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Observations of Gaia Microlensing Events in Abastumani

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Abstract

Gaia is now one of the most successful and leading transient space mission. It discovers nearly 2000 objects annually from all over the sky, down to about 20 mag, covering all possible classes of transients from supernovae and cataclismic variables to rare phenomena like microlensing events or pair-instability supernovae. The long time baseline of Gaia data allows for more robust detections of photometric anomalies. The gravitational microlensing method is especially sensitive to compact-object lenses in the Milky Way, including white dwarfs, neutron stars or black holes. The team, involved in the photometric follow-up observations of Gaia microlensing events, is collaborating with the International Working Group of Gaia Science Alerts through the BHTOM platform since 2020. Currently, we mainly use the 36-cm SCT-14 telescope of the Georgian National Astrophysical Observatory (Abastumani, Georgia) which is equipped with large format CCD and UBVRI filter set. At present we have processed and submitted for combined light curves observational data of 16 moderately bright Gaia alerts. Some of them clearly show the microlensing event type of light curves, though they need more detailed investigation. Here we present preliminary results of data connected with two such events: Gaia19dke and Gaia21dnc.

Keywords: *Gaia events, gravitational microlensing*

1. Introduction

Gravitational Microlensing is the amplification of the light of a background star due to the transit on the line of sight between this star and an observer of a massive compact object, which acts as a gravitational lens. The lens can be a neutron star, a white or brown dwarf or a black hole, sometimes called MACHOs (MAssive Compact Halo Objects). This phenomenon depends on an effect first discussed by Albert Einstein in his early papers on general relativity (Einstein, 1911, 1915), where he showed how light that passed a massive object would be deflected by the object's gravity. This effect was demonstrated by Eddington's observations during the total Solar eclipse of 29 May 1919 (Dyson et al., 1920).

Gravitational lensing differs from conventional optical lensing as there is not a single point of focus in a focal plane and multiple distorted images of the source appear around the lens. In case of a point-like compact lens it will always produce two images, while a binary lens will generate three or five images. In the special case when lens and source are in perfect alignment towards an observer, the multiple images all merge to form a bright ring around the lens or the so-called 'Einstein ring'.

In the 1964 independent theoretical studies by Liebes and Refsdal (Liebes, 1964, Refsdal, 1964) showed the usefulness of lensing for astronomy. In particular Sjur Refsdal derived the basic equations of gravitational lens theory and subsequently showed how the gravitational lens effect can be used to determine Hubble's constant by measuring the time delay between two lensed images.

In 1979 the gravitational lensing method gained a real boost when the first double quasar Q0957+561 was discovered and confirmed to be a real gravitational lens by Walsh, Carswell and Weymann (Walsh et al., 1979).

In 1986 Paczyński (Paczyński, 1986) suggested a method which greatly increased probability to observe microlensing events. If one could continuously observe the brightness of stars of our neighbouring galaxy Large Magellanic Cloud (LMC) one should see typical fluctuations in some of these stars due to the fact that every now and then one of these compact halo objects passes in front of the star and magnifies its brightness. Due to the relative motion of observer, lensing Macho and source star the projected impact parameter between lens and source changes with time and produces a time dependent magnification.

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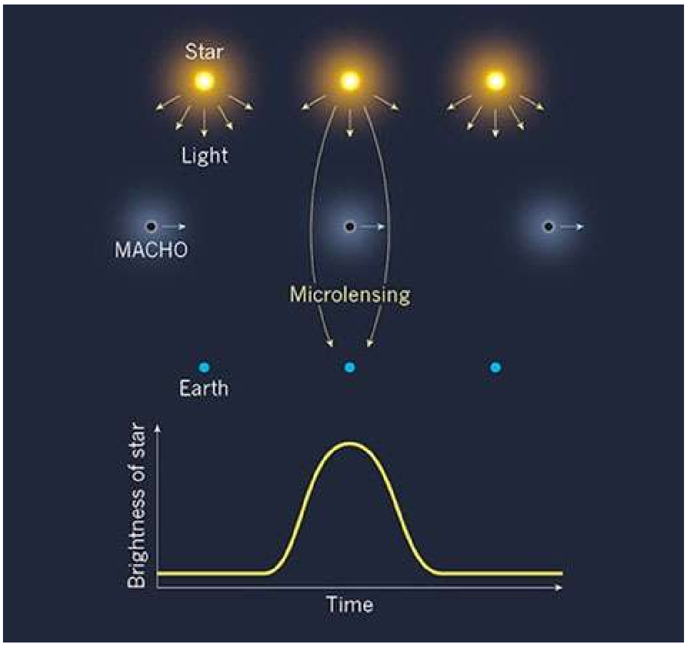

Figure 1. General drawing of a microlensing transit event.

2. Basics of Microlensing Phenomena

Main parameters of a microlensing event are the following (see Figure 2):

- D_L - distance of the lens from the observer;
- D_S - distance of the source from the observer;
- D_{LS} - distance of the lens from the source;
- M_L - mass of the lens;
- α - angular separation of the lens from the observer-source line of sight;
- $\theta_{1,2}$ - angular separation of images of the source from the center of the lens;
- $\epsilon_{1,2}$ - deflection of a light ray passing at radius r from the lens.

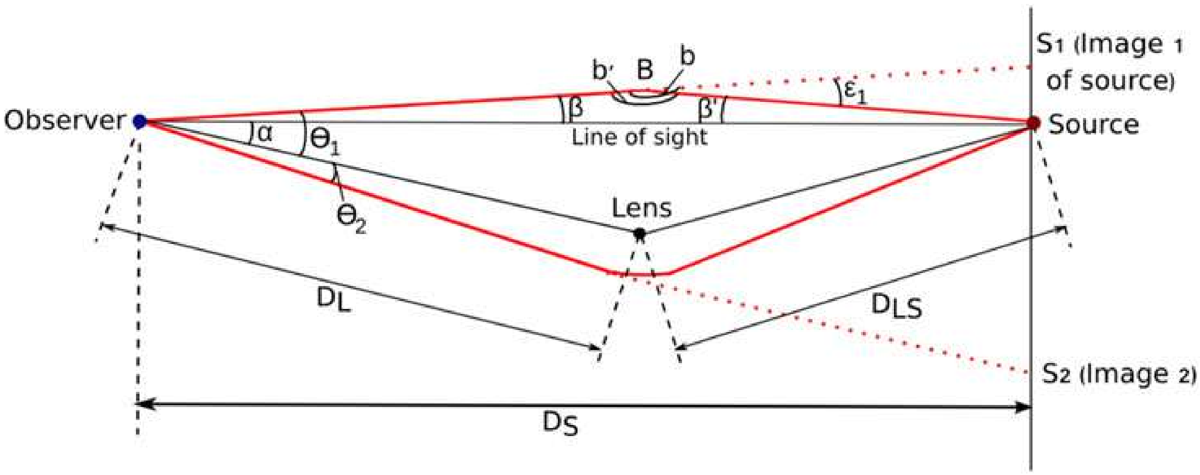

Figure 2. The geometry of a single lens microlensing event.

The closer the light rays get to the lens, the more they are deflected and according to Einstein's equation:

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$$\epsilon = \frac{4GM_L}{rc^2}. \tag{1}$$

Making relevant transformation we can get a lens equation:

$$\theta_1^2 - \alpha\theta_1 - \frac{4GM_L D_{LS}}{c^2 D_L D_S} = 0, \tag{2}$$

and finally brightness change or magnification of an image relative to the unlensed source, an Einstein radius and crossing timescale - the time taken for the source to pass behind the Einstein ring of the lens:

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}, \tag{3}$$

$$\theta_E = \sqrt{\frac{4GM_L D_{LS}}{c^2 D_L D_S}}, \tag{4}$$

$$\theta_E = \sqrt{\frac{4GM_L D_{LS}}{c^2 D_L D_S}}, \tag{5}$$

$$t_E = \frac{\theta_E}{\mu_{rel}}. \tag{6}$$

Here u is called an *impact parameter* and μ_{rel} is the (relative) transverse velocity of the lens. Typically $t_E \sim 45$ days, so to detect microlensing events we need to observe about once per day.

For a galactic microlensing events, when the stars in the disk of the Milky Way act as lenses for bulge stars close to the center of the Galaxy, the scale defined by the Einstein radius in milliarseconds is:

$$\theta_E \approx 0.5\sqrt{\frac{M_L}{M_\odot}}. \tag{7}$$

In order to derive an average estimate for the size of θ_E, we can consider an M-dwarf lens star ($M_L = 0.3M_\odot$) at a distance of $D_L = 6.5$ kpc from the Earth, and a source star at a distance $D_S = 8.5$kpc. The corresponding size of the angular Einstein ring radius is then approximately

$$\theta_E \sim 300 \ \ \mu as. \tag{8}$$

if we use equation (6) and assume a typical value for the transverse velocity of $\mu_{LS} \sim 15\mu$as/d, then for lenses of about one Earth-mass t_E is of the order of hours, while in the case of Solar-mass objects the lensing effect may last for a few months (Tsapras et al., 2016, Wood & Mao, 2005, Łukasz Wyrzykowski et al., 2015).

Note that from equation (6) it is obvious that it is not possible to determine the mass of the lens from one individual microlensing event. The duration of an event is determined by three unknown parameters: the mass of the lens, the transverse velocity and the distances of lens and source. It is impossible to disentangle these for individual events. Only with a model for the spatial and velocity distribution of the lensing objects and comparison with "simulated microlensing events" it is possible to obtain information about the masses of the lensing objects and their density (Wambsganss, 1998).

3. Microlensing Event Scenarios

3.1. Single-to-Single Lensing

The basic concepts of microlensing are easier to introduce by considering a simple scenario: a point lens in the foreground bending the light of a point background source. This is commonly referred to as "point source-point lens" (PSPL) lensing model. Modeling single-lens event light curves is quite straightforward as they are simple, smooth and symmetric and usually involves three parameters that describe the shape of the curve, such as u_0, t_0 and t_E (see Figure 1).

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3.2. Binary Source Lensing

The case of a binary source is simple, as it generates a linear sum of two single-lens light curves. Naturally, since the two stellar components may have different luminosities and colors, the resulting light curve may be chromatic. If the distance between the two source stars is large and the lens trajectory is along the line joining the two, we may have the perception of two independent microlensing events separated by a few months or years, which are both produced by the same lens. Of course, if the binary source is a gravitationally bound system, it is possible that orbital motion effects may also be detectable.

Binary source events are not as commonly detected as originally predicted (Griest & Hu (1992) estimated that $\sim 10\%$ of all events should show binary source features).

3.3. Binary or Exoplanet Lens

If the lens is multiple, as is the case when the lens is a binary star or a star with planets, the magnification pattern experienced by a background source is no longer circularly symmetric on the sky. In this case, the shape and maximum amplitude of the lightcurve depends on relative path the background source takes through the lens magnification pattern. The resulting lightcurve can exhibit large changes in shape over rather short periods of time if the background star passes near what is known as a caustic in the lensing pattern (Mao & Paczyński, 1991).

The Figure 3 shows variations of brightness of the star Gaia16aye caused by a microlensing event, as a massive object passed across its line of sight. After the initial discovery of this 14.5 magnitude star with Gaia (dark circles on Figure 3), follow-up observation were continued with different terrestrial telescopes (coloured circles), revealing a rather peculiar pattern of brightness variations.

Instead of a single rise and fall, the star has undergone two consecutive brightness peaks of roughly two magnitudes, then became fainter for a few weeks. It later exhibited a sharp increase to magnitude 12 and rapidly declined again.

The intricate pattern of variations suggests that the star is not being lensed by a single object but rather by a binary system. The black line shows the expected brightness variation from a microlensing model with a binary lens, which most likely consists of two stars, but might also involve a planet or even a black hole.

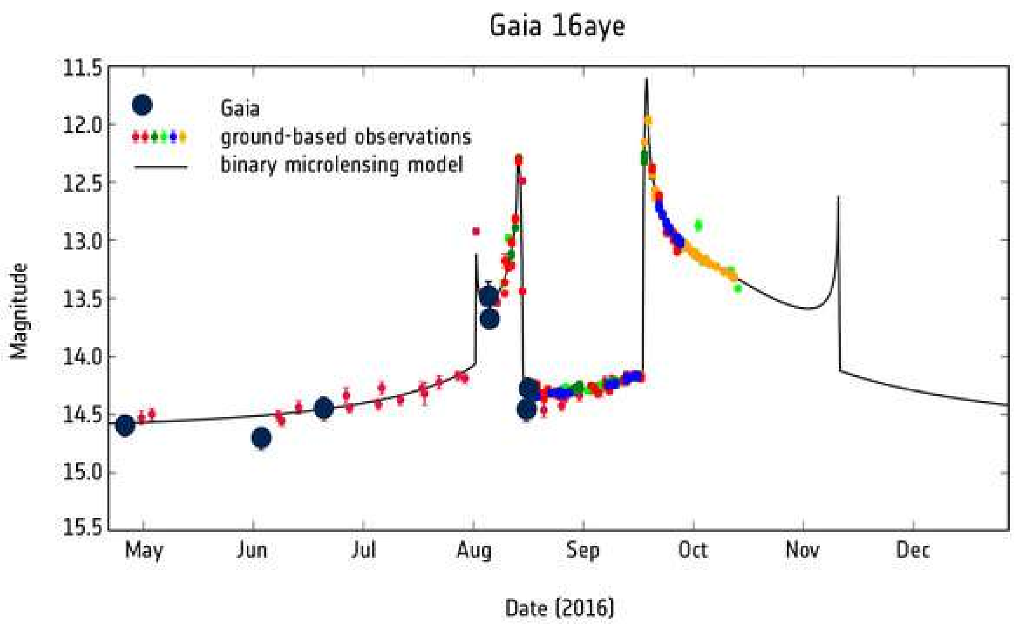

Figure 3. Light curve of binary microlensing event detected by Gaia. Copyright: ESA/Gaia/DPAC, P. Mroz, L. Wyrzykowski, K.A. Rybicki (Warsaw)

The Figure 4 depicts the microlensing event MOA-2011-BLG-028 / OGLE-2011-BLG-0203 follow-up photometric observations. The light curve clearly shows the discovery of a Neptune-mass planet orbiting

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a $0.8 \pm 0.3 M_\odot$ star in the Galactic bulge. The planet manifested itself during the microlensing event as a low-mass companion to the lens star. The analysis of the light curve provides the measurement of the mass ratio: $(1.2 \pm 0.2) \cdot 10^{-4}$, which indicates the mass of the planet to be 12–60 Earth masses. The lensing system is located at 7.3 ± 0.7 kpc away from the Earth near the direction to Baade's Window. The projected separation of the planet, at the time of the microlensing event, was 3.1–5.2 AU. Although the "microlens parallax" effect is not detected in the light curve of this event, preventing the actual mass measurement, the uncertainties of mass and distance estimation are narrowed by the measurement of the source star proper motion on the OGLE-III images spanning eight years, and by the low amount of blended light seen, proving that the host star cannot be too bright and massive (Skowron et al. (2016)).

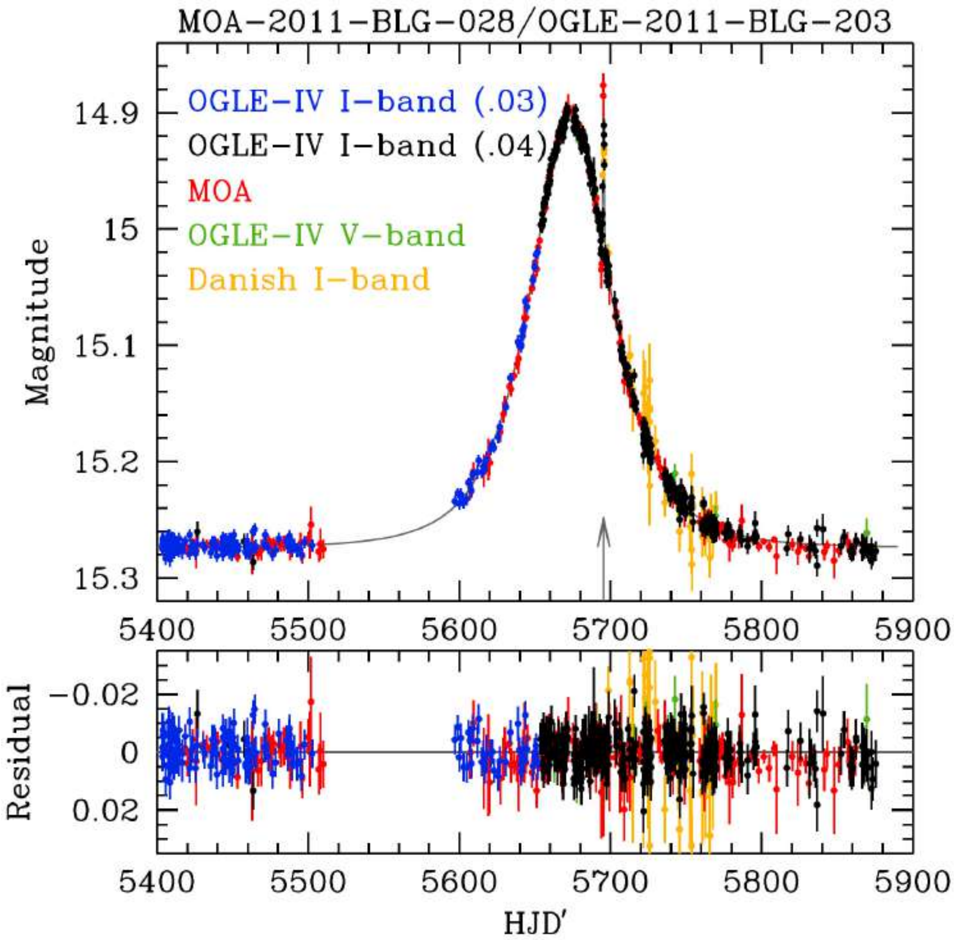

Figure 4. The Light Curve of the Microlensing Event MOA-2011-BLG-028 / OGLE-2011-BLG-0203. The whole OGLE light curve for this object spans 15 years. The black line marks the best-fit microlensing model where the light of a Galactic bulge giant is magnified for ∼200 days (around 2011 April 22nd) by a stellar object near the light's path and is additionally disturbed for ∼2 days (around 2011 May 13th) by a low-mass companion of that object. Copyright: Skowron et al. (2016).

4. Microlensing Event Observations in Abastumani

To obtain adequate photometric data coverage for detailed study of microlensing events, international follow-up photometric network is needed. Currently the network is consisting of several tenths of observatories throughout the world having special web service called the Black Hole Target Observation Management (BHTOM). The BHTOM is an interface for viewing and sharing observational photometric and spectroscopic data of time-domain targets, and for requesting and managing follow-up observations obtained with a network of telescopes. The BHTOM was built within the Time-Domain Work Package of the OPTICON EC Horizon 2020 grant no. 730890.

The Georgian National Astrophysical Observatory (Abastumani, Georgia) has actively joined the network in 2020. We use the 36mm Schmidt-Cassegrain telescope SCT-14 (see Figure 5) for these follow-up photometric observations, which is equipped with the Starlight Express SX-36 CCD camera and standard

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Johnson-Cousins UBVRI filter set. The field of view equals 28 x 19 arcmin and pixel size is 0.35 arcsec. The limiting magnitude of this photometric setup reaches 17 magnitude in V. The lowest observable declination equals −35 deg.

The CCD observational images usually are calibrated with bias, dark and flat field frames using MaximDL software tools and several short exposures are stacked to get final images with high S/N. The resulting CCD images are uploaded to the BHTOM service for final photometric calibration and inclusion into collective follow-up photometric data set.

Figure 5. The SCT-14 equipped with the Starlight Express SX-36 CCD, UBVRI filter set and guiding system.

During the last 2 years we have observed 16 Gaia events following the BHTOM system alerts and observing priorities. The data of objects are listed in the Table 1. Nine of these 16 are confirmed microlensing events.

Table 1. List of Gaia alerts observed in Abastumani

Gaia event Name	**RA DEC (J2000)**	**Mag.**	**Event Type**
Gaia19dke	19:25:58 +28:24:24	15.49	Long-term microlensing with parallax
Gaia21efs	20:29:41 +31:17:42	15.78	Bright microlensing
Gaia22awa	19:04:51 -08:34:00	15.11	Microlensing candidate
Gaia22duy	18:41:09 -10:23:47	17.03	Long bright microlensing near the Bulge
Gaia21dnc	21:38:10 +26:27:59	15.48	Microlensing event with a planetary anomaly
Gaia20fnr	06:01:04 -18:58:03	13.16	Bright microlensing
Gaia21bfr	18:46:08 -10:12:26	17.02	Bright microlensing
Gaia20dwf	18:26:29 -20:04:52	16.73	Microlensing candidate
Gaia23bay	19:49:42 +10:43:41	11.99	Bright microlensing candidate
Gaia21arx	05:36:24 -06:17:30	12.24	! Young stellar object
Gaia21ecy	19:01:22 +11:52:03	14.28	! Possibly a Be-type star outburst
Gaia18arn	21:35:15 +50:28:50	17.23	! Microlensing not confirmed
Gaia21cgt	19:52:39 +26:11:34	15.15	! Most likely a Be-type outburst
Gaia21asp	19:28:32 +19:50:11	14.59	! Microlensing not confirmed
8C0716_714	07:21:53 +71:20:36	14.00	! Highly variable BL Lac S5 0716+714
TCrB	15:59:30 +25:55:12	10.00	! Very bright symbiotic star to explode soon

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5. Preliminary Results of Some Microlensing Events

5.1. Gaia19dke

Gaia19dke event was reported by the Gaia Science Alert system (Hodgkin et al., 2021) on the 8th of August 2019 as a small rise of brightness in the Gaia G-band in a previously non-varying star. While Gaia scans the sky, it returns to the same location on average within 30 days. Each visit typically provides two independent measurements separated by 106 minutes coming from the two fields of view of the spacecraft. As of October 2022, Gaia collected 145 measurements for Gaia19dke. The light curve from Gaia is collected in the Gaia broad-band filter G-band and exhibited multiple peaks, with the main peak reaching about 14.8 mag in G-band. As the event at its baseline was relatively bright with G ∼15.5 mag, it was possible to collect a vast number of follow-up observations using small-sized telescopes including the SCT-14 of the Abastumani Observatory. The earliest follow-up started 21 days after the announcement on the event on the Gaia Science Alerts web page. The modeling of the event with single point source single lens microlensing model with annual parallax gives the following preliminary parameters (see Table 2):

Table 2. Some preliminary microlensing parameters of Gaia19dke for lens mass distribution of $\propto M^{-1.75}$

Parameter	Value
Source star	G5m III
Source distance D_S	4.9±1.2 kpc
Lens mass M_L	0.81 $M_\odot$
Lens distance D_L	2.21 kpc
Lens type probability - White Dwarf	66%
Lens type probability - Neutron Star	18%
Lens Type probability - Black Hole	9%

5.2. Gaia21dnc

First alert of Gaia21dnc event as AT2021uey was announced by the ZTF survey (Bellm et al., 2019, Masci et al., 2019) on 11 June 2021. The alert was named ZTF18abktckv, and the confirmation of the microlensing nature of the alert was made three months later by Möller & et al. (2021) due to the peculiar shape of the signal. The ASAS-SN survey alerted it on 7 July 2021. The Gaia Science Alert system (Hodgkin et al., 2021) alerted the same event on 27 July 2021 as Gaia21dnc. The alert was recognized to be candidate microlensing event, which triggered follow-up observations by smaller telescopes. The light curve of Gaia21dnc well covered by different datasets and is 1.5 mag brighter than the baseline. There is a 3-day long anomaly at HJD = 2459400. During the anomaly, photometry was obtained only by the ASAS-SN and ZTF surveys. The data modeling indicates that the lens of this microlensing event is an M-dwarf star with a Jupiter-like planet. The preliminary parameters are listed in the Table 3.

Table 3. Some preliminary microlensing parameters of Gaia21dnc

Parameter	Value
Source star	Metal-poor F giant
Source distance D_S	6.9±2.4 kpc
Lens mass M_L	0.59±0.24 $M_\odot$
Lens distance D_L	0.9 kpc
Lens type	M-dwarf
Jupiter-like planet mass	1.61±0.66 M_{jup}
a (AU)	3.8:
lg(P), day	3.6:

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References

Bellm E. C., et al., 2019, Publ. Astron. Soc. Pac. , 131, 018002

Dyson F., Eddington A., Davidson C., 1920, Philos. Trans. R. Soc. Lond. Ser. A, 220, 291

Einstein A., 1911, Ann. Phys., 340, 898

Einstein A., 1915, Sitzungsber. Preuss. Akad. Wiss., 1, 831–839

Griest K., Hu W., 1992, The Astrophysical Journal, 397, 362

Hodgkin S. T., et al., 2021, Astron. Astrophys. , 652, A76

Liebes S., 1964, Phys. Rev., 133, 835

Mao S., Paczyński B., 1991, The Astrophysical Journal, 374

Masci F. J., et al., 2019, Publ. Astron. Soc. Pac. , 131, 018003

Möller A., et al. 2021, Mon. Not. R. Astron. Soc. , 501, 3272

Paczyński B., 1986, Astrophys. J., 304, 1

Refsdal S., 1964, MNRAS, 128, 295

Skowron J., et al., 2016, The Astrophysical Journal, 820, 4

Tsapras Y., et al., 2016, Monthly Notices of the Royal Astronomical Society, 457, 1320

Walsh D., Carswell R., Weymann R., 1979, Nature, 279, 381

Wambsganss J., 1998, Living Reviews in Relativity, 1

Wood A., Mao S., 2005, MNRAS, 362, 945

Łukasz Wyrzykowski et al., 2015, The Astrophysical Journal Supplement Series, 216, 12

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