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Time delay estimation in GLQ B1422+231

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The data from a three-year monitoring of the gravitationally lensed quasar (GLQ) B1422+231 are analyzed. The results of photometric analysis are presented: light curves that indicate significant microlensing in the lensed components of the source, as well as the probable values of time delays between the three pairs of components: $\Delta t_{AB} = -52.4 \pm 3$ days, $\Delta t_{AC} = 14.2 \pm 2$ days and $\Delta t_{CB} = 48.4 \pm 2$ days.

Keywords: Gravitational lensing, individual: B1422+231, photometry, time delay

1 Introduction

The phenomenon of gravitational lensing is one of the most actively studied areas in modern astronomy. Research on gravitationally lensed systems (GLS) enables the exploration of related fundamental cosmological issues. For instance, it provides the opportunity for indirect observation and investigation of invisible matter, as well as for determining a number of cosmological parameters that have not yet been definitively established – such as the measurement of extragalactic distances, the refinement of the fine structure of galactic and quasar nuclei, and the discovery of new planets, protogalaxies, and forming galaxies, among others. In this regard, the study of GLS, including gravitationally lensed quasars (GLQ), is one of the most important tasks in modern astronomy and cosmology. Observational data on time delays, the nature of microlensing, and the parameters of the gravitational lens help shed light on a number of related cosmological and astrophysical problems. Specifically, through a combination of time delay measurements and modeling, we can obtain information about the geometry of the Universe; microlensing allows us to infer the presence and properties of dark matter both within lensing galaxies and in intergalactic space. Additionally, we can study their interstellar medium through dust absorption or through absorption lines that appear in the spectra of multiple images of the quasar, and so on (Kochanek et al., 2006).

However, in order to obtain the necessary information and use it for further analysis, it is essential to first have detailed and long-term data on light curves. On the

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other hand, such data is needed for as many lensed systems as possible, meaning that detailed statistics must be collected from a large number of such objects. In particular, the statistics of lensed quasars and the measurement of time delays between their lensed images provide researchers with physically meaningful constraints on cosmological parameters when constructing models (Turner, 1990).

2 Preliminary data on the study of B1422+231

The gravitationally lensed quasar B1422+231 is one of the least studied objects of its kind. It was discovered by Patnaik et al. (1992). Both optical and radio observations were carried out for this distant quasar with a redshift of $z_s = 3.62$, and it was first identified as a four-component system with a total apparent brightness of 16.5 mag (see Fig. 1). In the same year, infrared observations were also conducted. The processing of the observational data made it possible to identify the lensing galaxy in this system, whose redshift was found to be approximately $z_l \approx 1$ (Lawrence et al., 1992).

Optical observations confirmed previous findings, specifically identifying the four previously detected point-like sources and determining their brightness. Later, models were considered in which the lensing object was represented either as a combination of one galaxy with an isothermal sphere and two galaxies treated as point sources, or as a single isothermal ellipsoid. It was found that such models reproduce the gravitational lens system B1422+231 quite well. Later Yee & Ellingson (1996) once again attempted to determine more detailed parameters of the lensing galaxy. According to their analysis, the photometric properties of the system's components and the mass-to-light ratio of the galaxy suggest that it is likely an early-type galaxy with a redshift in the range of 0.4 to 0.8. A more precise estimate gives a redshift of $z_l = 0.647$. Photometric measurements of the system's total brightness in the R filter showed a combined magnitude of $M_{A+B+C+D} = 15.59 \pm 0.06$ mag, with individual component brightnesses: $A = 1.0$, $B = 1.52$, $C = 0.73$, $D = 0.037$. Microlensing in this system was first discussed in a paper by Hjorth et al. (1996), based on measurements and comparisons of the brightnesses of the components.

Subsequent photometric measurements revealed short-period variability of the quasar source in the gravitationally lensed quasar B1422+231 over the course of a single day. It was found that the flux ratios between the components in the optical and radio bands differ significantly, and the galaxy's color indices correspond to those of an elliptical galaxy with a redshift of approximately ~ 0.4. Further studies of the lensing galaxy showed that it is part of a compact galaxy cluster with a redshift of 0.338, a radius of $r_{\rm gr} = 35\ h^{-1}$ and a mass of $M = 1.4 \times 10^{13}\,(h^{-1}M_{\odot})$. Patnaik et al. (1992) measured the flux ratios between the components in several regions of the radio band and found significant discrepancies between the flux ratios in the optical, infrared, and radio ranges for component A. This can primarily be explained by the presence of microlensing (Patnaik & Porcas, 1998). In 2000, the time delays between the components of B1422+231 were measured for the first time by Patnaik & Narasimha (2001), and it was shown that the delays between the pairs were: $\Delta t_{BA} = 1.5 \pm 1.4$ days, $\Delta t_{AC} = 7.6 \pm 2.5$ days and $\Delta t_{BC} = 8.2 \pm 2.0$ days. According to model calculations, the time delay between components A and C is approximately

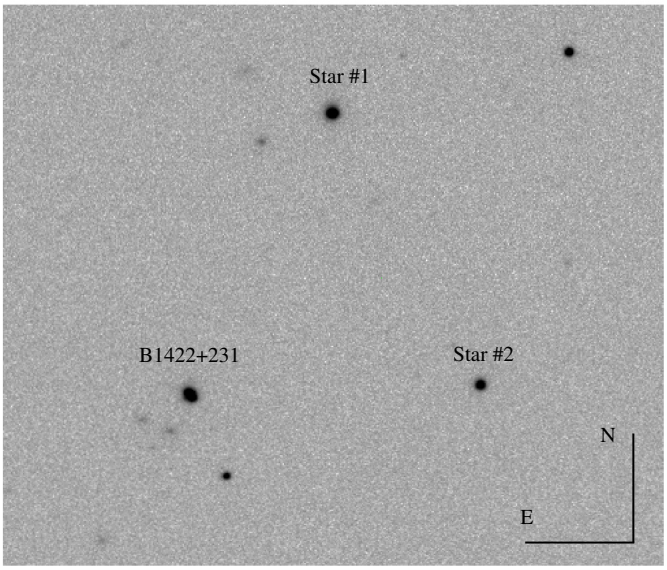


Figure 1 R-band CCD image of the GLQ B1422+231 obtained on May 17, 2003. The quasar images and the reference stars Star #1 and Star #2 are labeled. The field size is 2.8 arcmin × 3.5 arcmin.

$\sim$0.4 h^{-1}. In 2005, based on infrared observations of B1422+231, additional constraints were introduced regarding the structure of the lensing galaxy (Chiba et al. 2005). Akhunov (2018) attempted photometry and time delay estimation for this system and obtained delay values not exceeding one week between the three component pairs.

3 Light curves of the lensed components of B1422+231 and time delay

From the review of previous studies, it is evident that this gravitationally lensed quasar (GLQ) has been investigated quite extensively. However, due to the compact nature of the system (the maximum distance between components is approximately 1.3 arcsec), it is very difficult to achieve photometric resolution of the individual lensed components, and consequently, to obtain satisfactory light curves for them. Akhunov (2018) attempted photometric analysis of the components using the Galfit program (Peng , 2010). In that work, data from the years 2003–2008 in the R and V filters were processed. The brightness of the lensing galaxy is low, and its contribution to the flux of the lensed components can be considered negligible. The total brightness of the system showed noticeable variability (with an amplitude of about $\sim$0.25 magnitudes), which is associated with the intrinsic variability of the quasar source (Akhunov, 2018).

Here, we aim to present the light curves obtained using a completely different method proposed in Akhunov et al. (2017), which utilizes an adaptive numerical PSF fitting technique. The details of the corresponding photometric program used

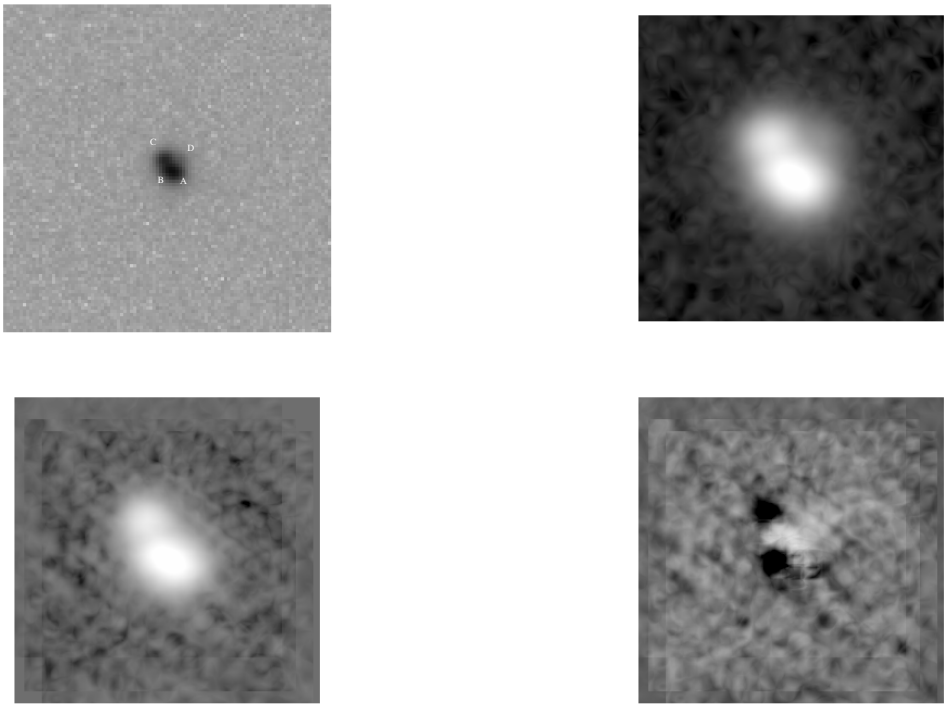


Figure 2 Results of the application of the adaptive PSF-fitting photometric method to our CCD frames. Left up: the original frame, zoom of the central part of B1422+231 in Fig. 1. The field size is 26.5 arcsec × 26.5 arcsec; Right up: 10-times pixelated and bi-cubic interpolated version of the original frame; Left down: the resulting adaptive PSF-fitting photometric model of the GLQ; Right down: the residual image between the real frame and the simulated one.

can also be found in Akhunov et al. (2024). A distinctive feature of the method described in Akhunov et al. (2017) is the use of interpolated observational data, which allows for an increase in the spatial resolution of the processed images (see Fig. 2). Left up panel shows the positions of the lensed components A, B, and C. The brightness of component D is too low to be visually detectable. Next is the spline-interpolated image. Following that are the interpolated image (Right up), the photometric model (Left down), and the residual (subtracted) image (Right down). It is evident that the resolution of the components has been visually enhanced; the model matches the observed configuration, as indicated by the clean residual image.

This method was applied to data from the years 2003–2005, and the resulting light curves are shown in Fig. 3. It can be seen that the components exhibit significant brightness variations, and these changes show only weak correlation with the overall brightness variations of the system. Specifically, in 2005, the brightness of the components increased by approximately 0.2 magnitudes. Microlensing, of course, plays a major role here as throughout all observing seasons from 2003 to 2005, the components behave differently from one another, and the differences in their brightness levels continuously change.

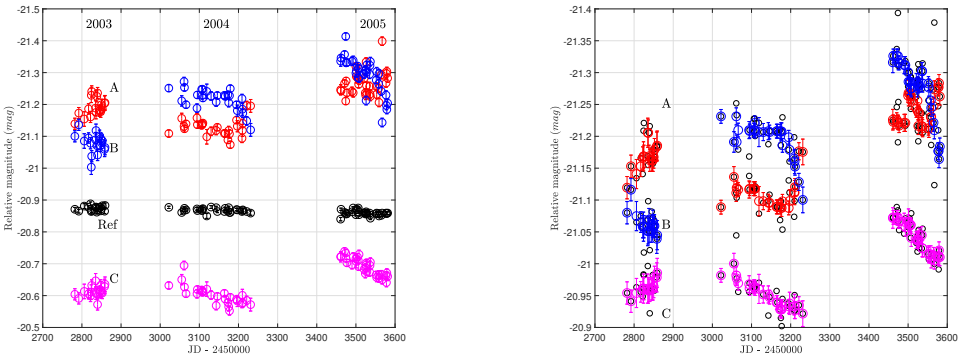


Figure 3 Left: Light curves of components A, B, and C, as well as a reference star; Right: Light curves of the components after median filtering. The brightness of component C has been shifted upward by –0.35 mag.

Based on the light curves of the components of B1422+231 obtained in this study, we attempted to measure the time delays between their brightness variations. To reduce the impact of random factors and low-intensity variations, we applied a median filtering technique to the light curves (see Fig. 3b). To determine the time delays, we used the well-known minimum dispersion method (Pelt, 1996). This method was applied to the data from the 2004 season, as it contains a sufficient number of observations and the brightness changes during this period are relatively smooth. Using the Monte Carlo method, we generated 5000 synthetic light curves for the three components. The results of applying the dispersion method to these synthetic curves are shown in Figure 4. The derived time delays between the components are as follows: $\Delta t_{AB} = -52.4 \pm 3$ days, $\Delta t_{AC} = 14.2 \pm 2$ days and $\Delta t_{CB} = 48.4 \pm 2$ days. The corresponding magnitude differences between the component pairs were: $\Delta m_{AB} = 0.1$ mag, $\Delta m_{AC} = -0.48$ mag and $\Delta m_{CB} = -0.59$ mag.

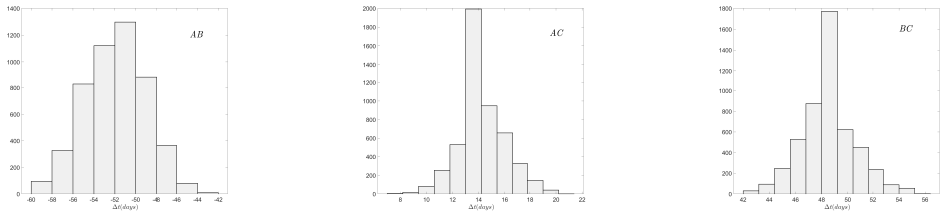


Figure 4 Histograms of the most probable time shifts between the three pairs of light curves in the GLQ B1422+231.

4 Conclusions

Thus, we have confirmed the long-term brightness variations of the lensed components in the quadruply imaged quasar system B1422+231. The amplitude of these

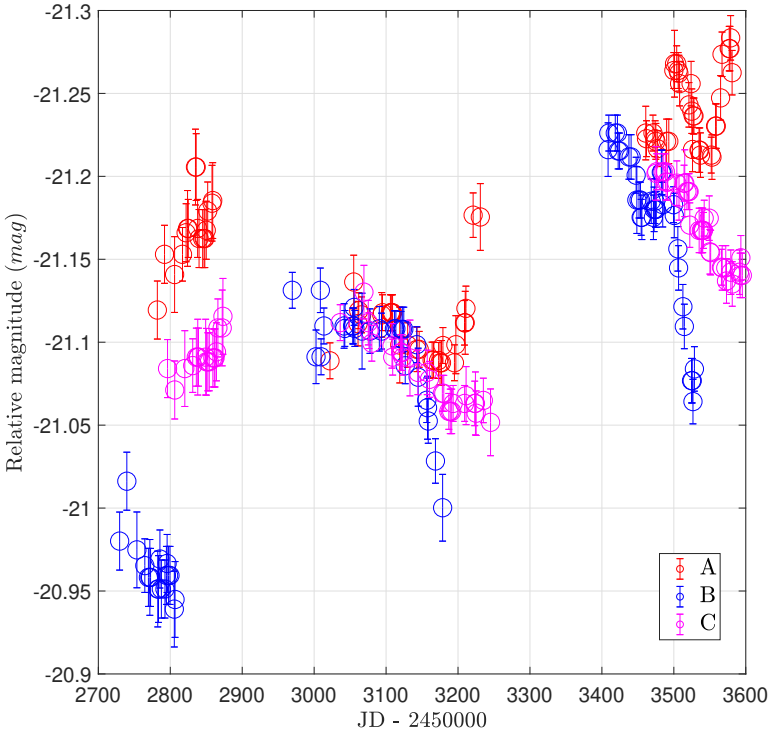


Figure 5 Combined light curves of B1422+231 during the 2003-2005 seasons with appropriate time delays and magnitude shifts.

variations reaches approximately 0.2 magnitudes. The light curves of the three components in this gravitationally lensed system, against the background of the source's intrinsic variability, consistently show signs of microlensing. This is clearly illustrated in Figure 5, where alignment of the components along the vertical axis in the combined light curve is observed only during the 2004 season – the very dataset we used for estimating the time delays. The influence of microlensing is particularly evident in component B, while the brightness difference between components A and C remains more or less stable across the observed seasons, the brightness of component B in 2004 and 2005 even exceeded that of component A. As for the time delays we obtained, they are significantly larger than both theoretical predictions and previously reported preliminary estimates. This result requires further verification using independent methods.

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