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Double gravitationally lensed quasar J1721+8842 observed at the Maidanak observatory

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This paper presents the results of observations and the light curve of the unique doubly gravitationally lensed quasar J1721+8842, observed at the Maidanak observatory from 2018 to 2024. It also includes the results of best image reduction using a deconvolution method that separates 6 lensed point-like images. Based on recent observations from space telescopes and related studies, a lensing model for quasar J1721+8842 involving two lensing galaxies is proposed. This two-lens model accounts for the formation of 6 point-like lensed images of the distant quasar, as well as the appearance of red arc-like structures, which result from the lensing of a distant red galaxy by a closer elliptical galaxy.

Keywords: Gravitational lensing, deconvolution, modeling

1 Introduction

Gravitationally lensed quasars (GLQs) are rare and unique cosmic objects formed as a result of strong gravitational lensing. In a GLQ, light from a distant quasar is deflected by the gravitational field of a foreground galaxy, producing multiple images of the quasar. This phenomenon may also give time delays between the images and microlensing effects. GLQs enable direct measurements of cosmological distances and the Hubble constant H0. The potential for using gravitational lensing to measure cosmic distances was first proposed by Refsdal (1964).

GLQs typically produce two lensed images, and more rarely, four – the latter often referred to as an Einstein Cross. The formation of such systems requires near-perfect alignment between a distant, sufficiently bright quasar and a foreground lensing galaxy along the observer's line of sight.

The GLQ J1721+8842 is an even more unique object, as it consists of six lensed images. It was initially discovered as a quadruple imaged quasar at redshift $zs = 2.38$ by Lemon et al. (2018). Subsequently, two additional images were identified using

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Gaia and Pan-STARRS data, leading to its interpretation as a doubly lensed active galactic nucleus (Lemon et al. 2022, Mangat et al. 2021).

However, recent work by Dux et al. (2025) has shown that all six images originate from a single quasar at redshift $z = 2.382$. This configuration is explained by the presence of a second lensing galaxy at redshift $z2 = 1.885$, in addition to the previously known lensing galaxy at $z1 = 0.184$. The second lens was previously interpreted as the host galaxy of the quasar – possibly involved in a post-merger scenario that could eject black holes proposed by Mangat et al. (2021).

2 Observations

Observations of the gravitationally lensed quasar J1721+8842 were carried out at the Maidanak Observatory using the 1.5-meter AZT-22 telescope from 2018 to 2024. Image data were acquired with a SI-4K×4K CCD camera using an R filter, with exposure times of 180 or 300 seconds, resulting in 10 or 5 frames per observation night, respectively. Figure 1 shows a part of the observation frame, with the target object marked at the center and five reference stars used for comparison.

Based on the results of comprehensive data reduction performed in the IRAF environment for astronomical image processing, the overall variability light curve of GLQ J1721+8842 was obtained for the observation period from May 25, 2018, to July 19, 2024. Differential photometry was conducted using a measurement aperture of 30 pixels (approximately 8″), relative to the mean magnitude of five selected comparison stars. Root-mean-square (RMS) photometric errors were also calculated. The resulting light curve of J1721+8842 in Fig. 2 shows characteristic optical variability, with a general amplitude of approximately 0.3 Mag.

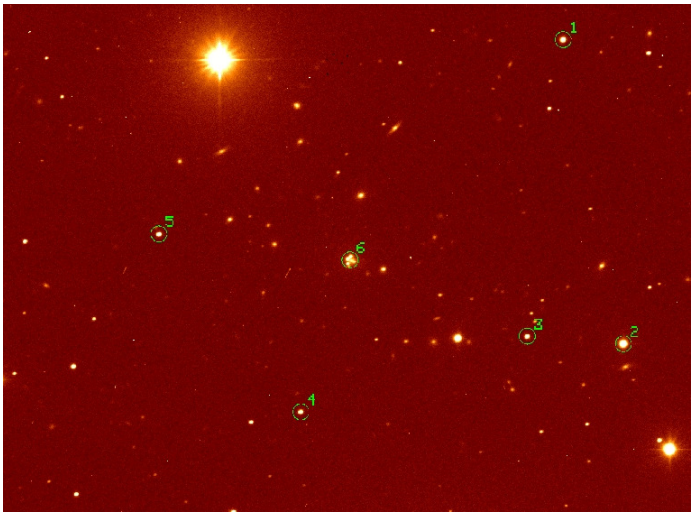


Figure 1 The region of the stellar field of observations of GLQ J1721+8842 with the 1.5-m telescope AZT-22 of the Maidanak observatory.

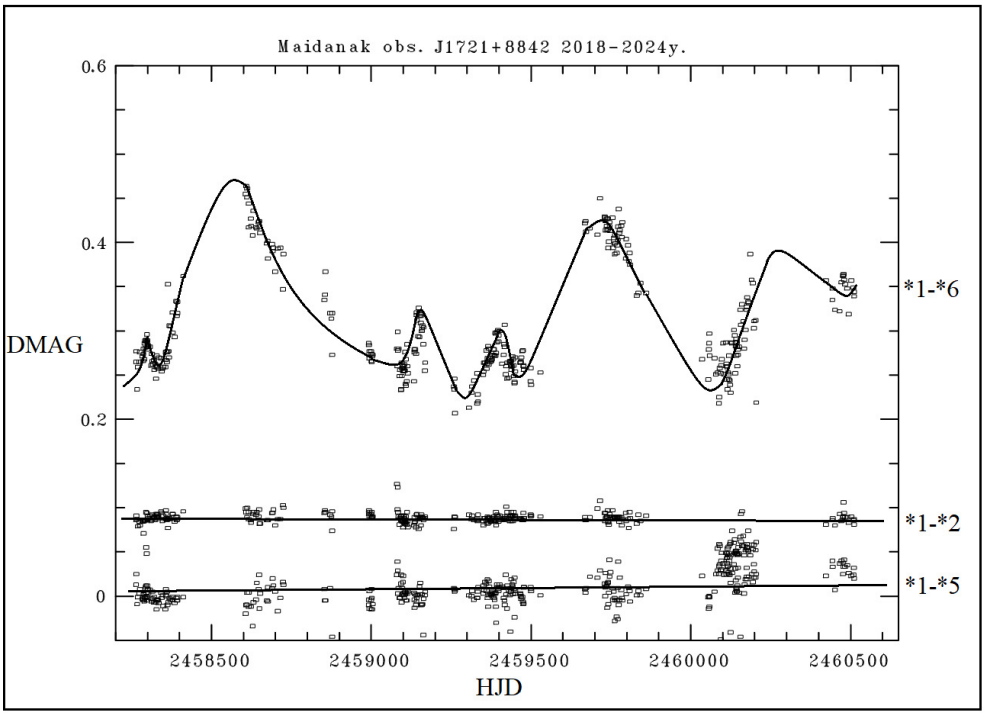


Figure 2 Overall light curve of GLQ J1721+8842 based on observations from the Maidanak Observatory during the period 2018–2024.

For further data reduction and separation of the individual lensed images of GLQ J1721+8842, the MCS deconvolution method was applied (Magain et al. 1998). This method enables the separation of lensed components by utilizing the best-quality observational data, with seeing conditions of 0.6–0.7″, and achieves high angular resolution with a full width at half maximum (FWHM) of 0.266″. Figure 3 shows the results of MCS deconvolution applied to GLQ J1721+8842 best image from Maidanak, along with a comparison with the corresponding Hubble Space Telescope (HST) image.

The separation of the lensed images of J1721+8842 using the MCS method enables the extraction of individual light curves for comparison, the identification of microlensing effects, and the calculation of time delays. Based on the MCS deconvolution of all observational data, light curves for all six lensed images of J1721+8842 are being constructed. These light curves, combined with data from other observatories, will be used to derive time delay values with high precision. Ongoing collaborative work on the comprehensive analysis of GLQ SDSS J1721+8842 is being conducted with colleagues from the Astrophysics Laboratory at EPFL (Switzerland).

3 Modeling

The initial studies of GLQ J1721+8842 by Lemon et al. (2018) showed that the quadrupole configuration, consisting of four bright lensed images A, B, C, and D, is at a redshift of 2.38. Subsequent spectroscopy revealed that image E is also at the same redshift (Lemon et al. 2018). For image F, no direct redshift measurements were available, and it was assumed to be part of a lensed doublet FE, possibly originating from the second component of a double quasar.

It is important to note that these analyses were based only on ground-based data. The red arcs near images F and E were discovered later in data from the Hubble Space Telescope (HST) and are marked as G2 in Fig. 3. However, the redshift of these arcs was initially unknown, and all previous lensing models of GLQ J1721+8842 assumed the presence of a single lensing galaxy (G1) and a single lens plane.

However, thanks to recent observations with the JWST/NIRSpec space telescope (Jakobsen et al. 2022), this hypothesis has finally been tested. The spectrum of part of the lensed arc G2 allowed the redshift to be determined as $z2 = 1.885 \pm 0.001$. This value does not match the redshift of the quasar, which was also determined from NIRSpec data as $ZQSO = 2.382 \pm 0.002$. Thus, the lensed arc is not a distant host galaxy of a second quasar, as previously assumed. Instead, it is a separate galaxy, G2, which is itself lensed and split into two arcs near images F and E by the foreground central lensing galaxy G1 at $z1 = 0.184$.

At the same time, G2 also acts as an intermediate lens for the quasar's light. Remarkably, the redshift $Z2 = 1.885$ of the red lensing galaxy G2 makes it the most distant spectroscopically confirmed lensing galaxy known to date. The previous most distant lens galaxy was found at $Z = 1.62$ for a galaxy in a cluster (Wong et al. 2014).

A schematic diagram illustrating the principle of multiple image formation is shown in Fig. 4, while Fig. 5 shows a 3D visualization of the light optical paths involved in the formation of GLQ J1721+8842. The first lensing of the point-like dis-

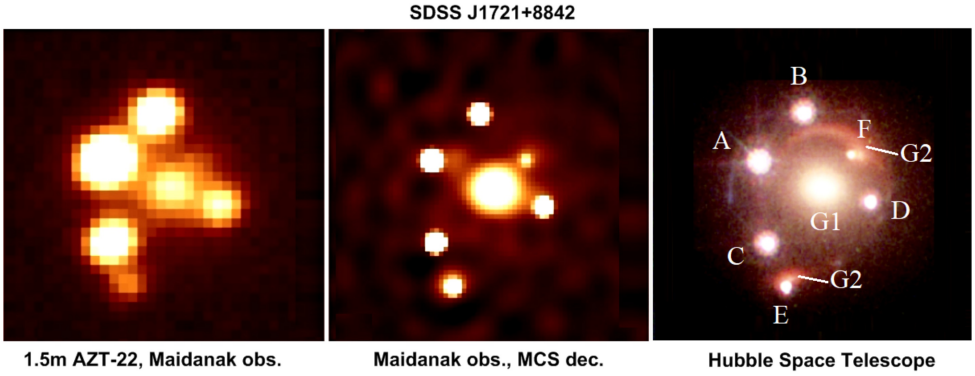


Figure 3 Left – Image of the gravitationally lensed quasar J1721+8842 obtained at the Maidanak Observatory under optimal observing conditions. Center – Result of image reduction using the MCS deconvolution method. Right – Comparison with the image from the Hubble Space Telescope (HST).

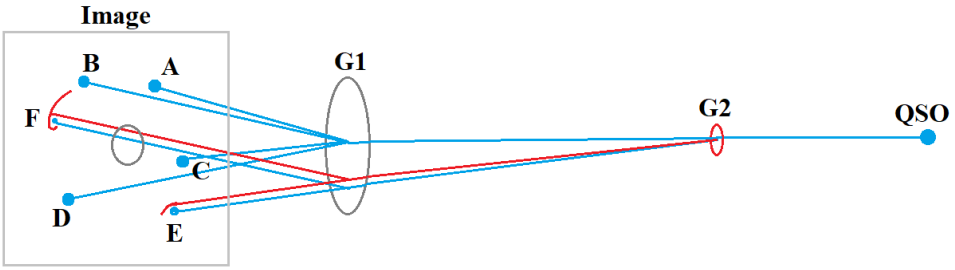


Figure 4 Schematic illustration of the formation of multiple images of the distant quasar (QSO) in GLQ J1721+8842 as a result of twice gravitational lensing by two galaxies, G2 and G1.

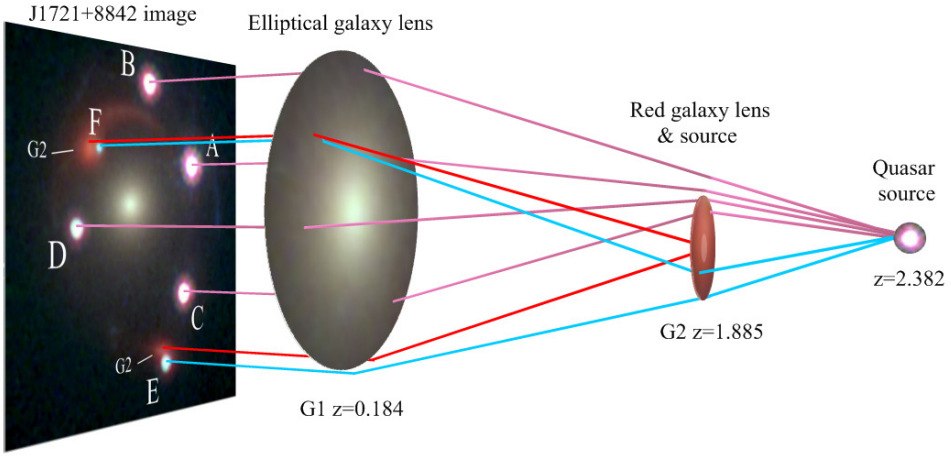


Figure 5 3D visualization of the light optical paths leading to the formation of the lensed images of GLQ J1721+8842. The light from the distant quasar is first split by the lensing galaxy G2 into two groups, which are then secondarily lensed by galaxy G1, forming in the observer's plane images A, B, C, D and E, F respectively. The light from galaxy G2 is also lensed by galaxy G1, forming images of two red arcs.

tant quasar at $z = 2.382$ (corresponding to 10.759 Gyr*) occurs on the red galaxy G2 at $z = 1.885$, producing two groups of light rays. One group (indicated in pink), after being further lensed by the elliptical galaxy G1 at $z = 0.184$, forms the quadruply lensed image configuration ABCD in the observer's plane. The second group (rays marked in blue) forms the doubly lensed configuration EF. Meanwhile, light from the red lensing galaxy G2 is also lensed by galaxy G1, forming an extended arc and a smaller arclet (G2) in the observer's plane, located near images F and E, respectively.

The redshift time conversion is based on the standard flat ΛCDM cosmological model with $H_0 = 70$ km/s/Mpc and $\Omega = 0.3$ (https://www.astro.ucla.edu/wright/CosmoCalc.html).

Thus, the unique observed configuration of GLQ J1721+8842 – consisting of the quadruple lensed images ABCD and the doubly lensed images EF of the distant quasar – is the result of double lensing by galaxies G2 and G1. Additionally, the light from the lensing galaxy G2 is itself lensed and distorted by G1, forming an extended arc near image F and a small arclet near image E of the lensed quasar.

Statistical calculations by Collett and Bacon (2016) have shown that the probability of forming such compound double-lens systems at z more than 2, resulting in six images, is approximately 10^{-8}. In other words, such a doubly lensed GLQ is expected to observe only once in every 100 million cases. However, only about 300 lensed quasars are currently known (Lemon et al. 2023), among which is GLQ J1721+8842. It is important to consider, though, that the magnification effect caused by lensing from two galaxies can significantly enhance the brightness, potentially increasing the detection probability of such systems by a factor of 100. As a result of recent large-scale sky surveys, billions of galaxy images have been collected, among which this unique doubly lensed quasar, GLQ J1721+8842, was discovered.

In the future, after a more detailed analysis of the obtained preliminary results, the parameters of the gravitational potentials will be calculated, and numerical simulations of the model will be performed taking into account the two lensing galaxies. Additionally, the analysis of long-term photometric observations will make it possible to detect microlensing effects, estimate the time delay in J1721+8842, and determine the Hubble constant.

4 Conclusions

As a result of observations of the gravitationally lensed quasar GLQ J1721+8842 at the Maidanak Observatory during 2018–2024, an overall light curve was obtained, demonstrating significant optical variability of the quasar with amplitude of up to 0.3 magnitudes. Image reduction using the MCS deconvolution method on the best-quality frame from Maidanak enabled the separation of six individual lensed images of J1721+8842 and the central elliptical lensing galaxy.

Analysis of HST data and recent studies by Dux et al. (2025) made it possible to model and interpret the lensing physics of GLQ J1721+8842, in which the light from the distant quasar at $z = 2.382$ is first lensed by the red galaxy G2 at $z = 1.885$, and then lensed by the elliptical galaxy G1 at $z = 0.184$. This compound double lensing results in the formation of six distinct lensed images of the quasar (A, B, C, D, and E, F), while the galaxy G2 is itself lensed into two red arcs.

Based on these findings, compared by Dux et al. (2025) we tried to create a more visual and understandable schematic representation of the image formation mechanism, along with a 3D visualization model of the optical paths leading to the lensed components of GLQ J1721+8842.

Thus, GLQ J1721+8842 stands out as a unique system with two lensing galaxies aligned along a single line of sight – a rarity even among the ∼300 known strong gravitational lensing systems, which typically involve only one lensing galaxy. Ongoing collaborative analysis of 7–8 years observation data from the Maidanak Observatory and joint analysis with the EPFL Laboratory of Astrophysics (Switzerland) holds

promise for determining time delays, modeling microlensing effects, and estimating the Hubble constant (H0).

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