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COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses

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Abstract. We describe a new project aiming at measuring time delays for most known lensed quasars, from optical light curves obtained with five (almost) dedicated 1-2 m telescopes in the Northern and Southern hemispheres. The goal is to evaluate the Hubble constant H_0 with a precision below 2%. We present here numerical simulations in order to define the optimal temporal sampling in our observations as a function of typical quasar variations, object visibility, and for a given accuracy on the individual photometric points. It is also emphasized that the ongoing effort to obtain deep imaging using *both* space and ground based facilities must be continued, as illustrated by the comparison of HST and VLT near-IR images of the "cloverleaf": H 1413+117.

1. Introduction

Although it is known since exactly 40 years that quasar time delays can yield a measurement of H_0 at truly cosmological distances and independent of any standard candle or local calibrators (Refsdal, 1964), no concerted and long term action has succeeded to implement the method at a level of precision really competitive with other techniques.

There are two main reasons for the limited interest the astronomical community has shown so far in the time-delay method. One is theoretical: H_0 can be derived only if the mass distribution in the lensing galaxy is well constrained, which, unfortunately, is not always the case (see Schechter 2005). The other is purely observational and is related to the measurement of the time delay itself. For a given lensed quasar, about half of the total uncertainty on H_0 is due to the lens model, the other half being due to the uncertainty on the time delay, which propagates linearly in the error budget. The typical accuracy on time delays measured by past monitoring programs is 5-10%. This implies, if nothing is done to improve the situation, that the maximum accuracy one can expect on H_0 is also 5-10%, independently of the quality of the lens model.

In the era where the target accuracy on H_0 is of the order of a few percents, it will be mandatory to work on several fronts, both improving lens models and time delay measurements. The COSMOGRAIL project concentrates on the latter point.

2. Description of the project

Measuring time delays is difficult, but not as difficult as it first appeared in the late 80s when the first monitoring programs were started. Obtaining regular observing time on telescopes in good sites was (and is still) not easy and the small angular separations between the quasar images require to perform accurate photometry of blended objects, sometimes with several quasar images plus the lensing galaxy within the seeing disk.

The COSMOGRAIL project, started in April 2004, addresses both issues of carrying out photometry of faint blended sources and of obtaining well sampled light curves. The project involves 5 telescopes: **(1)** the Swiss 1.2m *Euler* telescope located at La Silla, Chile, **(2)** the Swiss-Belgian 1.2 m *Mercator* telescope, located in the Canaria islands (La Palma, Spain), **(3)** the 2 m robotic telescope of the Liverpool University (UK), also located at La Palma, **(4)** the 1.5 m telescope of Maidanak observatory in Uzbekistan, and **(5)** the 2 m Himalayan Chandra Telescope. The project therefore involves many more people than in the present author list, spanning a broad range of expertises.

In order to use all the available data, even with bad seeing, the data are processed using the "MCS deconvolution algorithm" (Magain et al. 1998), which was also the main tool used by Burud et al. (2000, 2002a, 2002b) and Hjorth et al. (2001), who published within three years nearly half of the time delays known up to now.

3. Prior estimates of the accuracy on the time delay

Even if large amounts of telescope time are available for the COSMOGRAIL project, it is hard to ensure that all useful lensed quasars are monitored with a very high frequency, especially with new objects discovered about every month. An optimal temporal sampling has to be adopted for each target. The observations are taken only in the R filter in the first phase of the project. The target accuracy on the photometry is 0.01 mag (1σ), which is generally reached in 30 minutes of integration with the telescopes used.

Determining the optimal temporal sampling to be used for each object is critical, and can be estimated through numerical simulations with artificial light curves. While a detailed description of such simulations is given in Eigenbrod et al. (2005) we sketch the main lines of our work in the following and give the results in Figs. 1 and 2.

Two-year long continuous artificial light curves with a peak-to-peak amplitude A (in magnitudes) are first generated. The curves are shifted by a desired time delay and sampled in 3 different ways, with a regular 3-, 7- and 15-day step. A fourth sampling is also tested. We refer to it as "irregular", with 15 days chunks of points taken every second day followed by large 1 or 2 weeks gaps. Most of the past monitoring projects have worked with this kind of sampling. A small deviation to the perfectly regular sampling is introduced (± 30% of the sampling step) in order to take into account losses due to bad weather and scheduling constraints of the observations. The photometric points are affected by a 0.01 mag error and the curves are windowed in order to mimic different object visibilities along the year, i.e., 5, 8 and 12 months. The simulation consists of producing 100,000 such light curves per simulated value of the time delay, then shifting them back using standard cross-correlation techniques such as the one described in Pelt et al. (1994) and finally of measuring the standard deviation of the resulting distribution of recovered time delays. We take this standard deviation as the 1σ error bar on the time delay.

Fig. 1 gives the relative errors for 3 typical amplitudes A of the quasar variation (A=0.1, 0.2, 0.3 mag), plotted as a function of the sampling and for 3 object visibilities. Such curves can be used to infer the sampling to adopt for a given object and to give priority to the ones for which relative errors below 2% can be achieved. The only strong assumption is the amplitude A of the quasar variations, but even the largest one assumed is in fact small, A=0.3 mag. Note also that we do not assume sharp peaks in the light curves, but only smooth variations, on time-scales of the order of several weeks. We plot in overlay the relative errors for actually measured quasars with *optical* time delays. All match the predicted error except HE 2149-27 which would falls outside the plot, but this measurement was based on light curves with very smooth variations.

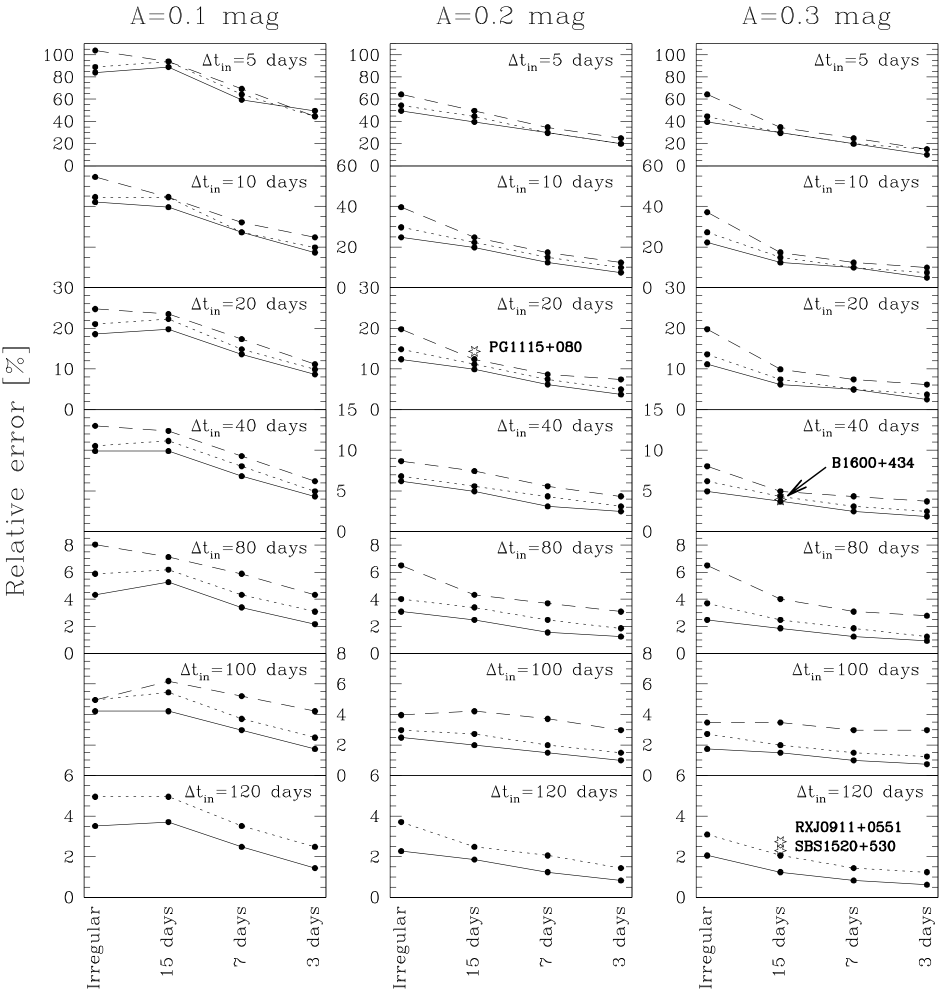

Figure 1. Predicted relative errors on the time delay for different temporal samplings and peak-to-peak amplitudes A of the quasar variations. Each panel shows the result for a different time delay. The solid curves are for circumpolar objects while the dotted and dashed curves correspond to the 8-month and 5-month visibilities. Microlensing has not been taken into account in these simulations. The star-shaped symbols correspond to the relative errors for objects with actually measured optical time delays. All match the predicted errors, although the simulations seems to be slightly more optimistic than reality, maybe due to microlensing.

Real lensed quasars display light curves that are more complicated than a simple time shift of the exact same photometric variations. Microlensing by stars in the main lens is producing additional erratic variations (e.g., Kochanek 2005) that make the quasar images show slightly different behaviours. Small time-scale microlensing, with variations of a few days is only adding extra noise to the light curves but and does not alter the overall shape of the curves. Long term microlensing, varying over several months is more of a problem and should be taken into consideration.

Fig. 2 is constructed from sets of light curves that include microlensing. In the simulation, one quasar image follows the intrinsic variations of the quasar while the other has an additional (long term) variation whose peak-to-peak amplitude A$_{\mu}$ is a fraction α of

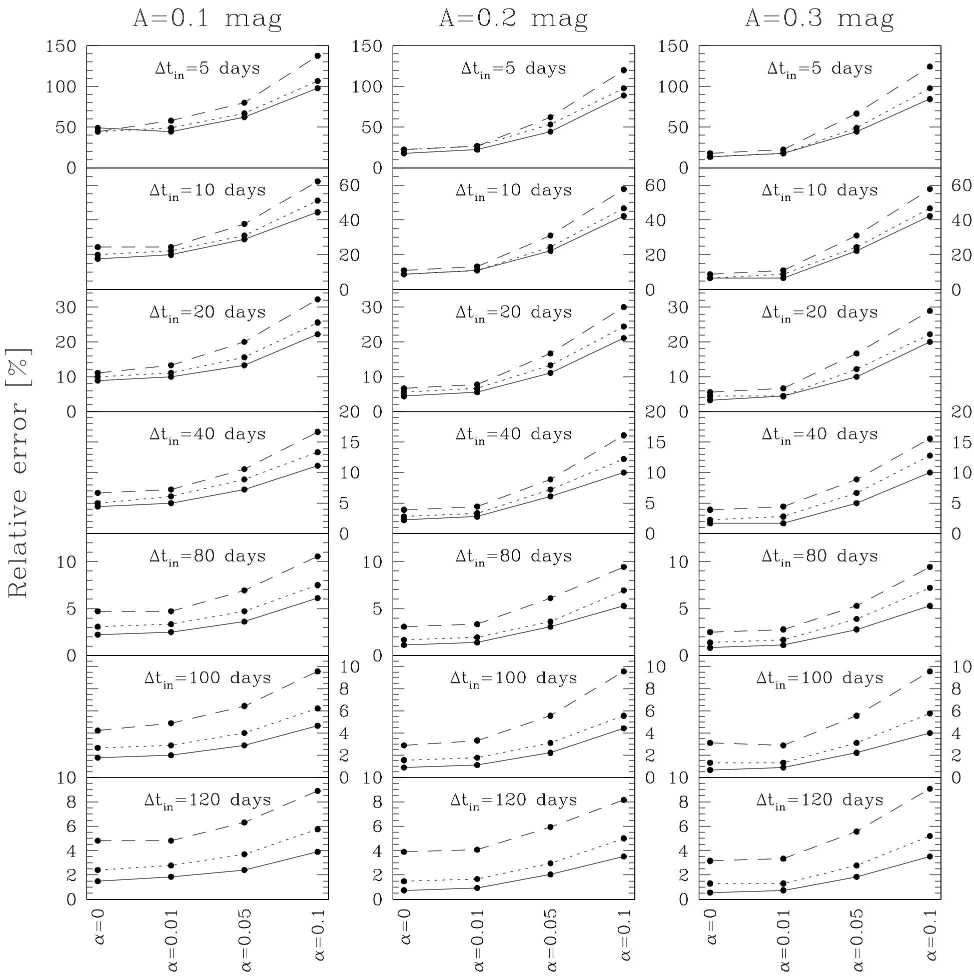

Figure 2. Predicted errors on the time delay when microlensing is also affecting the light curves. As in Fig. 1, the results are displayed for different quasar variations amplitudes and object visibilities. The coefficient α indicates the strength of the microlensing (see text) from 0% to 10%. The simulations shown here are for the 3-day sampling.

the intrinsic variation, i.e., $A_\mu = \alpha A$. Setting $\alpha = 0$ gives the no-microlensing case. Fig. 2 shows the results of the simulations, in the case of the 3-day sampling. The relative errors are now plotted for 3 "microlensing strengths" α (1%, 5%, 10%).

While 1% microlensing almost does not change the relative error, 5% microlensing, if not taken into account, is already implying error bars twice as large as the no-microlensing case, showing that removal of slow microlensing variations is mandatory at the percent level. See a more complete description of this work in Eigenbrod et al. (2005).

4. On the complementarity of space-based and ground-based imaging

In addition to the monitoring program, we are conducting an optical and infrared imaging campaign at the VLT, in order to explore the line of sight to selected lensed quasars up to the redshift of the source (e.g., Faure et al. 2005). The main goal is to

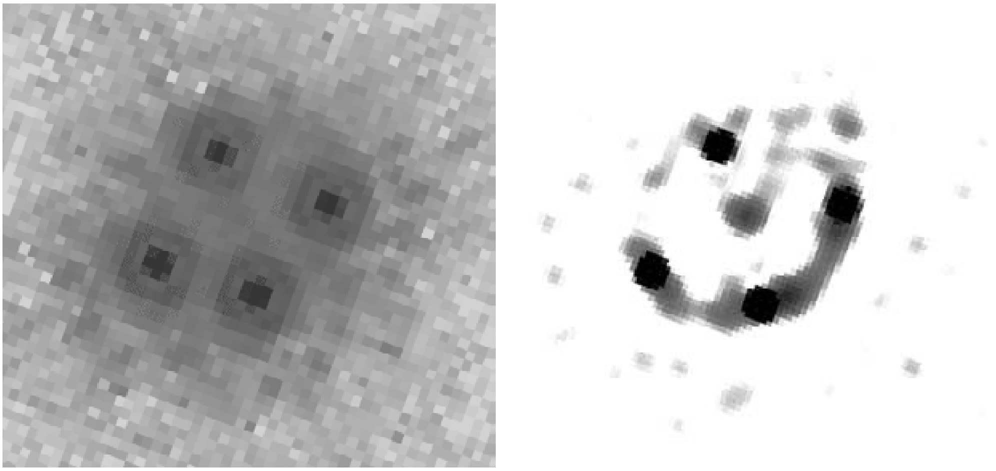

Figure 3. *Left:* HST/NICMOS image of the "cloverleaf", H 1413+117, obtained by the CASTLES group. The field of view in this F160W image is 2″ x 2″ and the exposure time is 1600 sec. *Right:* MCS deconvolution of the data, where the resolution is now 0.08″. The lensing galaxy and the lensed quasar host galaxy (Einstein ring) are well visible, giving stronger observational constraints to the models.

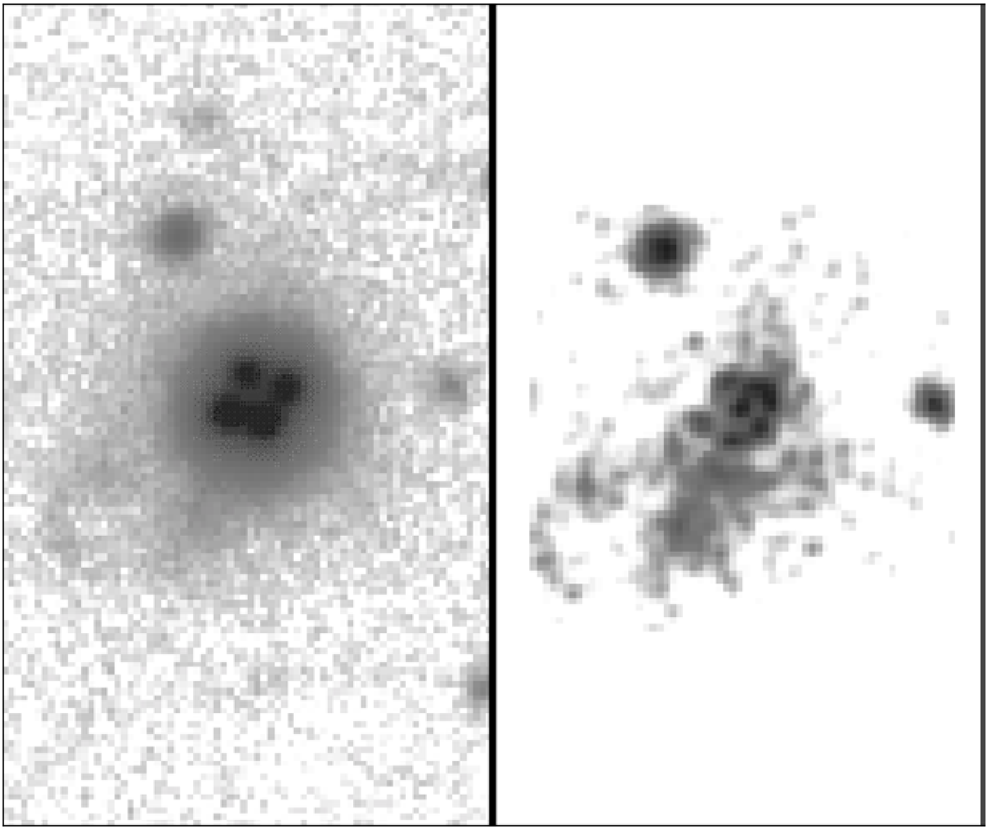

Figure 4. *Left:* VLT *K*-band image of H 1413+117, obtained in 2 hours of exposure with ISAAC. The seeing in this image is 0.45″. The field of view is 8″ x 15″. The orientation is the same as in Fig. 3 and many intervening galaxies are detected, some being superposed on the quasar images. *Right:* the quasar images have been removed, clearly showing the lensing galaxy, the Einstein ring, and extended fuzz missed by the HST data in spite of similar depth, hence illustrating the complementary of space and ground based images.

characterize the whole lensing potential responsible for the lensing effect, i.e., not only the main lensing galaxy, but also any intervening groups or clusters that modify significantly the main potential well.

Although most known lensed quasars have been imaged by the HST, complementary ground based VLT data are extremely useful in this respect, because of the larger field of view, and also because of the complementary characters of these two kinds of observation. While the HST is better than VLT at pinning down the details of the lens and of the host galaxy of the quasar source, the VLT is doing better than the HST at discovering faint extended objects.

The two images of the “cloverleaf”, H 1413+117 shown in the figures are of similar depth, with 20 minutes of exposure with the HST (Fig. 3) and 2 hours with the VLT (Fig. 4), in the H and K bands respectively. After deconvolution using the MCS algorithm, the HST image clearly reveals the main lensing galaxy, on which astrometry can be performed with an accuracy of a few milli-arcseconds. The lensed quasar host galaxy of the quasar is also visible as an almost complete Einstein ring. Models of the four images using the new accurate astrometry imply that the shear at the position of the images exceeds the one expected from the (visible) ellipticity of the lens (Saha, private communication). This source of ellipticity might be external to the main lens, as is shown in the VLT image of Fig. 4. The quasar images have been removed on the right panel of the figure. Although this is done using deconvolution, the two panels of the figure have the same spatial resolution: $0.45''$. The main lens and the Einstein ring are visible but other much more extended objects also appear. Although the limiting magnitude of the HST image would in principle allow to see them, they are missed, probably because we are in a noise regime still dominated by the sky background at the flux level of the objects, and because the pixel size of the HST is too small compared with the physical size of these galaxies. Interestingly, the ellipticity predicted by the lens models is oriented in the same direction as the objects discovered in the VLT image. Whether these galaxies are at the same redshift as the lensing galaxy or are other unrelated objects will require further (approved) VLT observations with integral field spectroscopy. They may also be the optical counterpart of the absorbers seen in the HST spectra of the quasar images by Monier et al. (1998).

5. Conclusions

The COSMOGRAIL project has started in April 2004 with five telescopes, using up to 50% of the total observing time of two telescopes and 10-20% of the time of two others. The main goal is the measurement of time delays with a precision close to 1 looking first for quality rather than quantity. In parallel, deep imaging and spectroscopy are carried out with 10m class telescopes in order to solve as many as possible of the observational challenges described by Paul Schechter in his talk (Schechter, 2005). As we believe golden lenses do not exist, and since quasar time delays are probably as important for the determination of H_0 as for the study of dark matter in individual lens galaxies (Kochanek 2005), it will be mandatory, within a few years, to at least double the present sample of objects with accurate time delays. Statistical analyses with quasar time delays shall soon become possible.

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