the number counts of quasars are taken from Hartwick and Schade (1990). The different curves refer to $\Omega_0 = 1$, $\Lambda_0 = 0$ (full), $\Omega_0 = 0$, $\Lambda_0 = 0$ (dotted), $\Omega_0 = 0$, $\Lambda_0 = 1$ (dashed) and, finally, $\Omega_0 = 1$, $\Lambda_0 = 0$ (long-dashed) with the number counts of quasars from Hawkins and Véron (1995)

mode (single integrations of 90 sec), which will ensure excellent flat-fields, the expected magnitude limits M_{lim} for point sources with a seeing of 0.7 arcsec, a 5σ photometric accuracy and combining a number of N repeated scans, are listed in Table 1 for various broad band filters. These data are taken from simulations made for the preparation of the "ESO Imaging Survey" (EIS 1997) with the NTT. Typically, in less than six weeks of effective observing time, a deep multi-color LMT survey would provide us with the necessary data to achieve the scientific goals exposed in this paper. Further identification of quasars based upon short-, medium- and large-timescales photometric variability observed in the proposed LMT survey will also be extremely valuable (see the contribution by Hawkins in these proceedings).

4 Additional interesting results and conclusions

A good site from where to carry out a GL direct imagery LMT survey should be characterized by excellent weather conditions (image and photometric quality) and allow access to sky areas at high galactic latitudes, the latter ones being also accessible to large telescopes such as the VLT to permit follow-up observations of interesting faint targets.

For instance, operation of a LMT (field of view $\simeq 30'$) from La Silla (latitude of 29 degrees 15 minutes South) would enable to cover approximately 90 square degrees of sky at high galactic latitude ($|b| > 30^o$), passing very near to the south galactic pole. At the same time, such a

Table 1: Broad band filter, requested number of scans and corresponding limiting magnitude achievable for the detection of point-like sources with a 5σ photometric accuracy

Filter	N of scans	M_{lim}
U	15	24.5
B	3	24.5
V	6	24.5
R	4	23.5
I	6	23.5
Gunn-z	2	22.3

LMT survey would probe regions near the galactic center, offering unique data for studies of the galactic structure, stellar populations, incuding accurate measurements of stellar proper motions (cf. red, white, brown dwarfs, faint halo stars, etc.) and detection of stellar microlensing effects caused by bulge stars, dark compact objects, etc.

As far as GL is concerned, the proposed multi-color and variable photometric survey would lead to the detection of $\simeq 50$ new multiply imaged quasars for which nearly daily photometric information will become available. Of course, the lenses can be first directly selected from those quasar candidates revealing a peculiar image morphology. From the statistical identification and study of these lenses, it will be possible to independently infer the most likely values for the cosmological parameters Ω_0 and Λ_0 and to precise the relation for the number counts of quasars at faint magnitudes. From the photometric monitoring of a selected sample of multiply imaged quasars, we shall derive in a statistical sense the value of the Hubble parameter H_0 from the measurement of the time delay between their multiple lensed images. We also expect that a significant number of these macro-lensed images will reveal photometric signs caused by micro-lensing effects. Photometric and VLT spectroscopic observations of these candidates should lead to interesting constraints on the size and structure of the various QSO emitting regions. High resolution spectroscopy of selected gravitational lens systems with the VLT will also lead to interesting estimates of the size and shape of intervening intergalactic absorbing clouds. Other astrophysical and cosmological applications relying on the studies of the LMT lenses include tracing the luminous and dark matter in the Universe, setting limits on the cosmological density of compact objects with mass $> 10^{10}\ M_{\odot}$, probing the extinction law of external galaxies responsible for differential reddening between multiple macro-lensed QSO images. In addition, such an extragalactic LMT survey will lead to the discovery of interesting supernovae, galaxies, clusters at high redshift and to a large sample of approximately 20,000 quasars down to $B_{lim} \simeq 24$ which will provide a unique grid of light probes to study the morphology, structure and size of large scale structures (heavy elements and hydrogen ones) in the Universe at scales ranging from several Mpc up to hundreds of Mpc.

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