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Period Changes in the Ultracompact Binary ZTF J213056.71+442046.5

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We performed the O–C analysis of period variations of the ultracompact binary system ZTF J213056.71+442046.5, a potentially detectable source of mHz gravitational waves for planned space laser interferometers. We combined our photometric observations carried out at the RC600 telescope of the Caucasus Mountain Observatory with publicly available ZTF survey data, thus increasing to 5.5 years the time interval covered with measurements. The O–C diagram is well fitted with linear light elements ($P = 0\overset{d}{.}0273195154$) but can be also described with quadratic light elements corresponding to a period decrease rate of $dP/dt = (-2.00 \pm 0.60) \times 10^{-12}$ s s^{-1}. This finding is in a good agreement with the predicted value of the orbital period decay of this binary system due to gravitational wave emission.

1 Introduction

In the light of the planned space projects aimed to observe mHz gravitational waves, e.g. LISA and TianQin, careful studies of potential sources producing measurable gravitational signal are topical. Such sources include Galactic binary systems with ultrashort periods. Ren et al. (2023) published a list of ultracompact binary stars that are potential sources of gravitational waves detectable by LISA (Amaro-Seoane et al., 2017) and TianQin (Luo et al., 2016) space laser interferometers. Galactic binaries with precisely known orbital parameters (orbital period, masses of the components, binary inclination, etc.) and distance (also known as "verification binaries") are primary sources for calibration of the space laser interferometers. Most of several dozen currently known verification binaries include, in particular, AM CVn stars, detached double white dwarfs, and subdwarf binaries that resulted from evolution of low-mass binaries. One of the binaries in the list with orbital periods shorter than one hour is ZTF J213056.71+442046.5 (hereafter ZTF J2130+44).

ZTF J2130+44 was found independently by G. Murawski (Rivera Sandoval et al., 2019) and Kupfer et al. (2020) in the public data release of the Zwicky Transient Facility (ZTF) survey as a very short period ($P = 0\overset{d}{.}0273195$) eclipsing variable star. Kupfer et al. (2020) proposed a model of the binary system consisting of a typical white dwarf and a helium low-mass hot subdwarf star filling its Roche lobe. For the derived binary system parameters, Kupfer et al. (2020) predict the orbital decay of the system due to gravitational-wave emission with a period decrease rate of $dP/dt = (-1.68 \pm 0.42) \times 10^{-12}$ s s^{-1}.

Although ZTF J2130+44 is not the brightest verification binary, we tried to measure the expected orbital decay rate due to emission of gravitational waves. This is an important task because the data analysis of gravitational wave sources requires as precise as

Table 1: Log of observations, RC600 telescope, V band

HJD range	Date, 2023	Number of frames
2460051.49951 – .55136	April 16/17	86
2460120.36373 – .41047	June 24	104
2460121.34266 – .47812	June 25	299
2460140.39830 – .52204	July 14/15	268
2460159.48402 – .51429	August 2/3	286
2460183.41566 – .55114	August 26/27	262
2460208.40522 – .54511	September 20/21	308
2460230.31552 – .45160	October 12	299

possible knowledge of the orbital period and its change rate to dig out the signal against the expected Galactic and extragalactic stochastic noise in the mHz frequency band for space interferometers like LISA or TianQin (Staelens & Nelemans, 2023). To study the period variations of a potentially detectable gravitational-wave source and to compare these variations with predictions, we started photometric monitoring of ZTF J2130+44.

2 Observations and Reduction

Our photometric observations of ZTF J2130+44 were carried out in April–October, 2023 with the automated ASA RC600 60-cm reflector of the Caucasus Mountain Observatory (CMO) of the Sternberg Astronomical Institute, Lomonosov Moscow University, equipped with an Andor iKon-L (DZ936N-BV) 2048 × 2048 CCD camera (Berdnikov et al., 2020). A total of 1912 CCD frames in the V band with exposure times of 30 seconds were collected. The log of observations is presented in Table 1. The corresponding light curves are shown in Fig. 1. The VaST[1] software (Sokolovsky & Lebedev, 2018) was used to perform the aperture photometry and magnitude calibration. V magnitudes of an ensemble of comparison stars within the field of view were derived from the APASS catalog.

3 O–C analysis

For the most accurate determination of the times of primary brightness minima, we apply the method by Hertzsprung (1919) algorithmized by Berdnikov (1992). To expand the time span of observations, we employed the SNAD ZTF object viewer[2] (Malanchev et al., 2023). ZTF g- and r-band data are very similar to our dataset in exposures (30 s) and photometric errors (about $0^{\rm m}_{\cdot}01$). The resulting time interval of ZTF J2130+44 brightness measurements suitable for our O–C analysis has thus increased to 5.5 years. The times of minima along with their O–C values are listed in Table 2. The O–C residuals were calculated using the linear light elements:

$$\text{HJD Min} = 2{,}459{,}247.796853(\pm 0.000004) + 0^{\rm d}_{\cdot}0273195154(\pm 0.0000000002) \cdot E. \quad (1)$$

[1]https://scan.sai.msu.ru/vast
[2]https://ztf.snad.space/

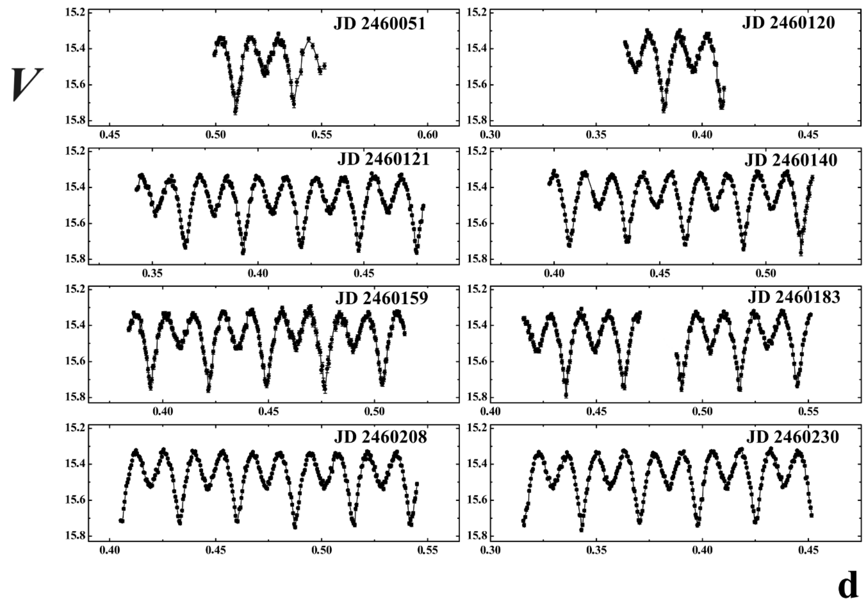

Figure 1. Individual light curves of ZTF J213056.71+442046.5, CMO V band observations.

The corresponding phased light curve of ZTF J2130+44 folded with the elements (1) is presented in Fig. 2. The linear light elements (1) match the current O–C residuals with very small uncertainties in deriving the period and the time of primary minimum. However, in the anticipation of the binary's orbital evolution, we have also fitted them with quadratic light elements. It resulted in the following ephemeris:

$$\text{HJD Min} = 2{,}459{,}247.796871(\pm 0.000007) + 0\overset{\text{d}}{.}02731951548(\pm 0.00000000014) \cdot E - 2.7271(\pm 0.8178) \times 10^{-14} \cdot E^2. \quad (2)$$

Both linear and quadratic approximations are shown in Fig. 3. The solid and dashed curves in the figure correspond to formulas (1) and (2), respectively.

The quadratic light elements (2) imply a linear decrease of the period with the rate $dP/dt = (-2.00 \pm 0.60) \times 10^{-12}$ s s^{-1}, which is consistent with the theoretical value published by Kupfer et al. (2020), i.e. $dP/dt = (-1.68 \pm 0.42) \times 10^{-12}$ s s^{-1}. Note, however, that the accuracy of our quadratic elements is low. Further observations would be very helpful to improve the quality of the expected quadratic fit and confirm the binary orbital decay in this source.

4 Conclusions

To study the period variations of the potential LISA verification source ZTF J213056.71 +442046.5, we have obtained 1912 V-band CCD frames with the 60-cm reflector RC600 of the Caucasus Mountain Observatory in 2023. To expand the time span of observations, we have used available ZTF data, enabling us to increase the resulting interval of ZTF J2130+44 brightness measurements suitable for our O–C analysis to 5.5 years.

Table 2: Times of minima for ZTF J213056.71+442046.5

min HJD	err, d	Source, band	N	O–C, d	Epoch
2458265.27775	0.00002	ZTF, g	51	–0.00005062	–35964
2458340.84358	0.00002	ZTF, r	154	–0.00000025	–33198
2458368.32699	0.00002	ZTF, g	87	–0.00002276	–32192
2458465.83036	0.00001	ZTF, r	461	–0.00000328	–28623
2458695.17770	0.00002	ZTF, r	122	0.00000482	–20228
2458701.40655	0.00002	ZTF, g	111	0.00000530	–20000
2458766.61823	0.00002	ZTF, g	72	0.00000200	–17613
2458768.50330	0.00002	ZTF, r	75	0.00002544	–17544
2459007.38514	0.00002	ZTF, g	63	0.00002265	–8800
2459015.38976	0.00001	ZTF, r	307	0.00002464	–8507
2459117.20959	0.00002	ZTF, g	125	0.00002068	–4780
2459121.85393	0.00002	ZTF, r	109	0.00004306	–4610
2459377.20940	0.00003	ZTF, r	53	0.00000248	4737
2459419.71856	0.00002	ZTF, g	82	–0.00000351	6293
2459491.86939	0.00004	ZTF, r	30	–0.00001372	8934
2459754.13674	0.00003	ZTF, r	56	–0.00001170	18534
2459757.63364	0.00002	ZTF, g	47	–0.00000968	18662
2459882.92102	0.00003	ZTF, g	38	0.00007263	23248
2459888.98590	0.00004	ZTF, r	33	0.00002021	23470
2460092.32503	0.00005	ZTF, g	22	–0.00000302	30913
2460092.32505	0.00005	ZTF, r	21	0.00001698	30913
2460051.50964	0.00004	CMO, V	85	–0.00003699	29419
2460121.14711	0.00002	CMO, V	403	–0.00001179	31968
2460140.46203	0.00001	CMO, V	266	0.00001082	32675
2460159.44908	0.00002	CMO, V	286	–0.00000240	33370
2460183.49024	0.00002	CMO, V	262	–0.00001596	34250
2460208.48759	0.00001	CMO, V	308	–0.00002257	35165
2460230.37053	0.00001	CMO, V	294	–0.00001442	35966

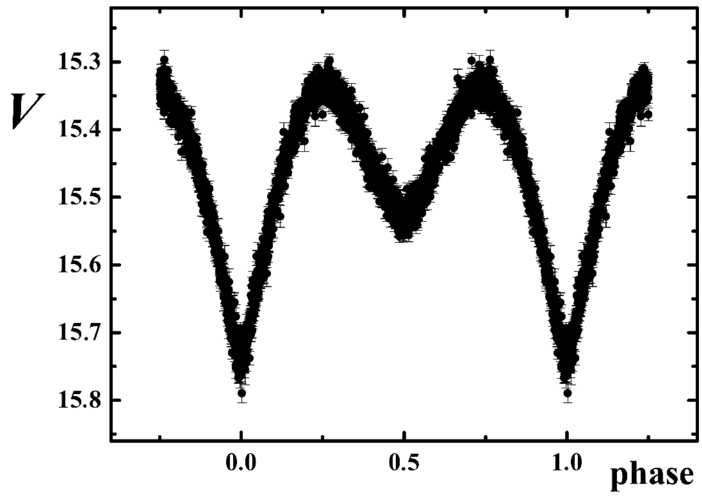

Figure 2. Phased light curve of ZTF J213056.71+442046.5.

We have derived 28 times of the primary minima of the close binary suitable for further O–C analysis. The constructed O–C diagram is in a good agreement with the linear light elements ($P = 0\overset{\text{d}}{.}0273195154$).

The attempt to fit the O–C residuals with quadratic light elements results in determination of the linear period changes at a rate of $dP/dt = (-2.00 \pm 0.60) \times 10^{-12}$ s s^{-1} that is very similar to the theoretical value assuming the orbital decay of the binary system solely due to gravitational wave emission. We stress the need for additional high-precision photometry of the source to definitely determine the orbital decay rate reported in this paper.

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References:

Amaro-Seoane, P., Audley, H., Babak, S., et al. 2017, *arXiv:1702.00786*

Berdnikov, L. N., 1992, *Soviet Astron. Letters*, **18**, 207

Berdnikov, L. N., Belinskii, A. A., Shatskii, N. I., et al., 2020, *Astron. Rep.*, **64**, 310

Hertzsprung, E., 1919, *Astron. Nachr.*, **210**, 17

Kupfer, T., Bauer, E.B., Marsh, T.R., et al. 2020, *Astrophys. J.*, **891**, id45

Luo, J., Chen, L.-S., Duan, H.-Z., et al. 2016, *Classical and Quantum Gravity*, **33**, id. 035010

Malanchev, K., Kornilov, M. V., Pruzhinskaya, M. V. et al., 2023, *Publ. Astron. Soc. Pacific*, **135**, id. 024503

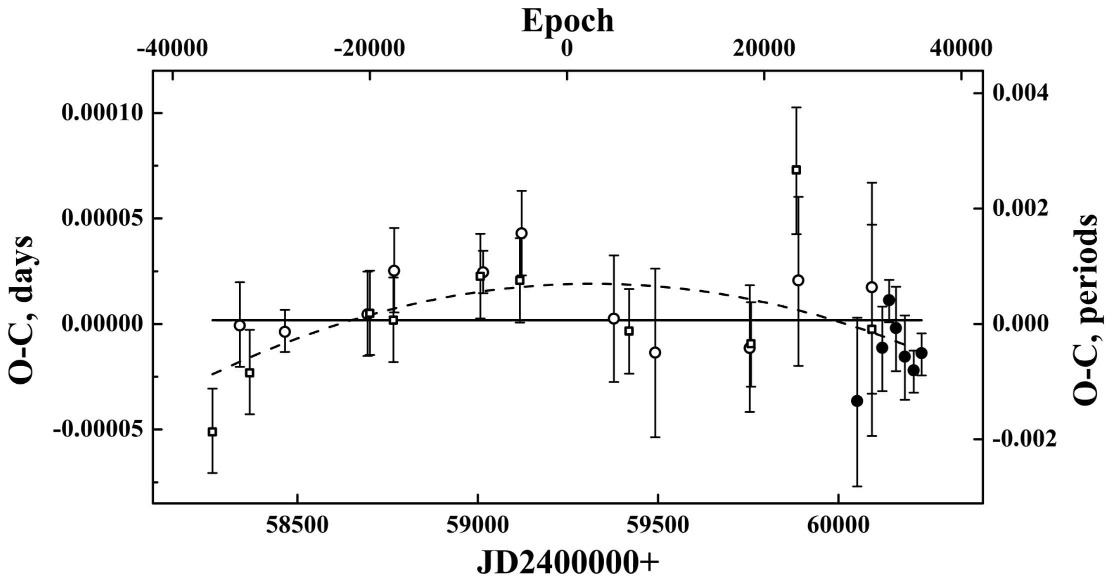

Figure 3. O–C diagram for ZTF J213056.71+442046.5 relative to the linear light elements (1). The solid line corresponds to the elements (1), the dashed curve corresponds to the elements (2). Open squares mark the ZTF g band, open circles are for ZTF r band, and the filled circles, for our V-band observations.

Ren, L., Li, C., Ma, B., et al., 2023, *Astrophys. J. Suppl.*, **264**, 39
Rivera Sandoval, L. E., Maccarone, T., & Murawski, G. 2019, *Astron. Tel.*, 12847, 1
Sokolovsky, K. V. & Lebedev, A. A., 2018, *Astron. and Computing*, **22**, 28
Staelens, S. & Nelemans, G., 2023, *Astron. & Astrophys.*, in press, *arXiv:2310.19448*