Estimating Time Delay in Gravitationally Lensed Fluxes

Extended Abstract

Peter Tiňo[1], Juan C. Cuevas-Tello[1,3],, and Somak Raychaudhury[2]

[1] School of Computer Science, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom, {J.C.Cuevas, P.Tino}@cs.bham.ac.uk
[2] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom, somak@star.sr.bham.ac.uk
[3] Engineering Faculty, Autonomous University of San Luis Potosí, México

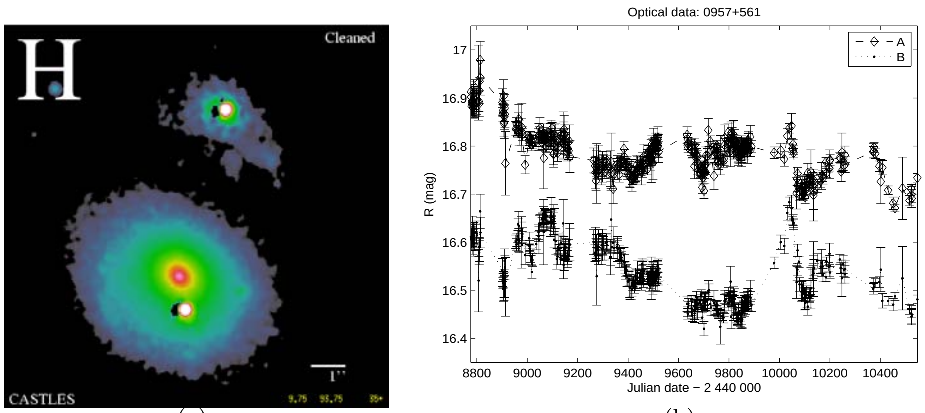
According to the General theory of Relativity, a ray of light (or any other form of electromagnetic radiation, e.g. radio or x-rays) travels along a geodesic, which could be locally curved due to the gravitational effect of clumps of matter like stars or galaxies. This is known as Gravitational lensing [1] and gives rise to interesting cosmic illusions like magnified and seriously distorted images of distant sources, sometimes splitting into multiple images (e.g. Fig. 1), caused by intervening matter along the line of sight. Since the distortion of the images depends on the distribution of matter in the lensing object, this is the most direct method of measuring matter (which is often dark) in the Universe [2].

The quasar Q0957+561, an ultra-bright galaxy with a super massive central black hole (see Fig. 1), was the first lensed source to be discovered and it is the most studied so far. The source is 3.2×10^{10} light-years away from us, being lensed by a galaxy (visible in Fig. 1), along the line of sight, only 0.6×10^{10} light-years away. The effect of the lens is to create two distinct images of the same source. The brightness of quasars varies on the time scales of days- and this variation shows up at different times in the two images since the path of light travel is different for them. Since such a *time delay* (phase shift) can provide a rare direct measure of the distances involved, this quantity is of great importance in astronomy, and thus it is not surprising that many attempts have been made to estimate it, e.g. see [3–6].

The observations can be made by both radio and optical astronomers, since theory predicts that the time delay is independent of the frequency of observation. For our purposes, the data are available as two unevenly sampled time series of fluxes (or logarithm thereof) of the two images. The observations are made at irregular intervals due to weather conditions, equipment availability, object visibility, among other practical considerations.

We analyze the brightness of the two images of quasar Q0957+561 (Fig. 1) as a function of time, to find the phase shift between the time series. Optical astronomers measure the brightness of a source using imaging devices, with filters to restrict the range of wavelength/frequency of light observed. The flux

Dagstuhl Seminar Proceedings 09081
Similarity-based learning on structures
http://drops.dagstuhl.de/opus/volltexte/2009/2037



(a) (b)

Fig. 1. Quasar Q0957+561. **(a)** Image taken by the Hubble Space telescope (http://www.cfa.harvard.edu/castles). The two point images are of the same distant quasar, 32 billion light-years away, multiply-imaged due to the gravitational effect of the "lensing" galaxy, seen as the extended object, which is along the line of sight, 6 billion light-years away from us. **(b)** The two time series represent the brightness of the two images (in logarithmic units (mag), such that brighter means lower values; see text) as a function time (the abscissa is measured in *days*). Image A is shifted up by 0.2 mag for visualization purposes. This is data set DS3 with measurement error bars (std. deviations).

f of light from a source is expressed in logarithmic units known as magnitudes (mag), defined as mag $= -2.5\log_{10} f +$ constant. The errors on mag mainly measurement errors, assumed to be zero-mean Gaussian. The green (g) and red (r) bands represent measurements obtained with filters in the wavelength range 400–550 nm and 550–700 nm, respectively. We use the data sets DS1 and DS2 [5], obtained through a monitoring program at the Apache Point Observatory, New Mexico, USA, and DS3, from images taken at Fred Lawrence Whipple Observatory, Mt. Hopkins, Arizona, USA. [6].

Since the true time delay on the quasar Q0957+561 is unknown, the best way to compare the performance of methods is through a set of controlled experiments where the true time delay is known. We use optical-like artificial data to compare our approach with the commonly used dispersion spectra method. In [7], we used radio-like artificial data with an imposed time delay of 500 days over an observational season of 13.6 years.

Here, the artificial data is generated as in [7], but with an observational season of 1.3 years, 50 irregular samples, a true time delay of 5 days, an offset $M = 0.1$, three levels of noise of 0.03%, 0.106% and 0.466% of mag (minimum, average and maximum of DS3, respectively), and "observational" gap size of zero to five continuously missing samples per block (five blocks randomly located).

We use ten different underlying functions, 100 realizations per level of noise and ten realizations per gap size. This gives us an amount of 153,510 data sets under analysis. So, these data sets simulate optical data with low time delay and low offset with high precision [6]. To make our comparison fair, each method was subjected to the same collection of artificial data sets. In all cases the time delay under analysis is from 0 to 10 days; with increments of 0.1 days.

We compare our kernel based estimator that explicitly models the underlying shifted and rescaled flux curves with the current methods used in astrophysics. Our approach shows a superior performance in both the model bias and variance.

On the real observations, the set DS1 leads to the minimum standard deviation for both dispersion spectra methods, as well as for our kernel-based approach (randomization through Monte Carlo simulations). With our methods, we get consistent results for DS1 and DS2. On the other hand, Kundic et al. did not find such a concord with the four methods studied in [5]. Rather, they adopted the time delay of 417 ± 3 days given by *Linear method* [5]. Therefore, the best time delay for DS1 and DS2 is 420 days rather than 417 days [5]. Nevertheless, nobody knows the true time delay for the quasar Q957+561 so far, and as more observations are gathered more time delay estimates appear.

References

1. Saha, P.: Gravitational Lensing. Encyclopedia of Astronomy and Astrophysics (2000)
2. Kochanek, C., Schechter, P.: The Hubble constant from gravitational lens time delays. Carnegie Observatories Astrophysics Series **2** (2004)
3. Pelt, J., Kayser, R., Refsdal, S., Schramm, T.: Time delay controversy on QSO 0957+561 not yet decided. Astronomy and Astrophysics **286**(1) (1994) 775–785
4. Pelt, J., Kayser, R., Refsdal, S., Schramm, T.: The light curve and the time delay of QSO 0957+561. Astronomy and Astrophysics **305**(1) (1996) 97–106
5. Kundic, T., Turner, E., Colley, W., Gott-III, J., Rhoads, J., Wang, Y., bergeron, L., Gloria, K., Long, D., Malhorta, S., Wambsganss, J.: A robust determination of the time delay in 0957+561A,B and a measurement of the global value of Hubble's constant. Astrophysical Journal **482**(1) (1997) 75–82
6. Ovaldsen, J., Teuber, J., Schild, R., Stabell, R.: New aperture photometry of QSO 0957+561; application to time delay and microlensing. Astronomy and Astrophysics **402**(3) (2003) 891–904
7. Cuevas-Tello, J., Tiňo, P., Raychaudhury, S.: How accurate are the time delay estimates in gravitational lensing? Astronomy and Astrophysics (2006) Accepted, http://arxiv.org/abs/astro-ph/0605042.