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First Apsidal Motion Analysis of Four Eclipsing Binary Systems with Eccentric Orbits

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Abstract

In this study, the apsidal motion parameters of the eccentric eclipsing binary systems GSC 08691-00026 (P = 2.47 days), GSC 09010-01931 (P = 2.31 days), GSC 07645-00517 (P = 3.21 days), and GSC 09022-01175 (P = 3.23 days were determined for the first time through an analysis of their (O–C) diagrams. The (O–C) diagrams were constructed using previously published times of minimum light together with new minima derived from TESS photometric data. The derived apsidal motion periods are U = 195 ± 26, 142 ± 25, 112 ± 14, and 345 ± 140 years for GSC 08691-00026, GSC 09010-01931, GSC 07645-00517, and GSC 09022-01175, respectively. The corresponding rates of change of the longitude of periastron were found to be $0\overset{\circ}{.}0124 \pm 0\overset{\circ}{.}0017$, $0\overset{\circ}{.}0160 \pm 0\overset{\circ}{.}0028$, $0\overset{\circ}{.}0282 \pm 0\overset{\circ}{.}0035$, and $0\overset{\circ}{.}0092 \pm 0\overset{\circ}{.}0063$ per cycle. All four systems have orbital eccentricities below 0.2.

Resumen

En este estudio, los parámetros de movimiento apsidal de los sistemas binarios eclipsantes excéntricos GSC 08691-00026 (P = 2.47 días), GSC 09010-01931 (P = 2.31 días), GSC 07645-00517 (P = 3.21 días), y GSC 09022-01175 (P = 3.23 días) han sido determinados por primera vez mediante un análisis de sus diagramas (O-C). Los diagramas (O-C) se construyeron utilizando tiempos de luz mínima previamente publicados junto con nuevos mínimos derivados de datos fotométricos de TESS. Los períodos de movimiento apsidal derivados son U = 195 ± 26, 142 ± 25, 112 ± 14 y 345 ± 140 años, respectivamente. Las tasas de cambio correspondientes de la longitud del periastron fueron de $0\overset{\circ}{.}0124 \pm 0\overset{\circ}{.}0017$, $0\overset{\circ}{.}0160 \pm 0\overset{\circ}{.}0028$, $0\overset{\circ}{.}0282 \pm 0\overset{\circ}{.}0035$ y $0\overset{\circ}{.}0092 \pm 0\overset{\circ}{.}0063$ por ciclo. Los cuatro sistemas presentan excentricidades orbitales inferiores a 0.2.

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1. Introduction

The study of eclipsing binary systems provides fundamental insights into stellar astrophysics. In particular, eclipsing binaries exhibiting apsidal motion have long been recognized as valuable laboratories for investigating stellar internal structure. Apsidal motion—the rotation of the line of apsides in eccentric binary systems—is governed by the internal mass (density) distributions of the stellar components. Consequently, observations of apsidal motion enable direct observational tests of the internal structure constants predicted by theoretical stellar models (Claret & Giménez 2010; Bulut et al. 2017; Claret et al. 2021). In addition, apsidal motion studies provide an important mean of testing predictions of general relativity by measuring the relativistic contribution to the observed apsidal advance (Giménez 1985; Claret & Giménez 1993).

In the (O–C) diagrams of eclipsing binary systems exhibiting apsidal motion, the primary and secondary minima follow sinusoidal variations with identical periods but are shifted in phase by 180°. The period of these oscillations corresponds to the apsidal motion period of the binary system. Because apsidal motion periods typically span several decades, reliable determinations require eclipse timing data that cover very long observational baselines.

In this study, apsidal motion analyses are presented for the first time for four eccentric eclipsing binary systems: GSC 08691-00026, GSC 09010-01931, GSC 07645-00517, and GSC 09022-01175. The basic catalog information for these systems, obtained from the SIMBAD database, is summarized in Table 1. All four systems are also listed in the catalog of eclipsing binary stars with eccentric orbits compiled by Kim et al. (2018).

2. Apsidal Motion Analysis

The apsidal motion in selected eclipsing binary star systems was investigated by analyzing (O–C) diagrams. The apsidal motion

Table 1. Basic catalog information of the target systems, the TESS observation sectors, and the numbers of newly minima

System	R.A.	Dec.	V (mag)	Sector No.	Numbers of Newly Minima
GSC 08691-00026	$14^h26^m54^s.71$	$-58°21'48''.98$	11.310	11, 38, 65, 99, 100	136
GSC 09010-01931	$14^h17^m22^s.1$	$-62°47'43''.02$	9.982	11, 12, 38, 65, 99, 100	110
GSC 07645-00517	$07^h48^m44^s.6$	$-38°01'48''.20$	10.360	7, 8, 34, 35, 88	135
GSC 09022-01175	$15^h40^m51^s.1$	$-61°43'43''.21$	9.254	12, 39, 65	99

analyses were performed using a computer program developed by Zasche et al. (2009), based on mathematical theory developed by Giménez & Bastero (1995).

When constructing the (O-C) diagrams of the systems, newly determined minimum light times derived from Transiting Exoplanet Survey Satellite (TESS) photometric data were combined with previously published minimum times obtained from the VarAstro database[1]. The high-quality and high-cadence photometric data provided by TESS allow minimum times to be determined with high precision. The TESS photometric data for the target systems were obtained from the Mikulski Space Telescopes Archive (MAST)[2]. According to the TESS archive, the sectors in which the target systems were observed are listed in Table 1.

The times of minimum light and their associated uncertainties were determined from the TESS photometric data using the Kwee–van Woerden method (Kwee & van Woerden 1956), which is widely recognized for its reliability in determining eclipse timings. Based on the TESS observations, the total number of newly determined times of minimum light for the target systems is listed in Table 1, while the determined minimum times are listed in Tables A1–A4.

For consistency in the apsidal motion analysis, all previously published times of minimum light, originally reported in the Heliocentric Julian Date (HJD), were converted to the Barycentric Julian Date (BJD) using the method suggested by Eastman et al. (2010).

Five independent variables were identified using this method: the sidereal period P_s, the eccentricity of the orbit e, the rate of advancement of the periastron $\dot{\omega}$, the position of the periastron ω_0, and the initial epoch T_0. U is defined as the period of apsidal motion ($U = 360°P_a/\dot{\omega}$), while $P_s = P_a(1 - \dot{\omega}/360°)$ is the relationship between the sidereal period (P_s) and the anomalistic period (P_a).

2.1. GSC 08691-00026

GSC 08691-00026 (TIC 263532376, TYC 8691-26-1, ASAS J142655-5821.8) is a detached binary system that was discovered by Pojmanski (2002). Kim et al. (2018) classified this system as an eclipsing binary with an eccentric orbit and reported that the phase of the secondary minimum is 0.485. According to the Gaia DR2 catalog, the effective temperature of the system is 7665 K. The linear light ephemeris for the system, as given in the VarAstro database, is as follows:

$$Pri.Min(HJD) = 2451904.9900 + 2^d.46996 \times E. \quad (1)$$

Apsidal motion analysis was performed using 143 eclipse timings (78 primary and 65 secondary), consisting of minimum times obtained from the VarAstro database together with the new minimum times listed in Table A1. The resulting parameters and their associated uncertainties are listed in Table 2. From this analysis, the

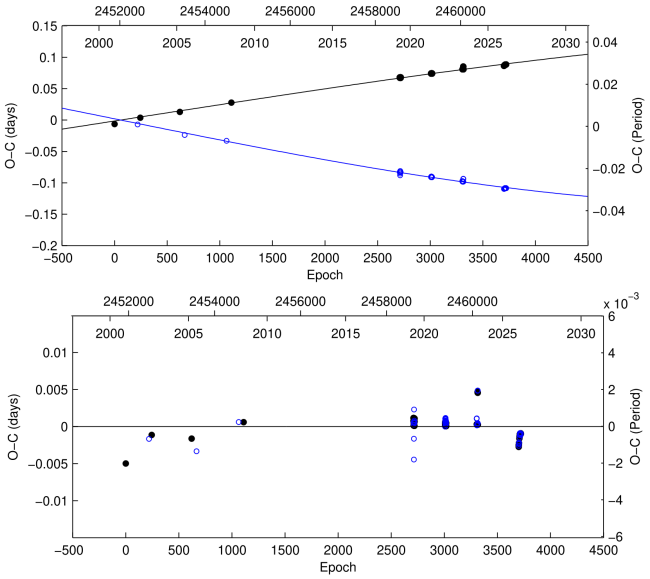


Figure 1. The upper panel shows the O-C diagram, while the lower panel shows the residuals corresponding to the apsidal motion of the GSC 08691-00026 system. The primary and secondary minima are shown by the filled black and empty blue circles, respectively.

apsidal motion period of GSC 08691-00026 was determined to be $U = 195 \pm 26$ yr, with an orbital eccentricity of $e = 0.1749 \pm 0.0177$. The best-fit model for the (O–C) diagram and the corresponding residuals are shown in Figure 1. The residuals of the (O–C) diagram showed no evidence of cyclic modulation, which would indicate the presence of a tertiary component in the system.

2.2. GSC 09010-01931

GSC 09010-01931 (TIC 335341747, TYC 9010-1931-1, HD 124671) is an early-type eclipsing binary system. It was identified in the spectral survey of the southern Milky Way by Sundman et al. (1974), who provided a general description and catalogue for the region l = 136° - 318°. Kim et al. (2018) later classified the system as an eclipsing binary with an eccentric orbit and reported that the phase of the secondary minimum occurs at 0.472. According to the Gaia DR3 catalogue, the effective temperature of the system is 12747 K. The linear light ephemeris of the system listed in the VarAstro database is given as follows:

$$Pri.Min(HJD) = 2452495.3880 + 2^d.31255 \times E. \quad (2)$$

Apsidal motion analysis was performed using 117 eclipse timings (58 primary and 59 secondary minima), including previously published times obtained from the VarAstro database, together with the new minima listed in Table A2. The resulting apsidal motion

[1] https://var.astro.cz/en/
[2] https://archive.stsci.edu/missions-and-data/tess

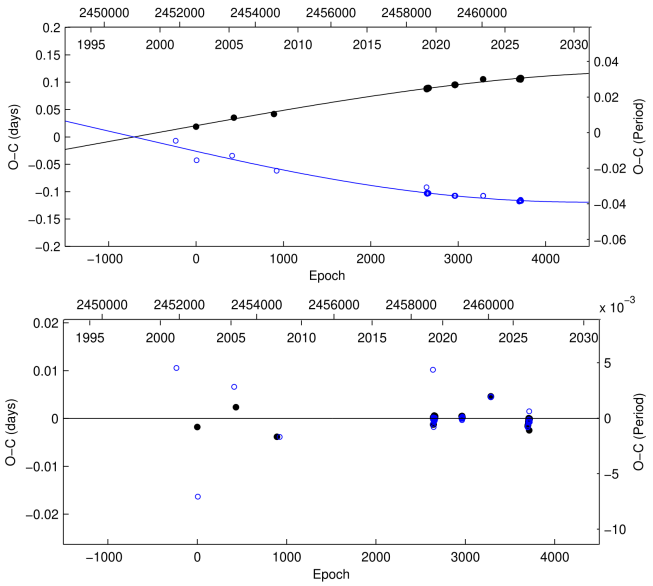


Figure 2. (O-C) diagram (upper) and residuals (bottom) of GSC 09010-01931. The labels are as in Figure 2.

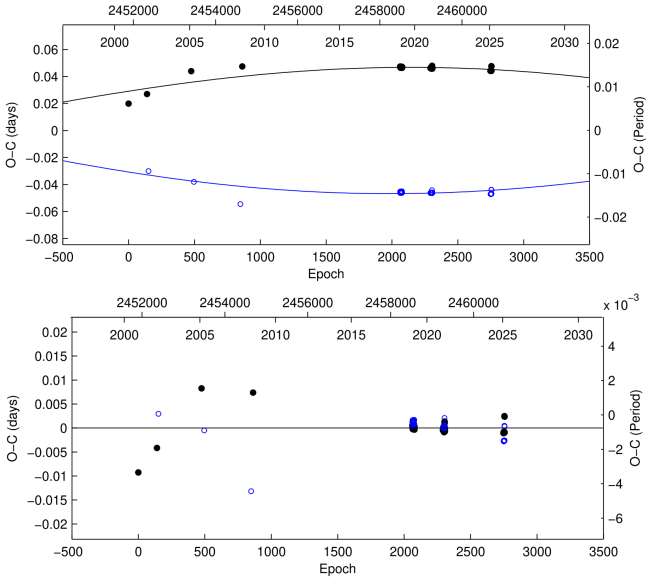


Figure 3. The (O-C) diagram (upper) and residuals (bottom) of GSC 07645-00517. The labels are as in Figure 3.

parameters and their associated uncertainties are presented in Table 2. The analysis yielded an apsidal motion period of $U = 142 \pm 25$ yr and an orbital eccentricity of $e = 0.1607 \pm 0.0123$ for GSC 09010-01931. The best-fitting model to the (O-C) diagram, along with the corresponding residuals, is shown in Figure 2. The residuals of the (O–C) diagram do not exhibit any cyclic variations, indicative of a tertiary component.

2.3. GSC 07645-00517

GSC 07645-00517 (TIC 130875223, TYC 7645-517-1, ASAS J074845-3801.8) is a detached eclipsing binary system. It was first identified as a variable star by Pojmanski (2002). Later, Kim et al. (2018) classified the system as an eclipsing binary with an eccentric orbit and reported that the phase of the secondary minimum occurs at 0.475. According to the Gaia DR2 catalogue, the effective temperature of the system is 6855 K. The linear light ephemeris of the system listed in the VarAstro database is given as follows:

$$Pri.Min(HJD) = 2451884.3 + 3^{\mathrm{d}}.20504 \times E. \quad (3)$$

Apsidal motion analysis was performed using 80 eclipse timings (45 primary and 35 secondary minima), including previously published times obtained from the VarAstro database, together with the new minima listed in Table A3. The compiled minimum times span the period from 2001 to 2025, corresponding to a time baseline of approximately 24 years. The resulting apsidal motion parameters and their associated uncertainties are listed in Table 2. The analysis yielded an apsidal motion period of $U = 112 \pm 14$ yr and an orbital eccentricity of $e = 0.0466 \pm 0.0175$ for GSC 07645-00517. The best-fitting model applied to the (O–C) diagram, together with the corresponding residuals, is shown in Figure 3. The residuals of the (O–C) diagram show no evidence of cyclic modulation, which would indicate the presence of a tertiary component.

2.4. GSC 09022-01175

GSC 09022-01175 (TIC 423508877, NT TrA, HD 139337, Sp = B9IV) is a detached binary of early type. Strohmeier et al. (1964) discovered that the system has a binary structure. The database of eclipsing binaries with eccentric orbits by Bulut & Demircan (2007) includes this system. Kim et al. (2018) classified the system as an eclipsing binary with an eccentric orbit and reported that the phase of the secondary minimum occurs at 0.568. According to the Gaia DR3 catalogue, the effective temperature of the system is 10134 K. The linear light ephemeris for the system, as given in the VarAstro database, is as follows:

$$Pri.Min(HJD) = 2452062.5570 + 3^{\mathrm{d}}.230 \times E. \quad (4)$$

The apsidal motion analysis was performed using 63 eclipse timings (31 primary and 32 secondary minima), including previously published times obtained from the VarAstro database, together with the new minima listed in Table A4. The compiled minimum times cover the interval from 2002 to 2023, corresponding to a time baseline of approximately 21 years. The resulting apsidal motion parameters and their associated uncertainties are presented in Table A2. The analysis yielded an apsidal motion period of $U = 345 \pm 140$ yr and an orbital eccentricity of $e = 0.1427 \pm 0.0154$ for GSC 09022-01175. The best-fitting model applied to the (O–C) diagram is shown in Figure 4. As seen in the middle panel of Figure 4, the residuals of the apsidal motion fit exhibit cyclic modulation, suggesting the presence of a tertiary component. The periodic variation in the (O-C) diagram was modeled using the classical light-travel time effect (LITE) formulation proposed by Irwin (1959). The analysis reveals a cyclic variation with a semi-amplitude of $A = 0.0108$ days and a modulation period of $P_3 = 15.07$ years. From this solution, the projected semi-major axis of the eclipsing binary around the center of mass of the triple system was found to be $a_{12} \sin i_3 = 1.9$ AU. The orbital eccentricity, longitude of periastron, and mass function of the third body were derived as $e_3 = 0.388$, $\omega_3 = 215°$, and $f(M_3) = 0.034, M_\odot$, respectively. To estimate the mass of the possible tertiary component, the masses of the binary components and the orbital inclination were required. The corresponding best-fit LITE model is illustrated in the middle panel of Figure 4.

Table 2. Apsidal motion elements

Parameters	GSC 08691-00026	GSC 09010-01931	GSC 07645-00517	GSC 09022-01175
T_0 (BJD)	2451904.9965 ± 0.0328	2452495.3693 ± 0.0356	2451884.2786 ± 0.0210	2452061.0385 ± 0.0302
P_s (days)	2.4699835 ± 0.0000104	2.3125580 ± 0.0000116	3.2050404 ± 0.0000197	3.2299938 ± 0.0000146
P_a (days)	2.4700692 ± 0.0000104	2.3126610 ± 0.0000116	3.2052917 ± 0.0000197	3.2300706 ± 0.0000146
e	0.1749 ± 0.0177	0.1607 ± 0.0123	0.0466 ± 0.0175	0.1427 ± 0.0154
$\dot{\omega}$ (deg/cycle)	0.0124 ± 0.0017	0.0160 ± 0.0028	0.0282 ± 0.0035	0.0092 ± 0.0063
ω_0 (deg)	89.3 ± 5.6	101.4 ± 9.2	128.1 ± 7.9	215.49 ± 7.62
U (yrs)	195 ± 26	142 ± 25	112 ± 14	345 ± 140

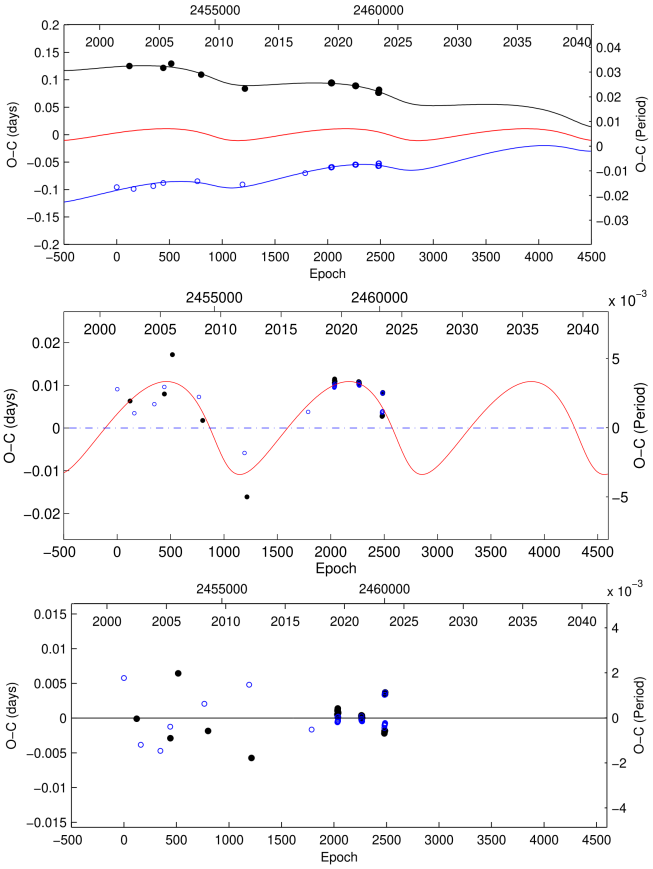


Figure 4. (O–C) diagram of the times of minimum light for GSC 09022-01175 (top panel). The middle panel shows the residuals after subtraction of the apsidal motion, representing the LITE contribution. The bottom panel displays the residuals after removal of both the apsidal motion and the LITE effect. The symbols are as in Figure 1.

3. Conclusions and Discussion

In this study, we present the first apsidal motion analysis of the eclipsing binary star systems GSC 08691-00026, GSC 09010-01931, GSC 07645-00517, and GSC 09022-01175. The apsidal motion parameters were derived from (O–C) diagrams constructed using times of minimum light collected from the literature together with new minima determined from TESS photometric observations. The analyses show that the apsidal motion periods of GSC 08691-00026, GSC 09010-01931, GSC 07645-00517 and GSC 09022-01175 are $U = 195 \pm 26$, 142 ± 25, 112 ± 14 and 345 ± 140 years, respectively, while the orbital eccentricities are $e = 0.1749 \pm 0.0177$, 0.1607 ± 0.0123, 0.0466 ± 0.0175 and 0.1427 ± 0.0154. These results demonstrate that all four systems exhibit clearly detectable apsidal motion.

Furthermore, the residuals of the (O–C) diagrams for the target systems, except for GSC 09022-01175, show no evidence of cyclic modulation indicative of a tertiary component. For GSC 09022-01175, the LITE analysis reveals a possible third body with an orbital semi-major axis of $a_{12} \sin i_3 = 1.9$ AU and an orbital period of $P_3 = 15.07$ years. The mass function of the tertiary component is derived to be $f(M_3) = 0.034, M_\odot$.

Continued monitoring and additional determination of minimum light times are essential for improving the accuracy of the apsidal motion parameters.

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APPENDICES

A. Mid-eclipse times

Table A1. New minimum times of GSC 08691-00026.

BJD+2400000	*E*	*O* − *C*	*Type*	Ref.	BJD+2400000	*E*	*O* − *C*	*Type*	Ref.
58598.7196	2710.0	0.0773	P	1	59357.0114	3017.0	0.0852	P	1
58598.7200	2710.0	0.0777	P	1	59358.0810	3017.5	-0.0802	S	1
58599.8042	2710.5	-0.0731	S	1	59358.0812	3017.5	-0.0799	S	1
58601.1896	2711.0	0.0773	P	1	59359.4810	3018.0	0.0849	P	1
58601.1900	2711.0	0.0777	P	1	59359.4814	3018.0	0.0853	P	1
58602.2741	2711.5	-0.0732	S	1	60069.4300	3305.5	-0.0854	S	1
58603.6590	2712.0	0.0767	P	1	60070.8430	3306.0	0.0926	P	1
58603.6595	2712.0	0.0772	P	1	60071.9000	3306.5	-0.0854	S	1
58604.7438	2712.5	-0.0735	S	1	60073.3130	3307.0	0.0926	P	1
58606.1293	2713.0	0.0771	P	1	60074.3690	3307.5	-0.0864	S	1
58606.1300	2713.0	0.0778	P	1	60075.7830	3308.0	0.0927	P	1
58607.2140	2713.5	-0.0732	S	1	60076.8390	3308.5	-0.0863	S	1
58608.5995	2714.0	0.0773	P	1	60078.2530	3309.0	0.0927	P	1
58608.6000	2714.0	0.0778	P	1	60079.3090	3309.5	-0.0863	S	1
58609.6790	2714.5	-0.0782	S	1	60080.7230	3310.0	0.0927	P	1
58609.6818	2714.5	-0.0754	S	1	60081.7790	3310.5	-0.0863	S	1
58611.0694	2715.0	0.0772	P	1	60083.1930	3311.0	0.0927	P	1
58611.0700	2715.0	0.0778	P	1	60084.2490	3311.5	-0.0863	S	1
58612.1557	2715.5	-0.0715	S	1	60085.6630	3312.0	0.0927	P	1
58613.5390	2716.0	0.0768	P	1	60086.7190	3312.5	-0.0863	S	1
58613.5397	2716.0	0.0775	P	1	60088.1330	3313.0	0.0928	P	1
58614.6239	2716.5	-0.0733	S	1	60089.1890	3313.5	-0.0862	S	1
58616.0094	2717.0	0.0772	P	1	60090.6030	3314.0	0.0928	P	1
58616.0100	2717.0	0.0778	P	1	60090.6074	3314.0	0.0972	P	1
58617.0941	2717.5	-0.0730	S	1	60091.6590	3314.5	-0.0862	S	1
58618.4790	2718.0	0.0769	P	1	60091.6634	3314.5	-0.0818	S	1
58618.4796	2718.0	0.0775	P	1	60093.0730	3315.0	0.0928	P	1
58619.5639	2718.5	-0.0732	S	1	60093.0773	3315.0	0.0971	P	1
58620.9490	2719.0	0.0769	P	1	60094.1290	3315.5	-0.0862	S	1
58620.9495	2719.0	0.0774	P	1	60094.1334	3315.5	-0.0818	S	1
58622.0337	2719.5	-0.0734	S	1	60095.5430	3316.0	0.0928	P	1
58623.4196	2720.0	0.0775	P	1	61046.4920	3701.0	0.0995	P	1
58623.4200	2720.0	0.0779	P	1	61047.5310	3701.5	-0.0964	S	1
59334.7810	3008.0	0.0847	P	1	61048.9622	3702.0	0.0998	P	1
59334.7813	3008.0	0.0850	P	1	61050.0012	3702.5	-0.0962	S	1
59335.8510	3008.5	-0.0803	S	1	61051.4323	3703.0	0.0999	P	1
59335.8515	3008.5	-0.0798	S	1	61052.4713	3703.5	-0.0961	S	1
59337.2510	3009.0	0.0847	P	1	61053.9026	3704.0	0.1001	P	1
59337.2514	3009.0	0.0851	P	1	61054.9414	3704.5	-0.0960	S	1
59338.3217	3009.5	-0.0796	S	1	61063.7832	3708.0	0.1008	P	1
59338.3220	3009.5	-0.0793	S	1	61064.8219	3708.5	-0.0954	S	1
59339.7210	3010.0	0.0847	P	1	61066.2534	3709.0	0.1011	P	1
59339.7215	3010.0	0.0852	P	1	61068.7235	3710.0	0.1012	P	1
59340.7916	3010.5	-0.0797	S	1	61069.7622	3710.5	-0.0951	S	1
59340.7920	3010.5	-0.0793	S	1	61071.1937	3711.0	0.1015	P	1
59342.1910	3011.0	0.0847	P	1	61072.2322	3711.5	-0.0950	S	1
59342.1914	3011.0	0.0851	P	1	61073.6636	3712.0	0.1013	P	1
59343.2617	3011.5	-0.0796	S	1	61074.7023	3712.5	-0.0950	S	1
59343.2620	3011.5	-0.0793	S	1	61076.1338	3713.0	0.1016	P	1
59344.6610	3012.0	0.0847	P	1	61077.1723	3713.5	-0.0949	S	1
59344.6613	3012.0	0.0850	P	1	61078.6038	3714.0	0.1016	P	1
59345.7318	3012.5	-0.0794	S	1	61079.6422	3714.5	-0.0950	S	1
59345.7320	3012.5	-0.0792	S	1	61081.0738	3715.0	0.1016	P	1
59348.2010	3013.5	-0.0802	S	1	61082.1121	3715.5	-0.0951	S	1
59348.2014	3013.5	-0.0798	S	1	61083.5438	3716.0	0.1017	P	1
59349.6010	3014.0	0.0848	P	1	61084.5820	3716.5	-0.0951	S	1
59349.6013	3014.0	0.0851	P	1	61086.0138	3717.0	0.1016	P	1
59350.6710	3014.5	-0.0802	S	1	61087.0519	3717.5	-0.0953	S	1
59350.6713	3014.5	-0.0799	S	1	61088.4839	3718.0	0.1017	P	1
59352.0710	3015.0	0.0848	P	1	61089.5220	3718.5	-0.0951	S	1
59352.0714	3015.0	0.0852	P	1	61090.9538	3719.0	0.1017	P	1
59353.1410	3015.5	-0.0802	S	1	61091.9920	3719.5	-0.0951	S	1
59353.1415	3015.5	-0.0797	S	1	61093.4239	3720.0	0.1018	P	1
59354.5410	3016.0	0.0848	P	1	61094.4620	3720.5	-0.0951	S	1
59354.5414	3016.0	0.0852	P	1	61095.8939	3721.0	0.1018	P	1
59355.6110	3016.5	-0.0802	S	1	61096.9318	3721.5	-0.0952	S	1
59355.6114	3016.5	-0.0798	S	1	61098.3639	3722.0	0.1018	P	1
59357.0110	3017.0	0.0848	P	1	61099.4019	3722.5	-0.0951	S	1

Min.type; P-Primary, S-Secondary minimums, Ref.; 1: TESS

Table A2. New minimum times of GSC 09010-01931.

BJD+2400000	*E*	*O* − *C*	*Type*	Ref.	BJD+2400000	*E*	*O* − *C*	*Type*	Ref.
58596.9617	2638.5	-0.0920	S	1	59347.5739	2963.0	0.0951	P	1
58598.2972	2639.0	0.0872	P	1	59348.5273	2963.5	-0.1077	S	1
58599.2629	2639.5	-0.1033	S	1	59349.8868	2964.0	0.0955	P	1
58600.6113	2640.0	0.0888	P	1	59350.8400	2964.5	-0.1076	S	1
58601.5763	2640.5	-0.1025	S	1	59352.1991	2965.0	0.0952	P	1
58602.9237	2641.0	0.0886	P	1	59353.1527	2965.5	-0.1074	S	1
58603.8889	2641.5	-0.1025	S	1	59354.5117	2966.0	0.0953	P	1
58605.2361	2642.0	0.0885	P	1	59355.4654	2966.5	-0.1073	S	1
58606.2019	2642.5	-0.1020	S	1	59356.8242	2967.0	0.0952	P	1
58607.5488	2643.0	0.0886	P	1	59357.7775	2967.5	-0.1078	S	1
58608.5143	2643.5	-0.1022	S	1	59359.1368	2968.0	0.0953	P	1
58612.1727	2645.0	0.0874	P	1	59360.0901	2968.5	-0.1077	S	1
58613.1375	2645.5	-0.1041	S	1	60092.2278	3285.0	0.1054	P	1
58614.4863	2646.0	0.0884	P	1	60093.1711	3285.5	-0.1076	S	1
58615.4515	2646.5	-0.1026	S	1	60094.5403	3286.0	0.1053	P	1
58616.7993	2647.0	0.0889	P	1	60095.4838	3286.5	-0.1075	S	1
58617.7637	2647.5	-0.1030	S	1	61047.3144	3698.0	0.1055	P	1
58619.1116	2648.0	0.0886	P	1	61048.2472	3698.5	-0.1180	S	1
58620.0767	2648.5	-0.1026	S	1	61049.6271	3699.0	0.1057	P	1
58621.4242	2649.0	0.0887	P	1	61050.5599	3699.5	-0.1178	S	1
58622.3891	2649.5	-0.1027	S	1	61051.9398	3700.0	0.1058	P	1
58623.7373	2650.0	0.0892	P	1	61054.2524	3701.0	0.1058	P	1
58626.0500	2651.0	0.0893	P	1	61055.1853	3701.5	-0.1175	S	1
58627.0141	2651.5	-0.1028	S	1	61063.5033	3705.0	0.1065	P	1
58628.3626	2652.0	0.0894	P	1	61064.4361	3705.5	-0.1170	S	1
58629.3270	2652.5	-0.1025	S	1	61065.8160	3706.0	0.1067	P	1
58630.6748	2653.0	0.0890	P	1	61066.7486	3706.5	-0.1170	S	1
58631.6397	2653.5	-0.1024	S	1	61068.1290	3707.0	0.1071	P	1
58632.9874	2654.0	0.0891	P	1	61069.0615	3707.5	-0.1167	S	1
58633.9520	2654.5	-0.1026	S	1	61070.4414	3708.0	0.1069	P	1
58635.3000	2655.0	0.0891	P	1	61071.3741	3708.5	-0.1166	S	1
58636.2647	2655.5	-0.1025	S	1	61072.7544	3709.0	0.1074	P	1
58637.6122	2656.0	0.0888	P	1	61073.6864	3709.5	-0.1169	S	1
58638.5767	2656.5	-0.1030	S	1	61075.0668	3710.0	0.1072	P	1
58640.8899	2657.5	-0.1024	S	1	61075.9992	3710.5	-0.1167	S	1
58642.2376	2658.0	0.0890	P	1	61077.3793	3711.0	0.1072	P	1
58643.2021	2658.5	-0.1027	S	1	61078.3120	3711.5	-0.1164	S	1
58644.5506	2659.0	0.0895	P	1	61079.6921	3712.0	0.1074	P	1
58645.5145	2659.5	-0.1029	S	1	61080.6243	3712.5	-0.1167	S	1
58646.8631	2660.0	0.0894	P	1	61082.0045	3713.0	0.1072	P	1
58647.8272	2660.5	-0.1028	S	1	61082.9369	3713.5	-0.1166	S	1
58649.1753	2661.0	0.0891	P	1	61084.3170	3714.0	0.1072	P	1
58650.1397	2661.5	-0.1028	S	1	61085.2492	3714.5	-0.1169	S	1
58651.4882	2662.0	0.0894	P	1	61086.6273	3715.0	0.1049	P	1
59334.6523	2957.5	-0.1074	S	1	61087.5639	3715.5	-0.1147	S	1
59336.0113	2958.0	0.0953	P	1	61088.9421	3716.0	0.1072	P	1
59336.9646	2958.5	-0.1076	S	1	61089.8746	3716.5	-0.1166	S	1
59338.3239	2959.0	0.0954	P	1	61091.2548	3717.0	0.1073	P	1
59339.2773	2959.5	-0.1075	S	1	61092.1872	3717.5	-0.1166	S	1
59340.6364	2960.0	0.0953	P	1	61093.5674	3718.0	0.1074	P	1
59341.5898	2960.5	-0.1076	S	1	61094.4997	3718.5	-0.1166	S	1
59342.9486	2961.0	0.0950	P	1	61095.8799	3719.0	0.1073	P	1
59343.9025	2961.5	-0.1074	S	1	61096.8122	3719.5	-0.1167	S	1
59345.2614	2962.0	0.0952	P	1	61098.1926	3720.0	0.1074	P	1
59346.2145	2962.5	-0.1080	S	1	61099.1244	3720.5	-0.1170	S	1

Min.type; P-Primary, S-Secondary minimums, Ref.; 1: TESS

Table A3. New minimum times of GSC 07645-00517.

BJD+2400000	*E*	*O* – *C*	*Type*	Ref.	BJD+2400000	*E*	*O* – *C*	*Type*	Ref.
58493.1199	2062.0	0.0482	P	1	59246.3032	2297.0	0.0471	P	1
58494.6297	2062.5	-0.0445	S	1	59247.8132	2297.5	-0.0455	S	1
58496.3249	2063.0	0.0482	P	1	59249.5083	2298.0	0.0471	P	1
58497.8338	2063.5	-0.0454	S	1	59251.0183	2298.5	-0.0454	S	1
58499.5298	2064.0	0.0480	P	1	59252.7135	2299.0	0.0473	P	1
58501.0398	2064.5	-0.0445	S	1	59255.9178	2300.0	0.0465	P	1
58502.7349	2065.0	0.0481	P	1	59257.4284	2300.5	-0.0454	S	1
58505.9399	2066.0	0.0481	P	1	59259.1234	2301.0	0.0471	P	1
58507.4498	2066.5	-0.0446	S	1	59260.6337	2301.5	-0.0451	S	1
58509.1443	2067.0	0.0474	P	1	59262.3285	2302.0	0.0472	P	1
58510.6548	2067.5	-0.0446	S	1	59263.8384	2302.5	-0.0455	S	1
58512.3499	2068.0	0.0480	P	1	59265.5337	2303.0	0.0473	P	1
58513.8598	2068.5	-0.0446	S	1	59267.0454	2303.5	-0.0435	S	1
58515.5549	2069.0	0.0479	P	1	59270.2483	2304.5	-0.0456	S	1
58518.7597	2070.0	0.0477	P	1	59271.9452	2305.0	0.0487	P	1
58518.7600	2070.0	0.0480	P	1	59273.4536	2305.5	-0.0454	S	1
58520.2698	2070.5	-0.0447	S	1	59275.1489	2306.0	0.0474	P	1
58521.9650	2071.0	0.0480	P	1	59276.6586	2306.5	-0.0454	S	1
58523.4749	2071.5	-0.0447	S	1	59278.3532	2307.0	0.0467	P	1
58525.1700	2072.0	0.0479	P	1	60691.7739	2748.0	0.0446	P	1
58526.6792	2072.5	-0.0454	S	1	60693.2853	2748.5	-0.0466	S	1
58528.3748	2073.0	0.0477	P	1	60694.9791	2749.0	0.0447	P	1
58531.5800	2074.0	0.0478	P	1	60696.4902	2749.5	-0.0467	S	1
58536.2955	2075.5	-0.0442	S	1	60698.1841	2750.0	0.0447	P	1
58537.9899	2076.0	0.0477	P	1	60699.6953	2750.5	-0.0466	S	1
58539.4996	2076.5	-0.0452	S	1	60701.3893	2751.0	0.0448	P	1
58541.1946	2077.0	0.0473	P	1	60702.9005	2751.5	-0.0465	S	1
59230.2779	2292.0	0.0470	P	1	60704.5943	2752.0	0.0448	P	1
59231.7879	2292.5	-0.0456	S	1	60706.1054	2752.5	-0.0466	S	1
59233.4829	2293.0	0.0469	P	1	60707.7992	2753.0	0.0447	P	1
59234.9930	2293.5	-0.0455	S	1	60709.3105	2753.5	-0.0466	S	1
59236.6880	2294.0	0.0470	P	1	60711.0042	2754.0	0.0446	P	1
59238.1981	2294.5	-0.0454	S	1	60712.5156	2754.5	-0.0465	S	1
59239.8933	2295.0	0.0472	P	1	60714.2127	2755.0	0.0481	P	1
59243.0983	2296.0	0.0472	P	1	60715.7236	2755.5	-0.0435	S	1
59243.0984	2296.0	0.0473	P	1	60717.4176	2756.0	0.0479	P	1
59244.6080	2296.5	-0.0456	S	1					

Min.type; P-Primary, S-Secondary minimums, Ref.; 1: TESS

Table A4. New minimum times of GSC 09022-01175.

BJD+2400000	*E*	*O* – *C*	*Type*	Ref.	BJD+2400000	*E*	*O* – *C*	*Type*	Ref.
58625.9411	2032.5	-0.0688	S	1	59378.5346	2265.5	-0.0642	S	1
58627.7100	2033.0	0.0851	P	1	59380.2937	2266.0	0.0799	P	1
58629.1711	2033.5	-0.0688	S	1	59381.7649	2266.5	-0.0639	S	1
58630.9399	2034.0	0.0850	P	1	59383.5233	2267.0	0.0795	P	1
58632.4012	2034.5	-0.0687	S	1	59384.9948	2267.5	-0.0640	S	1
58634.1706	2035.0	0.0857	P	1	59386.7533	2268.0	0.0795	P	1
58635.6313	2035.5	-0.0686	S	1	59388.2246	2268.5	-0.0642	S	1
58637.4008	2036.0	0.0859	P	1	60069.7510	2479.5	-0.0669	S	1
58638.8613	2036.5	-0.0686	S	1	60071.4996	2480.0	0.0667	P	1
58640.6295	2037.0	0.0846	P	1	60072.9813	2480.5	-0.0666	S	1
58642.0915	2037.5	-0.0684	S	1	60074.7297	2481.0	0.0668	P	1
58643.8603	2038.0	0.0854	P	1	60076.2157	2481.5	-0.0622	S	1
58645.3214	2038.5	-0.0685	S	1	60077.9598	2482.0	0.0669	P	1
58647.0901	2039.0	0.0852	P	1	60079.4414	2482.5	-0.0665	S	1
58648.5517	2039.5	-0.0682	S	1	60081.1897	2483.0	0.0668	P	1
58650.3201	2040.0	0.0852	P	1	60082.6713	2483.5	-0.0666	S	1
58651.7821	2040.5	-0.0678	S	1	60084.4197	2484.0	0.0668	P	1
59362.3849	2260.5	-0.0640	S	1	60085.9014	2484.5	-0.0665	S	1
59364.1438	2261.0	0.0799	P	1	60087.6496	2485.0	0.0667	P	1
59365.6147	2261.5	-0.0642	S	1	60089.1356	2485.5	-0.0622	S	1
59367.3739	2262.0	0.0800	P	1	60090.8848	2486.0	0.0720	P	1
59368.8453	2262.5	-0.0636	S	1	60092.3615	2486.5	-0.0663	S	1
59370.6033	2263.0	0.0794	P	1	60092.3659	2486.5	-0.0619	S	1
59372.0747	2263.5	-0.0641	S	1	60094.1150	2487.0	0.0722	P	1
59373.8336	2264.0	0.0798	P	1	60095.5914	2487.5	-0.0664	S	1
59377.0635	2265.0	0.0797	P	1					

Min.type; P-Primary, S-Secondary minimums, Ref.; 1: TESS

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