PyCS3: A Python toolbox for time-delay measurements in lensed quasars

Martin Millon[1], Malte Tewes[2], Vivien Bonvin[1], Bastian Lengen[1], and Frederic Courbin[1]

1 Institute of Physics, Laboratory of Astrophysique, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland **2** Argelander-Institut für Astronomie, Bonn, Germany

Summary

Time-delay cosmography is a competitive technique for measuring the current expansion rate of the Universe, that is, the Hubble Constant (see, e.g., Riess, 2019 for a review; Wong et al., 2020 for recent results). It relies on the strong gravitational lensing effect that happens when a massive foreground galaxy deviates the light from a background object, producing 2 or 4 mirage images of the same background source. In this configuration, the optical path length is slightly different in each multiple image and thus, the travel time of the photons along those paths is also slightly different. If the background source is varying, the same variations are visible in all multiple images with different delays. Lensed quasars or lensed supernovae are ideal targets to measure such (relative) time delays, because they are variable on short timescale, and are sufficiently bright to be observed at cosmological distance. These measured delays can be used to infer the so-called time-delay distance, $D_{\Delta t}$, which is directly inversely proportional to the Hubble Constant. The method relies on three main ingredients :

- a precise and accurate determination of the time delays
- a model of the mass distribution of the lensing galaxy
- an estimate of the mass of all the galaxies along the line of sight that also deviates the light rays, and thus perturbs the time delays.

Obtaining the time delays of lensed quasars typically requires a decade of continuous observation to produce long light curves which contain several variations of the quasars that can unambiguously matched between the multiple images. An example of the light curves of the multiple images of the lensed quasar RXJ1131-1231 is presented in Figure 1. The aim of the PyCS3 software is to measure time delays between such curves.
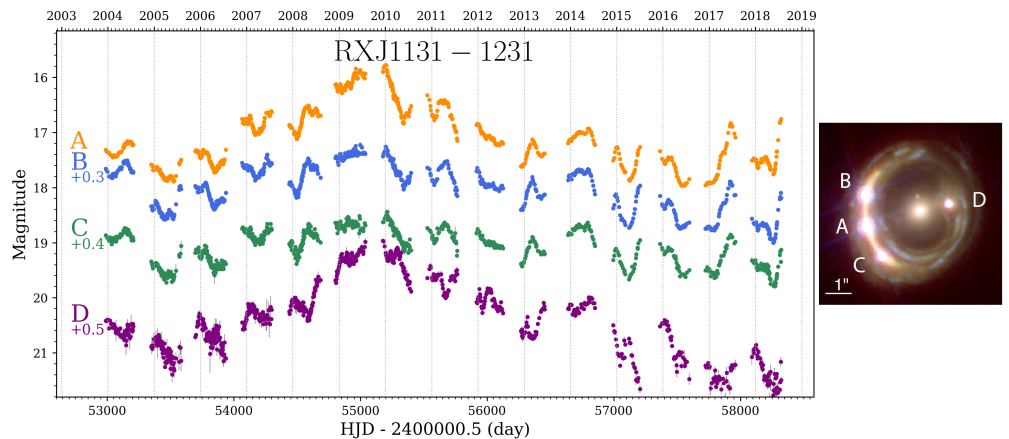
Figure 1: Light curves of the lensed quasar RXJ1131-1231 presented in M. Millon, Courbin, Bonvin, Paic, et al. (2020) (left panel). The same quasar variations can be seen in image D 92 days after in image A, whereas images A, B, and C arrive approximately at the same time. The right panel shows an Hubble Space Telescope image of RXJ1131-1231 (Suyu et al., 2017).

Statement of need

The "simple" problem of measuring time delays between irregularly sampled light curves has received attention for almost three decades (e.g., Press, Rybicki, & Hewitt, 1992). A complicating factor is the microlensing of the multiple images which happens when stars in the lens galaxy are passing in front of the quasar images, also acting as gravitational lenses and affecting the shape of the light curves. Microlensing effects perturb the light curve of each quasar image individually. Ignoring these perturbations would often result in significant biases on the measured time delays, that directly propagate to the Hubble Constant.

PyCS3 is a python package developed by the COSMOGRAIL collaboration and designed to address this problem. It allows us to measure time delays in lensed quasars in the presence of microlensing by providing a flexible and data-driven model of the "extrinsic" variations with splines to account for microlensing and recover an accurate estimate of the time delays. A realistic estimation of the uncertainties is also extremely important for cosmography. The approach followed by PyCS3 is based on best-fit point estimation and a framework to faithfully simulate the input data and assess the uncertainties following a Monte Carlo approach. While a Bayesian inference of the delay, given a model for quasar variability and microlensing, would be very attractive, it is hampered by the difficulty to accurately model microlensing and the high number of nuisance parameters in the problem.

The previous version of the package (PyCS) was first presented in Tewes et al. (2013) and successfully applied to real data in Tewes, Courbin, et al. (2013); Bonvin et al. (2017); Bonvin et al. (2018) and Bonvin et al. (2019). The method was also tested on simulated light curves of the Time-Delay Challenge (Bonvin et al., 2016; Liao et al., 2015) and was empirically shown to provide excellent results, even if the light curves are strongly affected by microlensing.

We have now developed an automated pipeline based on PyCS3 to measure time delays in a large sample of lensed quasars (M. Millon, Courbin, Bonvin, Buckley-Geer, et al., 2020; M. Millon, Courbin, Bonvin, Paic, et al., 2020). Such improvements toward automation of the procedure is necessary with the hundreds of new lensed quasars expected to be discovered in the near future.

Functionality

The basic functionality of PyCS3 is built around a LightCurve class to manipulate photometric monitoring data. It has methods to import, shift, fit and export light curves. These are located in the `pycs3.gen` subpackage.

PyCS3 contains two time-delay estimators, namely the free-knot splines and the regression difference, that are in the `pycs3.spl` and `pycs3.regdiff` subpackages. These two estimators are fundamentally different and allows us to check the robustness of the measured time delays. The subpackage `pycs3.sim` is used to generate simulated light curves in order to estimate the uncertainties of the time-delay measurements. PyCS3 ensures that the simulated curves have the same constraining power than the original data which is crucial for a correct estimation of the uncertainties. These simulated curves can then be shifted with either the free-knot splines or the regression difference estimator.

The `script` folder contains a pipeline to automate the measurement of the time delays. The functions that are used by this pipeline are located in the `pycs3.pipe` subpackage. It automatically explores several set of estimator parameters, generates simulated light curves, returns the best fit value and the associated uncertainties before selecting and combining the different sets of estimator parameters. It also makes use of the subpackage `pycs3.tdcomb` to display and combine the final time-delay estimates. The details of the method can be found in M. Millon, Courbin, Bonvin, Paic, et al. (2020).

Finally, the `tdlmc_test` folder contains an ensemble of python scripts to apply PyCS3 on the simulated data generated for the Time-Delay Challenge (Liao et al., 2015). It provides a benchmark test framework to assess the precision and accuracy of the PyCS3's curve-shifting algorithms.

Acknowledgement

References

Bonvin, V., Chan, J. H. H., Millon, M., Rojas, K., Courbin, F., Chen, G. C. F., Fassnacht, C. D., et al. (2018). COSMOGRAIL. XVII. Time delays for the quadruply imaged quasar PG 1115+080. *Astronomy and Astrophysics*, *616*, A183. doi:10.1051/0004-6361/201833287

Bonvin, V., Courbin, F., Suyu, S. H., Marshall, P. J., Rusu, C. E., Sluse, D., Tewes, M., et al. (2017). H0LiCOW - V. New COSMOGRAIL time delays of HE 0435-1223: H_0 to 3.8 per cent precision from strong lensing in a flat ΛCDM model. *Monthly Notices of the Royal Astronomical Society*, *465*(4), 4914–4930. doi:10.1093/mnras/stw3006

Bonvin, V., Millon, M., Chan, J. H. H., Courbin, F., Rusu, C. E., Sluse, D., Suyu, S. H., et al. (2019). COSMOGRAIL. XVIII. time delays of the quadruply lensed quasar WFI2033-4723. *Astronomy and Astrophysics*, *629*, A97. doi:10.1051/0004-6361/201935921

Bonvin, V., Tewes, M., Courbin, F., Kuntzer, T., Sluse, D., & Meylan, G. (2016). COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses. XV. Assessing the achievability and precision of time-delay measurements. *Astronomy and Astrophysics*, *585*, A88. doi:10.1051/0004-6361/201526704

Liao, K., Treu, T., Marshall, P., Fassnacht, C. D., Rumbaugh, N., Dobler, G., Aghamousa, A., et al. (2015). Strong Lens Time Delay Challenge. II. Results of TDC1. *The Astrophysical Journal*, *800*, 11. doi:10.1088/0004-637X/800/1/11

Millon, M., Courbin, F., Bonvin, V., Buckley-Geer, E., Fassnacht, C. D., Frieman, J., Marshall, P. J., et al. (2020). TDCOSMO II: 6 new time delays in lensed quasars from high-cadence monitoring at the MPIA 2.2m telescope. *arXiv e-prints*, arXiv:2006.10066. Retrieved from http://arxiv.org/abs/2006.10066

Millon, M., Courbin, F., Bonvin, V., Paic, E., Meylan, G., Tewes, M., Sluse, D., et al. (2020). COSMOGRAIL. XIX. Time delays in 18 strongly lensed quasars from 15 years of optical monitoring. *Astronomy and Astrophysics*, *640*, A105. doi:10.1051/0004-6361/202037740

Press, W. H., Rybicki, G. B., & Hewitt, J. N. (1992). The Time Delay of Gravitational Lens 0957+561. I. Methodology and Analysis of Optical Photometric Data. *The Astrophysical Journal*, *385*, 404. doi:10.1086/170951

Riess, A. G. (2019). The expansion of the Universe is faster than expected. *Nature Reviews Physics*, *2*(1), 10–12. doi:10.1038/s42254-019-0137-0

Suyu, S. H., Bonvin, V., Courbin, F., Fassnacht, C. D., Rusu, C. E., Sluse, D., Treu, T., et al. (2017). H0LiCOW - I. H_0 Lenses in COSMOGRAIL's Wellspring: program overview. *Monthly Notices of the Royal Astronomical Society*, *468*(3), 2590–2604. doi:10.1093/mnras/stx483

Tewes, M., Courbin, F., & Meylan, G. (2013). COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses. XI. Techniques for time delay measurement in presence of microlensing. *Astronomy and Astrophysics*, *553*, A120. doi:10.1051/0004-6361/201220123

Tewes, M., Courbin, F., Meylan, G., Kochanek, C. S., Eulaers, E., Cantale, N., Mosquera, A. M., et al. (2013). COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses. XIII. Time delays and 9-yr optical monitoring of the lensed quasar RX J1131-1231. *Astronomy and Astrophysics*, *556*, A22. doi:10.1051/0004-6361/201220352

Wong, K. C., Suyu, S. H., Chen, G. C. F., Rusu, C. E., Millon, M., Sluse, D., Bonvin, V., et al. (2020). H0LiCOW XIII. A 2.4% measurement of H_0 from lensed quasars: 5.3σ tension between early and late-Universe probes. *Monthly Notices of the Royal Astronomical Society*. doi:10.1093/mnras/stz3094