LENSED QUASARS TO BE OBSERVED BY LSST, ZTF AND JWST

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ABSTRACT

When the source in strong gravitational lensing systems is time-variable, measuring the time delay between different images is possible, allowing for a tool to constrain the Hubble constant, H_0, which is currently a subject of tension in cosmology. The present paper informs about the ability of the Large Synoptic Survey Telescope (LSST), the Zwicky Transient Facility (ZTF) and the James Webb Space Telescope (JWST) to observe lensed quasars. We develop a Monte Carlo simulation using the mass-luminosity distribution function of galaxies and the redshift distributions of galaxies and quasars to estimate the rate of lensed quasars observed by them. Further on, adopting a singular isothermal sphere (SIS) model for lens galaxies, we calculate the time delay between lensed images.

***Keywords*:** strong gravitational lensing, cosmological parameters, time delay

1. INTRODUCTION

Strong gravitational lensing (SGL) by galaxies, since the first proposal by Zwicky (1937), plays today an extremely relevant role for the comprehension of the formation and evolution of the structures in the universe, the measure of the parameters of the so-called cosmological standard model, and the testing alternative gravity theories (Collett *et al.*, 2018, and references therein). In particular, SGL of a background quasar by a galaxy occurs when a galaxy happens to be closely aligned along the line of sight to the distant quasar and then splits its light into multiple and distinct (i.e. resolved by a telescope) images. Since the light of these images follows different paths, the intrinsic variations of the source are shown at different times in each image. A time delay could be measured by comparing the different light curves and used to independently constrain the cosmological parameters.

The present paper considers the strong lensing of quasars by foreground galaxies. Quasars are very powerful and bright distant galaxies with an active galactic nucleus (AGN). Being very far and with extremely high intrinsic luminosity, they are considered important instruments for discovering the content and the history of the Universe. The first extragalactic gravitational lens, namely the quasar *QSO 0957+561*, was accidentally discovered in 1979 by Walsh *et al*., (1979). Today, the search for gravitationally lensed quasars has increased, and a more efficient methodology is used. By different surveys as the Cosmic Lens All Sky Survey (CLASS) in (Myers *et al*., 2003), or the Sloan Digital Sky Survey (SDSS) in (York *et al*., 2000) are provided huge amounts of photometric and spectroscopic data which greatly help to find gravitationally lensed quasars. They could be double, triple and quadruple systems. Strong lensed quasars are a means to address: i) the total mass within the Einstein radius; since the gravitational lensing is sensitive to all matter, it can be used to study the distribution of the dark matter; ii) the mass profile slope of lenses, iii) the features of the source, and iv) the cosmological parameters, in particular the Hubble constant, H_0. The last one is a fundamental parameter of current cosmological models, because it describes the actual expansion rate of the Universe, and because it sets the scale of extragalactic distances. Today, there is a tension about the value of H_0, as different results are found by different methods. Recently, the gravitational lensing of quasars is used to constrain the Hubble constant. Its determination requires a variety of observational data, and the time delay between images is very important, among them (Suyu et al., 2018, for more details).

The present paper informs about the Vera C. Rubin Observatory which is referred to as the Large Synoptic Survey Telescope (LSST), the Zwicky Transient Facility (ZTF)— ground-based telescopes— and the James Webb Space Telescope (JWST) is provided. We estimate the probability that a quasar observed by them is strongly lensed by a foreground galaxy. LSST is being constructed on top of the Cerro Pachón in Northern Chile and is scheduled to begin science operations in 2024[1]. It will observe 18,000 deg^2 of sky in six passbands over 10 years and the median free-air seeing is about *0.7 arcsec* in the *r* band (Zhan and Tyson 2018), which is also its typical angular resolution. ZTF is a new survey that had its first light at Palomar Observatory in 2017. ZTF uses a new camera with a $47deg^2$ field of view to scan more than 3750 deg^2 in one hour to a depth of about 20.5 *mag*. The median seeing of ZTF is about *1arcsec* (the angular resolution). JWST was launched on December 24, 2021 towards the second Lagrange point (L2) of the Earth-Sun

[1] https://www.lsst.org

system. It is optimized for observations in the near and mid infrared and has high angular resolution, about 0.1 arcsec.

Section 2 describes the methodology used and in Section 3 we show the results of its application in the case of the three instruments. Our conclusions are presented in Section 4.

2. METHODOLOGY

We have developed a Monte Carlo algorithm to simulate the strong lensing of quasars by a foreground galaxy (Hamolli *et al*.,). For each event, we generate the redshift of the quasar, z_S (Schneider *et al*., 2005), the redshift of the galaxy, z_L (Appenzeller *et al*., 2004) provided that it is smaller than the quasar redshift, extract the galaxy mass using the stellar mass function (Davidzon *et al*., 2017) and find its velocity dispersion σ from the relation between the galaxy's stellar mass and stellar velocity distribution (Zahid *et al*., 2016). Using the SIS model for galaxies (Schneider *et al*., 2006), we define Einstein angle θ_E for each quasar/galaxy pair, given by:

$$\theta_E = \frac{4\pi\sigma^2}{c^2}\frac{D_{LS}}{D_S} \tag{1}$$

where D_L, D_S, D_{LS} are the observer-lens, observer-source and lens-source angular diameter distances, respectively. Assuming a flat Universe ($\Omega_k = 0$), the three relevant angular diameter distances can be respectively expressed as (Liao, 2019):

$$D_L = \frac{c}{H_0(1+z_L)}\int_0^{z_L}\frac{dz}{E(z)}; \qquad D_S = \frac{c}{H_0(1+z_S)}\int_0^{z_S}\frac{dz}{E(z)};$$
$$D_{LS} = D_S - \frac{(1+z_L)}{(1+z_S)}D_L; \tag{2}$$

$$E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}$$

Here, H_0 is Hubble constant and Ω_m , Ω_k , Ω_Λ are the dimensionless density parameters, i.e., the sum of the cold dark matter and baryonic matter, the space-curvature, and the dark energy, respectively.

For a single galaxy, the probability to reside inside the Einstein angle about the observer-quasar direction would scale as $\theta_E^2/4$. Since, Appenzeller *et al*., (2004) give the redshift distribution of 7000 galaxies, we normalize the probability considering the whole number of galaxies, 200 billion, and find

$10^8\theta_E^2/14$. We compare this number with a number n, uniformly distributed in the interval (0,1), which is extracted by the Monte Carlo code. We keep this pair when its probability is smaller, otherwise we reject it. The procedure is repeated for all expected quasars to be observed by the telescope. For each aligned system, we solve the lens equation, $\theta - \beta = \theta_E \frac{|\theta|}{\theta}$ (Congdon 2018) and find the positions of the images: $\theta_1 = \beta + \theta_E$ and $\theta_2 = \beta - \theta_E$. Here, β is the angular source position. The time delay between two lensed images is calculated by:

$$\Delta t_{1,2} = \frac{1+z_L}{2c}\frac{D_L\, D_S}{D_{LS}}\left[\theta_1^2 - \theta_2^2\right]. \tag{3}$$

A quasar would be lensed by a foreground galaxy if the Einstein angle of the system is higher than the angular accuracy of the considered instrument. In our calculations we use the following cosmological parameters: $\Omega_m = 0.3$, $\Omega_k = 0$, $\Omega_\Lambda = 0.70$ and $H_0 = 70\frac{km}{s\cdot Mpc}$.

This algorithm has been tested for the SDSS and Chandra observations (Hamolli *et al*., 2021).

3. RESULTS

The aforementioned algorithm is used to investigate the possibility of observing lensed quasars by LSST, ZTF and JWST telescopes. If the image separation which is of the order of the Einstein angle, is higher than the accuracy of the telescope, we can assume that a strong lensing event is detectable by the telescope. By these simulations we find, in the case of LSST telescope with the angular accuracy 0.7 arcsec, the expectation that one quasar in 1100 observed ones will appear lensed by a foreground galaxy. In the case of the ZTF with the angular accuracy of 1 arcsec, we find that one quasar in 2800 observed quasars will appear lensed, whereas for the JWST telescope with the angular accuracy 0.1arcsec, we find that one quasar in 160 observed quasars will appear lensed.

In Figure 1 are plotted the predictions for the redshift distributions of the lenses (galaxies) and sources (quasars) in strong lensing events observed by ZTF, LSST and JWST telescopes. As can be seen, in all considered observations the redshift of galaxies is approximately smaller than 1, while the redshift of quasars goes up to 5.

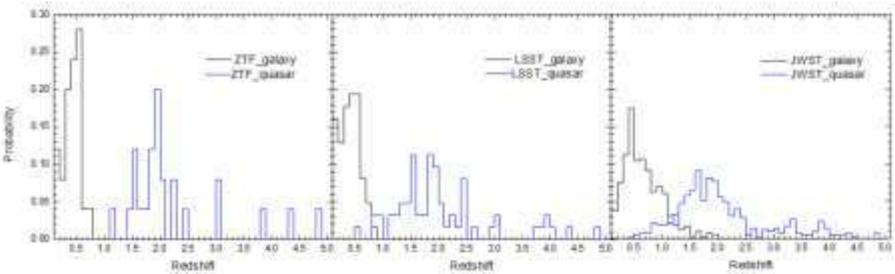

Fig. 1: Redshift distribution of the lens galaxies (black line) and source quasars (blue line) in simulated strong gravitational lensing events expected to be observable by ZTF (left panel), LSST (central panel) and JWST (right panel).

For each couple of images expected to be observed, we calculate the time delay between them, following the equation (3). Figure 2 depicts the time delay distributions of these strong lensing events. We see that the time delay spans a large range, from the order of hours to years, and the most frequent value of time delay is around 10 days in the case of JWST, and around 100 for the two other telescopes.

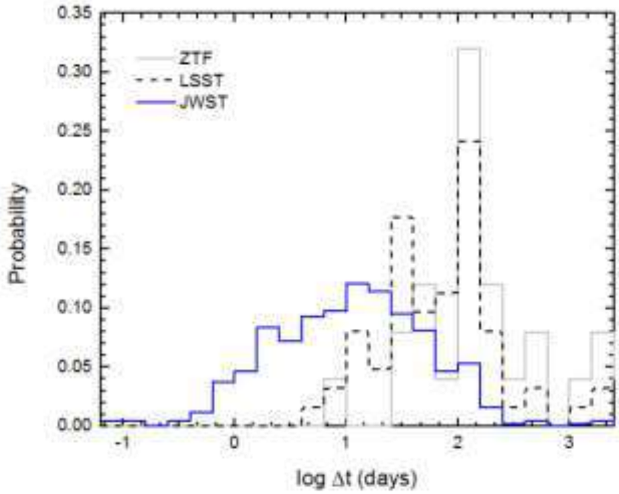

Fig. 2: Time delay distribution of the strong gravitational lensing events expected to be observable by ZTF (grey line), LSST (dashed black line) and JWST (blue line).

4. CONCLUSIONS

Today there is a discrepancy in the reported measurements of H_0 by different methods. A useful possibility for its determination is the measurement of the time delay in strong lensing systems. Until now more than

200 lensed quasars are known[2], and this number is expected to grow by forthcoming surveys, such as the LSST, Euclid and Roman space telescope.

In the case of the LSST, since it will observe 10^7 quasars (Zhan and Tyson, 2018), we predict that about 9000 quasars should appear lensed by a foreground galaxy. This sample offers a remarkably good opportunity for cosmology. This is consistent with the results obtained (Oguri and Marshall, 2010).

We also calculate the time delay between lensed images, which could be measured in case when the sources are time-variable. We find that the most frequent value of time delays is around 10 days in the case of JWST and around 100 for the two other telescopes. These results offer an argument in planning the quasars surveys to constrain cosmological parameters and especially H_0.

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[2] https://research.ast.cam.ac.uk/lensedquasars/

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