Strong Gravitational Lensing in the Era of Big Data
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Time Delay Cosmograpy of SDSSJ1433 with the 2.1m Wendelstein Telescope

G. Queirolo

Universitäts-Sternwarte, Fakultät für Physik, Ludwig-Maximilians Universität München,
Scheinerstr. 1, 81679, München, Germany
Max Planck Institute for Extraterrestrial Physics,
Giessenbachstrasse 1, 85748 Garching, Germany. email: queirolo@usm.lmu.de

Abstract. Time delay cosmography is based on the study of multiply gravitationally lensed images of a variable source. Their time delay differences are linearly dependent on the Fermat potential differences at the images' positions and the Hubble parameter, whose exact value is to this date strongly debated in the framework of the *Hubble tension*. In this paper we present the study of SDSSJ1433, a quadruply lensed QSO, the time delays of which have been obtained after a 3-year observational campaign from the 2.1m Wendelstein telescope in the optical g' filter, and the corresponding mass model was constrained from multi-band archival *HST* observations. The resulting H_0 value is $77.4\frac{km}{s\,Mpc}$ with a precision of $\sim 6\%$.

Keywords. Gravitational lensing, cosmology, galaxies, Hubble constant

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1. Introduction

Strong gravitational lens systems offer the opportunity to measure gravitationally induced time delays in intrinsically varying sources. By combining these delays with mass-modelled Fermat potentials, the Hubble parameter can be constrained (Refsdal (1964)). The precision of individual systems depends on the modelling choices of lens features, source variability, photometric precision and cadence of the monitoring. Thus it can vary, in the best cases, between 2.5% and 10%. A combination of 7 such systems yielded a formal Hubble constant error of 2.4% and a value of $73.3\frac{km}{s\,Mpc}$ (Wong, et al. (2020)). Hubble parameter estimates can be made more accurate if profiles of elliptical galaxies (fulfilling the selection function of strong lensing systems) are known more precisely and if the numbers of such systems with accurate time delay measurements can be increased.

Therefore this project, following the path of the **H0LiCOW** collaboration, was envisioned to study the system SDSSJ1433+6007, a quadruply lensed QSO, and further test the methodology by following an independent implementation.

2. Lensing Model

To constrain the differences of Fermat Potential between the images' positions I and J, $\Delta\phi_{\mathrm{IJ}}$, the python library **Lenstronomy** (Birrer and Amara (2018)) was applied to *HST* archival observations in multiple filters; the modelling was done independently for each filter, given the same prior, and the posterior on $\Delta\phi_{\mathrm{IJ}}$ were combined by multiplying their likelihoods (see Figure 1 and Table 1).

Table 1. Results for the difference of Fermat potential $\Delta\phi$ and the time delay Δt at the images' position (mean and 1-σ).

	$\Delta\phi$	Δt
AB	$0.43^{0.02}_{0.04}$ arcsec^2	22.3±2.2 d
AC	$0.63^{0.03}_{0.04}$ arcsec^2	33.7±2.5 d
AD	$1.48^{0.06}_{0.1}$ arcsec^2	81.1±3.5 d

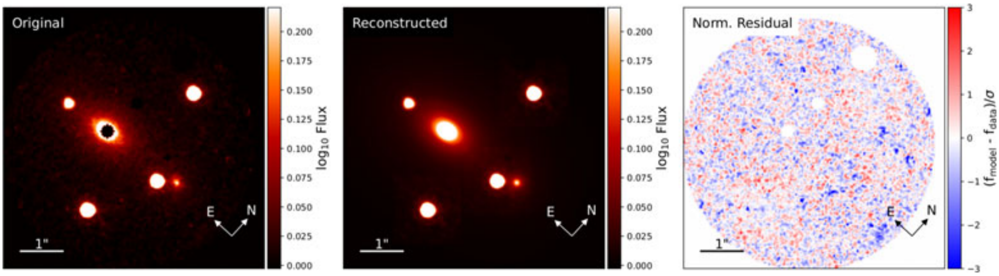
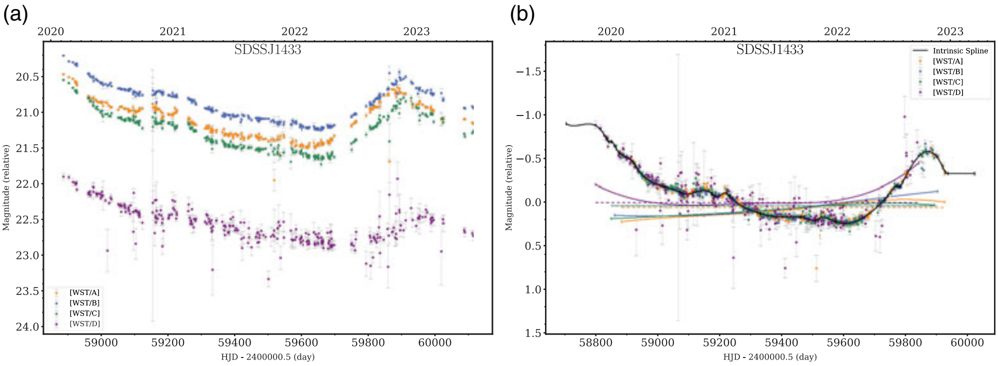


Figure 1. *HST* observation of SDSSJ1433 in the optical filter F814W, with the corresponding lens model and its residual.



Observed lightcurves from *WST*

Spline-fitted lightcurves with **PyCS3**

Figure 2. Time delay analysis of the lightcurves observed from *WST* with spline fitting.

3. Time Delay Measurement

The system was observed from the Wide Field Imager of the 2.1m Wendelstein Telescope (*WST*), surveying the QSO for over 3 years in the g' band. The final dataset is comprised of over 300 nights with an average cadence of 4 days and a median PSF of 1.07". Using our data reduction (Kluge, et al. (2020)) and difference imaging pipelines (Gössl and Riffeser (2002)) the lightcurves were obtained and then analysed with **PyCS3** (Millon, et al. (2020)) utilising the spline fitting method (see Figure 2).

4. H_0 Estimate

$P(H_0 \,|\, \Delta t_{\mathrm{IJ}}, \Delta\phi_{\mathrm{IJ}})$, the posterior on H_0 given the time delay posterior $P(\Delta t_{\mathrm{IJ}})$ and the Fermat potential difference posterior $P(\Delta\phi_{\mathrm{IJ}})$, is computed following Bayes' theorem. This yields the following equation:

$$P(H_0 \,|\, \Delta t_{\mathrm{IJ}}, \Delta\phi_{\mathrm{IJ}}) = \int d\Delta\phi_{\mathrm{IJ}} P(\Delta\phi_{\mathrm{IJ}}) \frac{P_{\Delta t\,\mathrm{map}}(\Delta\phi_{\mathrm{IJ}} \,|\, H_0) Prior(H_0)}{\int dH_0' P_{\Delta t\,\mathrm{map}}(\Delta\phi_{\mathrm{IJ}} \,|\, H_0')}$$

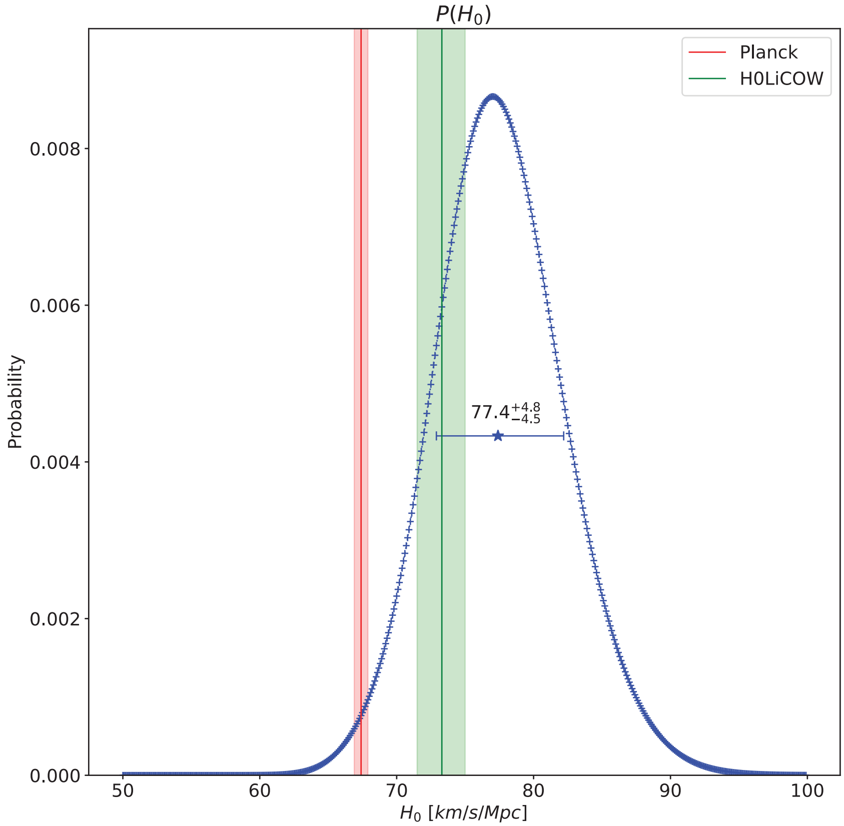


Figure 3. H_0 posterior compared with two characteristic results of the Hubble tension: Planck (Planck Collaboration (2020)) and H0LiCOW (Wong, et al. (2020)).

where $P_{\Delta \mathrm{t\,map}}(\Delta\phi_{\mathrm{IJ}} \,|\, H_0)$ is $P(\Delta t_{\mathrm{IJ}})$ which has been mapped into the $\Delta\phi_{\mathrm{IJ}}$ parametric space by assuming a value of H_0. This is then normalised over all possible values of H_0 and multiplied by $P(\Delta\phi_{\mathrm{IJ}})$, the posterior on $\Delta\phi_{\mathrm{IJ}}$ obtained from the lens modelling, and integrated over all $\Delta\phi_{\mathrm{IJ}}$. Finally a flat prior $Prior(H_0)$ is considered. Following this approach, the preliminary constraint on the Hubble constant yields $77.4\frac{km}{s\,Mpc}$ with a precision of $\sim 6\%$ (Queirolo, et al. (in prep.)) (see Figure 3). This computation assumes a flat ΛCDM and fixed, error free value of $\Omega_m = 0.30966$, in agreement with the cosmological result of the Planck Collaboration (2020). Possible biases, which are yet to be investigated, may arise from an unaccounted mass sheet degeneracy (Schneider and Sluse (2013)) or equivalently the assumed mass profile slope (Birrer, et al. (2020)).

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