ISSN 1063-7729, Astronomy Reports, 2015, Vol. 59, Nos. 11–12, pp. 1036–1052. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © V.S. Kozyreva, A.I. Bogomazov, B.P. Demkov, L.V. Zotov, A.V. Tutukov, 2015, published in Astronomicheskii Zhurnal, 2015, Vol. 92, No. 11, pp. 925–942.

An Exo-Jupiter Candidate in the Eclipsing Binary FL Lyr

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Received March 11, 2015; in final form, May 13, 2015

Abstract—Light curves of the eclipsing binary FL Lyr acquired by the Kepler space telescope are analyzed. Eclipse timing measurements for FL Lyr testify to the presence of a third body in the system. Preliminary estimates of its mass and orbital period are $\gtrsim 2M_J$ and $\gtrsim$7 yrs. The times of primary minimum in the light curve of FL Lyr during the operation of the Kepler mission are presented.

DOI: 10.1134/S1063772915110050

1. INTRODUCTION

Extra-solar planetary systems remained hypothetical objects until the 1990s, when modern means for their detection were developed. Since then, some 10^4 candidate exoplanets have been discovered using various methods; the existence of many of these exoplanets has been reliably confirmed [1]. The vast majority of the discovered planets orbit single stars or individual components of wide multiple systems.

Currently, we know of eight exoplanets in five stellar systems and two candidate planets that simultaneously orbit both components of binaries, with both stars on the main sequence. The first planet discovered in such a binary was Kepler-16 (AB)b [2]. Others include Kepler-34 (AB)b and Kepler-35 (AB)b [3], Kepler-38 (AB)b [4], Kepler-47 (AB)b and Kepler-47 (AB)c [5], PH1-Kepler-64b [6], Kepler-413 (AB)b [7, 8], a possible third planet in the Kepler-47 system [9], and the candidate planet KIC 9632895 (AB)b [10]. Several planets near cataclysmic variables and a planet near the young star FW Tau [1] have also been discovered.

Searching for planets in binary systems is important for a number of reasons. Though it follows from [11] that planetary orbits in binaries exhibit long-term stability, it remains to be confirmed from observations that planets can survive in systems with various parameters. The systems known up to now have very similar parameters. The presence or absence of planets in binary systems and the systems' parameters are very important for our understanding of the processes of star and planet formation (e.g., [12]). In addition, binary systems are more favorable for harboring life than single stars, and could in principle have several inhabited planets [13]. This makes searches for planets in various binary systems very important for searches for extraterrestrial, possibly even intelligent, life. A list of binary stars suitable for planetary searches can be found in [14], and includes the FL Lyr system.

In 2009–2014, the area of the sky containing FL Lyr was in the field of view of the Kepler space telescope [15], which was launched into near-solar orbit with the aim of searching for exoplanets. During these years, the telescope carried out a continuous photometric sky survey, during which a large amount of observing material was accumulated for FL Lyr. The Kepler observations can be used to study various scientific problems. In particular, a third body orbiting an eclipsing variable star gives rise to periodic shifts of the system's center of mass with respect to the observer, causing the observed orbital period of the binary to vary about a certain value. The aim of our current study is to study the light-time effect in the FL Lyr system[1].

2. THE ECLIPSING BINARY FL Lyr

The eclipsing variable FL Lyr was discovered on photographic plates in 1935 [16]. Its minima are

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[1] In other words, to perform timing of the minima of the FL Lyr light curve.

deep, with the change in the star's brightness at the primary and secondary minimum being different by a factor of two: $m_{\max} = 9.27^m$, $m_{\min\,\mathrm{I}} = 9.89^m$, $m_{\min\,\mathrm{II}} = 9.52^m$. According to the "General Catalog of Variable Stars" [17], $P_{orb} = 2.1781544^{\mathrm{d}}$. The stars in the system have different sizes and spectral types. In the 1950, Struve [18] obtained a spectroscopic radial-velocity curve of the primary and determined its spectral type to be G5.

In 1963, Cristaldi [19] obtained a photoelectric light curve and derived the photometric parameters of the system. He was able to estimate the masses of both components using earlier spectroscopy from various studies, both published and unpublished. The component parameters he found suggest that the two stars form an Algol-type system. In such systems, the primary (initially the higher-mass component) has left the main sequence (MS) and begun its expansion; in the process, the star has transferred some of its mass to the secondary. The mass of the primary becomes lower and its radius larger than its companion. At the same time, the primary is still on the MS, and the primary's luminosity is lower than the secondary's. This star is thus erroneously taken to be the secondary, while its companion, which initially had lower mass and is on the MS, is taken to be the primary.

Cristaldi [19] presents parameters calculated for the FL Lyr system: one of the components has a mass of $M_1 = 1\ M_\odot$, a relative radius[2] $r_1 = 0.132$, and a relative luminosity[3] in the V filter $L_1 = 0.234$, while the second component has $M_2 = 1.1\ M_\odot$, $r_2 = 0.114$, and $L_2 = 0.430$. This thus appears to be an Algol-type system, when the lower-mass star has a larger radius than the higher-mass one. A so-called "third light," $L_3 = 0.336$, is also present in the solution, and belongs to either a field star or a third component in the system. The binary components move in a plane almost orthogonal to the plane of the sky ($i = 89°$); the estimated product of the eccentricity and longitude of periastron is $e\cos\omega \leq 0.0002$. The orbits of the components are essentially circular. According to [19], the spectral types of the stars are estimated to be G0V + G5V.

In this study of the FL Lyr light curve, Botsula [20] found that the system's light decreased near the secondary minimum. He proposed that the system contained diffuse matter situated close to the secondary, which blocks some of the light in the secondary eclipse and distorts the shape of this part of the curve. This hypothesis is fully in accord with the physics of Algol-type stars, where the envelope of the more evolved primary flows toward the secondary. Moreover, the FL Lyr light curve displayed episodes of fading by as much as 0.04^m–0.05^m. It is possible that all these distortions have a random character, due to systematic errors in the particular part of the FL Lyr light curve studied in [20].

In 1986, Popper et al. [21] obtained photoelectric light curves and spectroscopic radial-velocity curves of FL Lyr. They derived a new photometric solution of the light curve ($r_1 = 0.140$, $r_2 = 0.105$, $i = 86.3°$, $L_1 = 0.79$, $L_2 = 0.21$), and estimated the stellar masses and spectral types: 1.22 $M_\odot$, 0.96 $M_\odot$, F8 + G8. The binary orbit is circular with high accuracy. Comparing the observed parameters of the system to those determined from theoretical evolutionary tracks of stars of the same mass, they estimated the age of the FL Lyr system to be 5.3×10^7–3.55×10^9 yrs, with the most likely age being 2.29×10^9 yrs [22]. Since the MS lifetime of a star with a mass of 1.2 $M_\odot$ is approximately 4.9×10^9 yrs [23, Eq. (6)], neither component of FL Lyr has left the MS. No third light was detected in [21]. When calculating the photometric parameters, an upper limit $k \leq 1$ was imposed on the parameter $k = r_2/r_1$ (the ratio of the radii of the secondary and the primary). This excludes all solutions for which the two stars form an Algol-type system, i.e., a system with a reversed component-radius ratio. However, Popper et al. [21] suggest that the correctness of their derived parameters is supported by the lack of systematic deviations between the calculated and observed values for the brightness difference as a function of time. The parameters of the stars differ considerably from the solution found by Cristaldi [19]. Among the characteristic features of the light curves, Popper et al. [21] noted a brightness modulation ($\Delta m = 0.007^m$), which they attributed to the axial rotation of the components.

3. OBSERVATIONS OF FL Lyr WITH THE KEPLER SPACE TELESCOPE

We studied data obtained with Kepler. The main goal of the Kepler project was to search for exoplanets using observations of their transits. We used the Kepler data for eclipse-timing measurements (determining the light-time effect) for FL Lyr. Detailed information on the Kepler space telescope can be found in [24].

The Kepler data we used can be found in the Barbara A. Mikulski Archive for Space Telescopes [25], which is supported by the Space Telescope Science Institute. The identification number of FL Lyr in the Kepler Input Catalog is 9641031. Detailed

[2] Expressed in fractions of the orbital semi-major axis of FL Lyr.

[3] Expressed in fractions of the system's combined luminosity.

information on the search and retrieval of data from the archive can be found in [24].

The Kepler archive consists of data files in FITS format. Two versions of these files are provided: LC (long cadence) and SC (short cadence). LC is the main version; these data were collected once each 30 minutes. One LC FITS file contains observations of one object over one quarter[4]. SC is a complementary version of the data (intended for variability and asteroseismology studies); these data were collected once each minute. A single SC FITS file provides data for one month for a single object. Because of the design of Kepler, SC data were not accumulated during every quarter of the telescope's operation. SC data for FL Lyr are fully available only for the observing quarters 7, 8, 13, 14, 15, and 16. To improve the accuracy of our study, we used the FITS files obtained in SC mode. We converted the FITS files to a form convenient for the analysis using the IRAF software with the PyRAF extension (the kepconvert routine, which converts FITS files to text files).

4. THE LIGHT-TIME EFFECT IN FL Lyr

One of the methods that can be used to detect a third body in an eclipsing system is to search for the light-time effect. The periods of the primary and secondary minima will oscillate if the distance between the center of the solar system and the center of the eclipsing system varies. Any third body in a binary system makes the system's center of mass move with the period of this body's orbit[5]. The comparatively short period of the stars' orbit about the common center (about two days) makes it possible to identify a large number of light curves within minima in the Kepler observations. Our aim is to look for the light-time effect in the FL Lyr system; i.e., to search for shifts in the observed times of minima relative to the calculated values.

The orbit of a binary system rotates due to tidal forces between the two stars and general relativistic effects. In the case of an elliptical orbit, this rotation is manifest through apsidal motion, which gives rise to a shift of the observed relative to the calculated times of minima. For FL Lyr, with its practically circular binary orbit ($e \leq 0.0002$), theoretical estimates of the apsidal motion predict the period of this motion to be longer than 100 years, and its amplitude to be below 10 s. This effect is very small over the time interval of the Kepler observations, can be neglected. We are looking for the light-time effect with much shorter periods.

We considered solely the primary minima. These are symmetric and deep ($\approx 0.6^m$)—more than twice as deep as the secondary minima—increasing the accuracy of the timing of the minima by the same factor. We identified about 600 Kepler light curves within primary minima of FL Lyr.

Kepler observations possess systematic errors (see, for instance, [24, Section 7.1])—so-called linear trends, which can reach several hundredths of a magnitude during the duration of a minimum in the FL Lyr light curve. Our study of the FL Lyr light curves already corrected for this linear trend using correction factors shows that the trend was not fully removed, so that the shape of the light curves during minima remains distorted. The brightness difference between the ingress and egress reaches several ten-thousandths of a magnitude, with different signs for different light curves. Distortions by one ten-thousandth of a magnitude for the primary minima of FL Lyr translate into an error of approximately 2 s in the times of minima. This is a large error, and is able to completely distort the light-time effect due to the presence of a planet with an amplitude of the order of 5–6 s.

Light-time effects for 1279 close eclipsing binary systems were studied by Conroy et al. [26], who report the discovery of 236 eclipsing binaries with suspected third bodies. This study will be supplemented with an analysis of orbital-period variations (Orosz et al., in preparation; see [26]). It will be very interesting to compare our results to those of Orosz et al..

We studied individual light curves of primary minima of FL Lyr obtained with Kepler and calculated individual correction factors to remove the linear trend in each case, based on the hypothesis that the brightnesses at the eclipse ingress and egress are intrinsically the same. Since changes in the trend correction factors occur only rarely, no more than twice during the period of FL Lyr, we adopted the hypothesis that the trend does not curve significantly within a light-curve minimum ($\approx$4 hours), and corrected the light curve using a single set of correction coefficients that were specific to each minimum. Even if the origins of the different brightnesses at the beginnings and ends of minima are physical, our approach enables us to search for the light-time effect, since we are studying the dynamics of changes in the times of minima. If the light curve changes slowly compared to the observing period, all the times of minima will be

[4] The light curves within the FL Lyr minima contain only five to six data points in the LC mode.

[5] The stability of planetary orbits in binary systems was studied in [11]; according to Table 6 in [11], the orbit of a planet around the central binary will be stable if the semi-major axis of the planet's orbit is approximately a factor of four or more larger than the semi-major axis of the binary orbit; i.e., if the orbital period of the planet is longer than the orbital period of the central binary star by a factor of 10 or more, as follows from Kepler's third law. Thus, the conditions for the long-term survival of planets in the FL Lyr system are satisfied for planetary orbital periods exceeding 20 days.

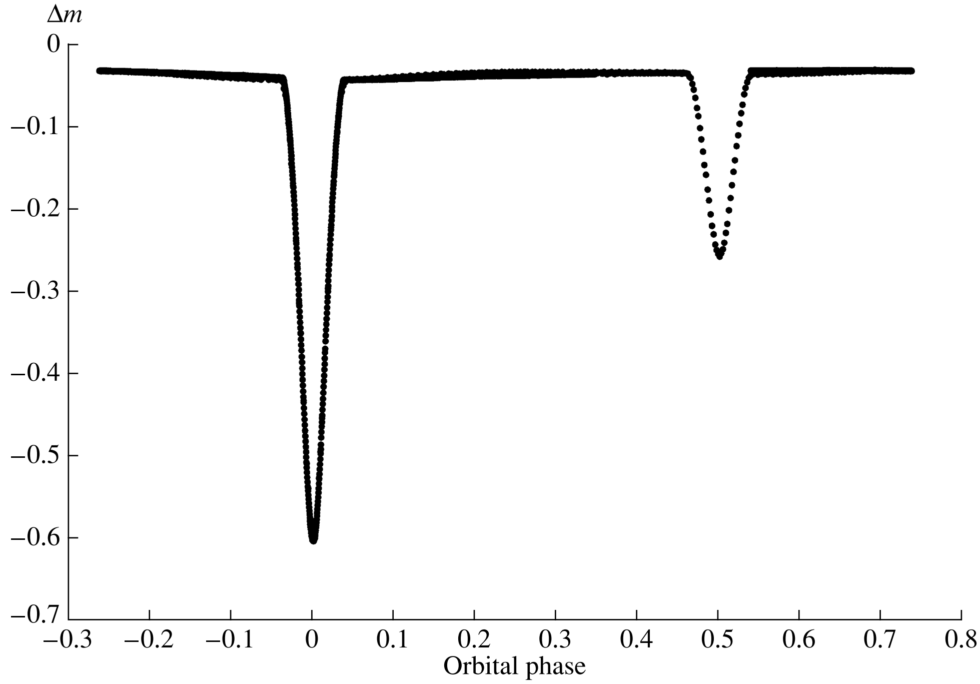

Fig. 1. Light curve of FL Lyr compiled from Kepler observations between HJD 55031.54198 and HJD 55042.44777. It includes the times of primary minimum HJD 55032.54697, HJD 55034.72509, HJD 55036.90328, HJD 55039.08140, and HJD 55041.25957. All HJD times actually correspond to HJD−2400000.

displaced relative to the true times, but the magnitude of this shift will not influence the amplitude of the light-time effect. If, however, the changes in the light curve are comparable to the duration of the observations, which is very improbable, the light-time effect will be determined with additional systematic errors. Nevertheless, the period of the light-time effect can be derived from the light curve. When determining the times of the primary minima, we used a template theoretical light curve calculated from the orbital elements and the relative parameters of the stars in this binary system.

When calculating the photometric elements, we used the combined light curves compiled from observations obtained in the SC mode; these contained only neighboring observations within primary and secondary minima (Fig. 1 shows a sample light curve of FL Lyr). The photoelectric light curves of FL Lyr obtained by Popper et al. [21] exhibit the same out-of-eclipse brightness level for both minima. We used this finding when selecting light curves used to calculate the photometric elements. Since the observations are distorted by the linear trend, we tried to select light curves for which this was minimal. The influence of the trend in each case is a random value, and the resulting sets of elements had nearly normal distributions. The parameter most important in the search for the light-time effect is the shift of the observed times of primary minimum relative to the calculated times (O−C). These shifts depended only weakly on variations of the other parameters we determined, presented in Table 1. Column 2 of this table contains the ranges of the parameters found for the various light curves of FL Lyr. Column 3 gives the set of parameters we used to derive the theoretical curve we then applied as a template.

The CCD chip of the spacecraft has a broad filter ranging from 430 to 890 nm, corresponding to the combined range of the B, V, and R filters of the Johnson photometric system. Therefore, it is not correct to compare photometric elements based on these light curves with elements derived using light curves obtained in the Johnson filters; this is especially true for the luminosities of the components.

We used a quasi-Newtonian method with analytical computation of the functional derivatives as a minimization algorithm[6]. The minimization functional contains the sum of the squared differences between the observed and theoretical magnitudes at each point, including simple and linear limitations for the parameter values we seek. Because of their very weak influence on the light curves, we did not vary the limb-darkening coefficients u_1 and u_2, and fixed them in accordance with the spectral types of

[6] The same algorithm was used earlier in [27−31], resulting in the discoveries of brown dwarfs in the HP Aur and AS Cam systems.

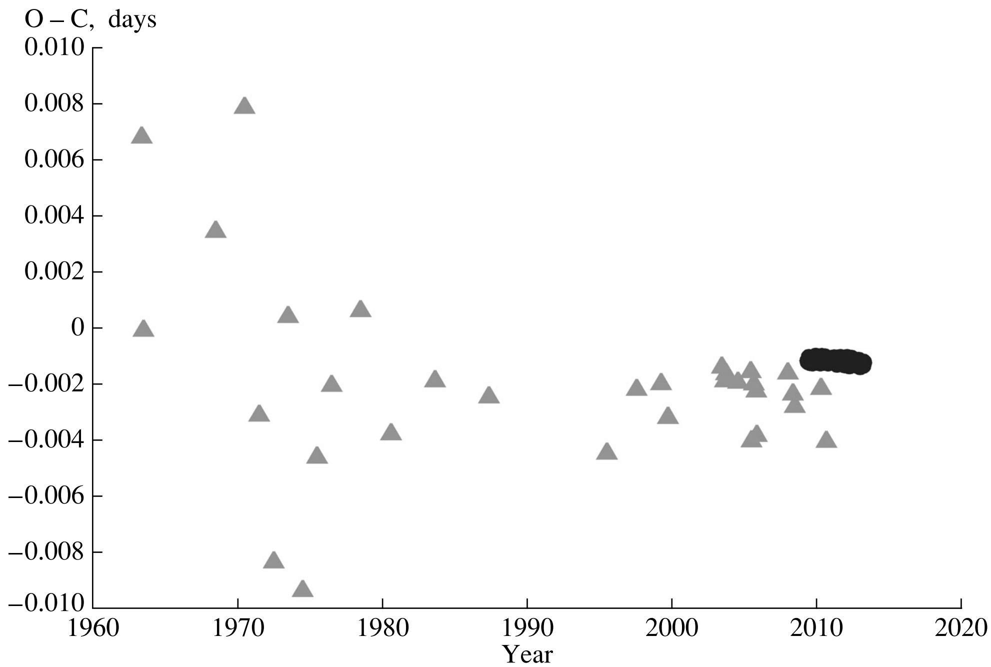

Fig. 2. Times of minima of FL Lyr. The black circles show Kepler data (Table 3), and the gray triangles data from ground-based observations (Table 2). The x axis plots the dates of the observations and the y axis the differences between the observed times of minimum and times of minimum calculated using (1).

the binary components (F8V + G8V [21]). Values for the theoretical coefficients u_1 and u_2 corresponding to wavelengths in the middle of the instrumental range were taken from [32]. Some of the parameters we determined in our free search for the orbital elements and parameters differ considerably from those obtained by Popper [21]; this is especially true for component luminosities. This can partially be explained by the different spectral ranges used. In our current study, we are interested in the set of elements only as a tool for deriving a theoretical curve that most closely approaches the observed curves at the primary minima.

Times of minima we collected from the literature are presented in Fig. 2 and Table 2. The scatter of the data points in Fig. 2, which includes photographic observations, is very large, up to ±15 minutes. The scatter of the photoelectric times of minima can reach ±1.5 minutes. This large scatter of the times of minima can be explained in many ways, some of them described above. Our aim was to find the amplitude of the light-time effect with an accuracy of seconds. The large scatter in the previously published times of minima makes those data unsuitable for this. Accordingly, we used only the long uniform series of Kepler observations, deriving the times of minima using the same algorithm.

We used only data points corresponding to primary minima of FL Lyr (phases from 0.94 to 1.06). After obtaining the light curve for an individual minimum without the linear trend, we then calculated the shift of the observed time of minimum from the calculated time. We applied an algorithm for calculating the minimal deviation between the observed and theoretical light curves;[7] the only free parameter was the shift of the primary minimum, with all other parameters being fixed at the values indicated in column 3 of Table 1. The criterion for our solution was a symmetric position of the deviations (between the observed and calculated light-curve points) relative to zero phase. We checked this by determining the linear trend in the O−C residuals, with the result being considered satisfactory only in the absence of any trend. This procedure was performed for all primary minima of FL Lyr observed with Kepler; the times of minima are collected in the first column of Table 3, while the second column contains the O−C residuals: the differences between the observed times of minima and the theoretical times of minima calculated with the ephemeris (1).

Searching for the light-time effect requires as accurate as possible knowledge of the binary's orbital period, on which the parameters of the light-time effect depend. We used three values of the orbital period of FL Lyr. The period $P_{10} = 2.17815440^d$ was taken from [19] (this is also the period given in [17]). The period $P_{11} = 2.17815408^d$ was obtained using all the data on the times of minima from ground-based

[7] See [27−31] for details.

Table 1. Parameters derived from the Kepler light curves and adopted in the calculations of the theoretical light curve of FL Lyr. r_1, r_2 are the radii of the primary and the secondary in units of the semi-major axis of FL Lyr; i the orbital inclination; e the orbital eccentricity; ω the longitude of periastron; L_1 and L_2 the luminosities of the primary and secondary in units of the system's luminosity; L_3 the "third light" in units of the system's luminosity; u_1 and u_2 limb-darkening coefficients for the primary and secondary; and $\sigma_{\text{O-C}}$ the standard (O−C) deviation

Parameters	Value for FL Lyr	Values adopted in the computations
r_1	0.122−0.133	0.123
r_2	0.118−0.126	0.123
i	85.3°−86.5°	85.9°
e	0−0.0002	0
ω	0°−360°	0
L_1	0.520−0.610	0.596
L_2	0.260−0.310	0.298
L_3	0.008−0.22	0.106
u_1	0.62 (fixed)	0.62 (fixed)
u_2	0.68 (fixed)	0.68 (fixed)
$\sigma_{\text{O-C}}$	−	0.00026^m

observations published since 1962, without Kepler data. Finally, the orbital period $P_{13} = 2.17815414^{\text{d}}$ was calculated using all the ground-based observations and six Kepler times of minima[8]. The system ephemerides for these three periods are

$$\text{Min I} = \text{HJD } 2438221.55250 + 2.17815440E, \quad (1)$$

$$\text{Min I} = \text{HJD } 2438221.55239 + 2.17815408E, \quad (2)$$

$$\text{Min I} = \text{HJD } 2438221.55211 + 2.17815414E. \quad (3)$$

The gray triangles in Fig. 2 are the O−C values calculated with the ephemeris (1) for the times of minima from the literature; the black circles are our values calculated using the Kepler observations. The shift in the times of minima we are seeking is clearly visible.

We carried out our further analysis of the data obtained for the three periods P_{10}, P_{11}, and P_{12}. The

[8] So that the space data would not dominate the other measurements, we took three Kepler times of minima for 2009 and three for 2014. The 2009 times of minima are HJD−2400000 = 54965.02424, 54967.20240, and 54969.38054, and the 2014 times are HJD−2400000 = 56385.18082, 56387.35900, and 56389.53716.

Table 2. Times of primary minima of FL Lyr from ground-based observations (the O−C deviations were calculated using the ephemeris (1))

Time of primary minimum, HJD−2400000	O−C, days	Reference
38173.6400	0.00690	[34]
38221.5525	0.00000	[19]
40038.1368	0.00350	[35]
40770.0011	0.00800	[35]
41133.7419	−0.00303	[35]
41499.6666	−0.00830	[35]
41865.6053	0.00050	[35]
42229.3473	−0.00930	[35]
42595.2820	−0.00454	[35]
42961.2145	−0.00197	[35]
43690.8989	0.00070	[35]
44459.7830	−0.00370	[36]
45572.8218	−0.00180	[36]
46925.4551	−0.00238	[37]
49909.5271	−0.00191	[38]
50654.4547	−0.00312	[39]
51266.5174	−0.00180	[40]
51440.7700	−0.00155	[41]
52806.4725	−0.00186	[42]
52911.0235	−0.00227	[43]
53209.4302	−0.00273	[44]
53531.7977	−0.00208	[45]
53555.7555	−0.00400	[45]
53612.3871	−0.00439	[46]
53673.3777	−0.00211	[46]
53684.2691	−0.00149	[47]
54466.2261	−0.00192	[48]
54583.8446	−0.00375	[49]
54594.7376	−0.00152	[49]
54642.6572	−0.00132	[49]
55304.8135	−0.00396	[50]
55437.6827	−0.00218	[50]

Table 3. Times of primary minima of FL Lyr found from Kepler data (the O−C deviations were calculated using the ephemeris (1))

Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days
54965.02424	−0.00113	55065.21935	−0.00113	55163.23632	−0.00110
54967.20240	−0.00113	55067.39750	−0.00113	55165.41448	−0.00110
54969.38054	−0.00114	55069.57563	−0.00115	55167.59263	−0.00110
54971.55866	−0.00118	55071.75385	−0.00109	55169.77094	−0.00095
54973.73682	−0.00117	55073.93203	−0.00106	55171.94888	−0.00116
54975.91499	−0.00115	55076.11020	−0.00105	55174.12705	−0.00115
54978.09314	−0.00116	55078.28829	−0.00111	55176.30523	−0.00112
54980.27127	−0.00118	55080.46645	−0.00111	55178.48340	−0.00110
54982.44946	−0.00115	55082.64459	−0.00112	55180.66164	−0.00102
54984.62759	−0.00117	55084.82276	−0.00110	55187.19601	−0.00111
54986.80578	−0.00114	55087.00089	−0.00113	55189.37422	−0.00106
54988.98393	−0.00114	55091.35710	−0.00123	55191.55238	−0.00105
54991.16210	−0.00113	55093.53539	−0.00109	55193.73047	−0.00111
54993.34026	−0.00112	55095.71356	−0.00108	55195.90868	−0.00106
54995.51841	−0.00112	55097.89167	−0.00112	55198.08687	−0.00102
54997.69669	−0.00100	55100.06984	−0.00111	55200.26502	−0.00103
55004.23105	−0.00110	55102.24797	−0.00113	55202.44317	−0.00103
55006.40922	−0.00109	55104.42610	−0.00115	55204.62133	−0.00103
55008.58736	−0.00110	55106.60426	−0.00115	55206.79947	−0.00104
55010.76549	−0.00113	55108.78242	−0.00114	55208.97767	−0.00100
55012.94365	−0.00112	55110.96060	−0.00112	55211.15577	−0.00105
55017.29999	−0.00109	55113.13873	−0.00114	55213.33390	−0.00107
55019.47812	−0.00111	55115.31692	−0.00111	55215.51200	−0.00113
55021.65625	−0.00114	55117.49504	−0.00114	55217.69013	−0.00115
55023.83439	−0.00115	55119.67321	−0.00113	55219.86829	−0.00115
55026.01257	−0.00113	55121.85135	−0.00114	55222.04642	−0.00117
55028.19073	−0.00112	55124.02950	−0.00114	55224.22459	−0.00116
55030.36885	−0.00115	55126.20765	−0.00115	55228.58090	−0.00116
55032.54697	−0.00119	55128.38578	−0.00117	55235.11540	−0.00112
55034.72509	−0.00122	55132.74208	−0.00118	55237.29356	−0.00111
55036.90328	−0.00119	55134.92022	−0.00120	55239.47174	−0.00109
55039.08140	−0.00122	55137.09838	−0.00119	55243.82801	−0.00113
55041.25957	−0.00121	55139.27653	−0.00119	55246.00621	−0.00108
55043.43771	−0.00122	55141.45468	−0.00120	55248.18439	−0.00105
55045.61584	−0.00125	55143.63282	−0.00121	55250.36247	−0.00113
55047.79406	−0.00118	55145.81099	−0.00120	55252.54061	−0.00114
55049.97218	−0.00121	55147.98918	−0.00116	55254.71876	−0.00115
55052.15043	−0.00112	55150.16731	−0.00119	55256.89700	−0.00106
55054.32850	−0.00120	55152.34548	−0.00117	55259.07514	−0.00108
55056.50666	−0.00120	55156.70175	−0.00121	55261.25326	−0.00111
55060.86302	−0.00115	55158.87990	−0.00121	55263.43145	−0.00108
55063.04122	−0.00110	55161.05809	−0.00118	55265.60958	−0.00110

Table 3. (Contd.)

Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days
55267.78771	−0.00112	55372.33909	−0.00116	55468.17791	−0.00113
55269.96587	−0.00112	55374.51723	−0.00117	55470.35605	−0.00114
55272.14398	−0.00116	55376.69534	−0.00121	55472.53419	−0.00116
55274.32208	−0.00122	55378.87356	−0.00115	55474.71229	−0.00121
55278.67836	−0.00125	55381.05167	−0.00119	55476.89043	−0.00123
55280.85650	−0.00126	55383.22987	−0.00115	55479.06858	−0.00123
55283.03465	−0.00127	55385.40802	−0.00115	55481.24671	−0.00126
55285.21281	−0.00126	55387.58616	−0.00117	55483.42489	−0.00123
55287.39099	−0.00123	55389.76436	−0.00112	55485.60302	−0.00125
55289.56916	−0.00122	55391.94264	−0.00100	55487.78119	−0.00124
55291.74733	−0.00120	55394.12078	−0.00101	55489.95944	−0.00114
55293.92549	−0.00120	55396.29897	−0.00097	55494.31569	−0.00120
55296.10362	−0.00122	55398.47699	−0.00111	55496.49389	−0.00116
55298.28180	−0.00120	55400.65524	−0.00101	55498.67206	−0.00114
55300.45997	−0.00118	55402.83331	−0.00110	55500.85025	−0.00111
55302.63812	−0.00118	55405.01151	−0.00105	55503.02841	−0.00110
55304.81631	−0.00115	55407.18966	−0.00106	55505.20660	−0.00106
55306.99439	−0.00122	55409.36777	−0.00110	55507.38474	−0.00108
55311.35074	−0.00118	55411.54600	−0.00102	55509.56290	−0.00107
55313.52889	−0.00119	55413.72416	−0.00102	55511.74103	−0.00110
55315.70703	−0.00120	55415.90226	−0.00107	55513.91917	−0.00111
55317.88525	−0.00114	55418.08049	−0.00100	55516.09734	−0.00110
55320.06334	−0.00120	55420.25857	−0.00107	55518.27549	−0.00110
55322.24152	−0.00117	55422.43676	−0.00104	55520.45362	−0.00112
55324.41968	−0.00117	55424.61487	−0.00108	55522.63181	−0.00109
55326.59804	−0.00096	55428.97120	−0.00106	55524.80995	−0.00110
55328.77600	−0.00116	55431.14933	−0.00108	55526.98808	−0.00113
55330.95426	−0.00105	55433.32744	−0.00113	55529.16624	−0.00112
55335.31062	−0.00100	55435.50560	−0.00112	55531.34442	−0.00110
55337.48874	−0.00104	55437.68373	−0.00115	55533.52251	−0.00116
55339.66684	−0.00109	55439.86184	−0.00119	55535.70065	−0.00118
55344.02316	−0.00108	55442.04001	−0.00118	55537.87880	−0.00118
55346.20128	−0.00111	55444.21819	−0.00115	55540.05696	−0.00117
55348.37940	−0.00115	55446.39635	−0.00115	55542.23514	−0.00115
55350.55753	−0.00117	55448.57448	−0.00117	55546.59147	−0.00113
55352.73568	−0.00118	55450.75262	−0.00118	55548.76963	−0.00112
55354.91386	−0.00115	55452.93078	−0.00118	55550.94781	−0.00110
55357.09203	−0.00113	55455.10892	−0.00119	55570.55110	−0.00120
55359.27017	−0.00115	55457.28713	−0.00114	55572.72927	−0.00118
55361.44831	−0.00116	55459.46531	−0.00111	55574.90746	−0.00114
55363.62648	−0.00115	55461.64348	−0.00110	55577.08559	−0.00117
55365.80460	−0.00118	55463.82164	−0.00109	55579.26373	−0.00118
55367.98278	−0.00116	55465.99978	−0.00110	55581.44194	−0.00113

Table 3. (Contd.)

Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days
55583.62010	−0.00112	55690.34958	−0.00121	55788.36667	−0.00107
55585.79823	−0.00115	55692.52779	−0.00115	55790.54489	−0.00100
55587.97637	−0.00116	55694.70594	−0.00116	55792.72297	−0.00107
55590.15452	−0.00117	55696.88411	−0.00114	55794.90112	−0.00108
55592.33267	−0.00117	55699.06225	−0.00116	55797.07925	−0.00110
55598.86711	−0.00119	55701.24044	−0.00112	55799.25740	−0.00111
55601.04526	−0.00120	55703.41853	−0.00118	55801.43556	−0.00110
55603.22343	−0.00118	55705.59667	−0.00120	55803.61371	−0.00111
55605.40162	−0.00115	55707.77467	−0.00135	55805.79183	−0.00114
55607.57978	−0.00114	55709.95298	−0.00120	55807.96999	−0.00114
55609.75796	−0.00112	55712.13117	−0.00116	55810.14815	−0.00113
55611.93609	−0.00114	55714.30934	−0.00115	55812.32630	−0.00113
55614.11423	−0.00115	55716.48749	−0.00115	55814.50448	−0.00111
55616.29246	−0.00108	55718.66564	−0.00116	55816.68261	−0.00113
55618.47067	−0.00102	55720.84373	−0.00122	55818.86073	−0.00117
55620.64884	−0.00101	55723.02189	−0.00121	55821.03886	−0.00119
55622.82710	−0.00090	55727.37829	−0.00112	55823.21710	−0.00111
55625.00513	−0.00103	55729.55646	−0.00111	55825.39518	−0.00118
55627.18320	−0.00111	55731.73468	−0.00104	55827.57334	−0.00118
55629.36134	−0.00112	55733.91276	−0.00112	55829.75152	−0.00115
55631.53942	−0.00120	55738.26903	−0.00115	55831.92960	−0.00122
55633.71776	−0.00101	55740.44726	−0.00108	55836.28598	−0.00115
55642.43022	−0.00117	55742.62547	−0.00102	55838.46413	−0.00116
55644.60847	−0.00108	55744.80362	−0.00103	55840.64225	−0.00119
55646.78657	−0.00113	55746.98179	−0.00101	55842.82045	−0.00115
55648.96475	−0.00110	55749.15991	−0.00105	55844.99861	−0.00114
55651.14298	−0.00103	55751.33807	−0.00104	55847.17675	−0.00115
55653.32105	−0.00111	55753.51623	−0.00104	55849.35494	−0.00112
55655.49912	−0.00120	55755.69433	−0.00109	55851.53301	−0.00120
55657.67740	−0.00107	55757.87245	−0.00112	55853.71115	−0.00122
55659.85545	−0.00118	55760.05061	−0.00112	55855.88933	−0.00119
55662.03376	−0.00102	55762.22869	−0.00119	55858.06744	−0.00124
55664.21186	−0.00108	55764.40680	−0.00124	55860.24565	−0.00118
55666.39007	−0.00102	55766.58501	−0.00118	55862.42379	−0.00120
55668.56813	−0.00111	55768.76315	−0.00120	55864.60193	−0.00121
55670.74631	−0.00109	55770.94133	−0.00117	55866.78009	−0.00120
55672.92436	−0.00119	55773.11953	−0.00113	55868.95822	−0.00123
55677.28069	−0.00117	55775.29767	−0.00114	55871.13645	−0.00115
55679.45889	−0.00113	55777.47579	−0.00117	55873.31456	−0.00120
55681.63700	−0.00117	55779.65396	−0.00116	55875.49279	−0.00112
55683.81515	−0.00117	55781.83212	−0.00115	55877.67097	−0.00110
55685.99329	−0.00119	55784.01024	−0.00119	55879.84907	−0.00115
55688.17145	−0.00118	55786.18851	−0.00107	55882.02721	−0.00117

Table 3. (Contd.)

Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days
55884.20530	−0.00123	55982.22232	−0.00116	56082.41739	−0.00119
55886.38349	−0.00119	55984.40043	−0.00120	56084.59558	−0.00115
55888.56164	−0.00120	55990.93486	−0.00124	56086.77377	−0.00112
55890.73973	−0.00126	55993.11305	−0.00120	56088.95187	−0.00117
55892.91789	−0.00126	55995.29120	−0.00120	56091.13003	−0.00117
55895.09595	−0.00135	55997.46934	−0.00122	56093.30819	−0.00116
55897.27421	−0.00125	55999.64750	−0.00121	56095.48629	−0.00122
55899.45237	−0.00124	56001.82566	−0.00121	56097.66443	−0.00123
55901.63047	−0.00129	56004.00383	−0.00119	56099.84256	−0.00126
55905.98673	−0.00134	56006.18199	−0.00119	56102.02071	−0.00126
55908.16495	−0.00128	56008.36016	−0.00117	56104.19885	−0.00127
55910.34310	−0.00128	56010.53822	−0.00126	56108.55520	−0.00123
55912.52125	−0.00129	56012.71645	−0.00119	56110.73337	−0.00122
55914.69954	−0.00115	56014.89457	−0.00122	56112.91154	−0.00120
55916.87759	−0.00126	56017.07265	−0.00130	56115.08969	−0.00121
55919.05580	−0.00120	56019.25077	−0.00133	56117.26788	−0.00117
55921.23397	−0.00118	56021.42895	−0.00131	56119.44606	−0.00114
55923.41208	−0.00123	56023.60710	−0.00131	56121.62421	−0.00115
55925.59032	−0.00114	56025.78530	−0.00127	56130.33683	−0.00115
55927.76846	−0.00116	56027.96348	−0.00124	56132.51495	−0.00118
55929.94663	−0.00114	56030.14168	−0.00119	56134.69314	−0.00115
55934.30273	−0.00135	56032.31980	−0.00123	56136.87126	−0.00118
55936.48115	−0.00109	56034.49793	−0.00125	56141.22754	−0.00121
55938.65905	−0.00134	56036.67620	−0.00114	56143.40564	−0.00126
55940.83741	−0.00113	56038.85433	−0.00116	56145.58383	−0.00123
55943.01557	−0.00113	56041.03247	−0.00118	56147.76194	−0.00127
55945.19372	−0.00113	56043.21064	−0.00116	56149.94015	−0.00122
55947.37191	−0.00110	56045.38880	−0.00116	56152.11831	−0.00121
55949.55006	−0.00110	56047.56695	−0.00116	56154.29644	−0.00124
55951.72812	−0.00120	56049.74509	−0.00117	56156.47455	−0.00128
55953.90642	−0.00105	56051.92322	−0.00120	56158.65285	−0.00113
55956.08457	−0.00105	56054.10136	−0.00121	56160.83101	−0.00113
55958.26278	−0.00100	56056.27953	−0.00120	56163.00918	−0.00111
55960.44078	−0.00115	56058.45768	−0.00120	56165.18734	−0.00111
55962.61903	−0.00106	56060.63583	−0.00121	56167.36547	−0.00113
55964.79718	−0.00106	56062.81401	−0.00118	56171.72170	−0.00121
55966.97532	−0.00108	56064.99215	−0.00119	56176.07805	−0.00117
55969.15349	−0.00106	56067.17031	−0.00119	56178.25616	−0.00121
55971.33167	−0.00104	56069.34844	−0.00121	56182.61266	−0.00102
55973.50978	−0.00108	56071.52663	−0.00118	56184.79079	−0.00105
55975.68789	−0.00112	56073.70473	−0.00123	56186.96889	−0.00110
55977.86600	−0.00117	56075.88309	−0.00103	56189.14696	−0.00119
55980.04415	−0.00117	56080.23923	−0.00120	56191.32514	−0.00116

Table 3. (Contd.)

Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days	Time of primary minimum, HJD−2400000	O−C, days
56193.50333	−0.00112	56258.84793	−0.00116	56330.72696	−0.00122
56195.68142	−0.00119	56261.02618	−0.00106	56332.90509	−0.00125
56197.85966	−0.00110	56263.20430	−0.00110	56335.08323	−0.00126
56200.03782	−0.00110	56265.38245	−0.00110	56337.26137	−0.00127
56202.21585	−0.00122	56267.56055	−0.00115	56339.43956	−0.00124
56206.57218	−0.00120	56269.73872	−0.00114	56341.61770	−0.00125
56208.75036	−0.00118	56271.91687	−0.00114	56343.79586	−0.00125
56210.92850	−0.00119	56274.09496	−0.00121	56345.97401	−0.00125
56213.10672	−0.00112	56276.27306	−0.00126	56348.15220	−0.00122
56215.28484	−0.00116	56278.45124	−0.00124	56350.33032	−0.00125
56217.46300	−0.00115	56280.62939	−0.00124	56352.50855	−0.00118
56219.64117	−0.00114	56282.80746	−0.00132	56354.68662	−0.00126
56221.81930	−0.00116	56284.98561	−0.00133	56356.86482	−0.00121
56223.99745	−0.00117	56287.16373	−0.00136	56361.22111	−0.00123
56226.17558	−0.00119	56289.34193	−0.00132	56363.39919	−0.00131
56228.35372	−0.00120	56291.52008	−0.00132	56365.57734	−0.00131
56230.53189	−0.00119	56293.69826	−0.00130	56367.75560	−0.00121
56232.71004	−0.00119	56295.87646	−0.00125	56369.93379	−0.00117
56234.88821	−0.00118	56298.05464	−0.00123	56372.11196	−0.00116
56237.06636	−0.00118	56300.23279	−0.00123	56374.29005	−0.00122
56239.24460	−0.00110	56302.41098	−0.00119	56376.46825	−0.00117
56241.42268	−0.00117	56306.76730	−0.00118	56378.64637	−0.00121
56243.60089	−0.00112	56308.94545	−0.00119	56380.82450	−0.00123
56245.77903	−0.00113	56322.01433	−0.00123	56383.00266	−0.00123
56252.31344	−0.00118	56324.19246	−0.00126	56385.18082	−0.00122
56254.49160	−0.00118	56326.37065	−0.00122	56387.35900	−0.00120
56256.66976	−0.00117	56328.54883	−0.00120	56389.53716	−0.00119

large scatter of the O−C deviations limits our ability to obtain many parameters of the light-time effect. To minimize the number of parameters, we adopted the simple hypothesis that the third body undergoes circular motion about the eclipsing binary. Using a Fourier expansion[9], we analyzed the O−C residuals obtained for each of the periods and the calculated parameters of the best-fit sine curve approximating the time dependence of the times of minima (the light-time effect). Table 4 presents the amplitudes and periods of this theoretical curve. Figure 3 presents the power spectrum for the O−C residuals calculated using the ephemeris (1), and Fig. 4 displays a part of Fig. 3 on a larger scale. The peak near a period of ≈2 days corresponds to the orbital period of FL Lyr; this is clearly visible in Fig. 5. A peak at about 5–6 yrs is also visible in Fig. 3; this is due to the light-time effect. It is difficult to search for a larger

Table 4. Amplitude of the theoretical curve and the orbital period of the third body obtained from a Fourier expansion using three values of the orbital period of FL Lyr

Orbital period of FL Lyr, days	Light-time effect amplitude, s	Light-time effect period, years
2.17815440	4.8	7.2
2.17815408	9.9	12.4
2.17815414	7.6	11.3

[9] We applied the PERDET (PERiod DETermination) code [33].

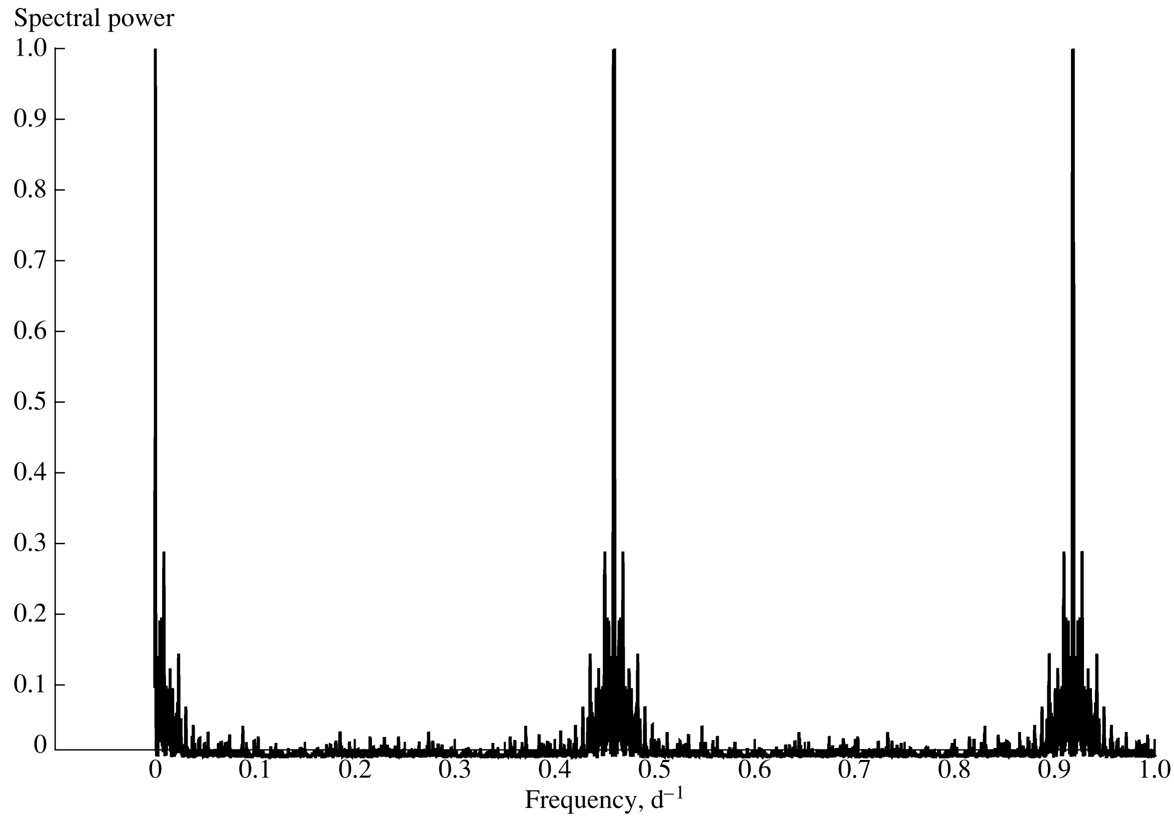

Fig. 3. Power spectrum of FL Lyr in relative units calculated using the ephemeris (1).

number of objects in the system due to the large scatter of the available times of minima, comparable to the amplitude of the light-time effect. The O–C calculations performed for all three periods P_{10}, P_{11}, and P_{12} demonstrate systematic deviations that can be explained as a light-time effect with a period somewhat larger than the entire time interval covered by the Kepler observations. Figures 6–8 show the O–C deviations of the times of minima as a function of the orbital phase of the third body.

If less than a half of the period of the light-time effect elapsed during the time covered by the Kepler observations, an alternative explanation for the observed systematic shifts could be a variation of the close-binary period ($dP/dt \sim 10^{-5}$ days/year). The system has already been observed for a long time, and period variations of this kind should already have been detected from the parabolic shape of the O–C curve. During the time interval of the observations (almost 60 years), the FL Lyr period variations would have already accumulated in the fourth place after the decimal point, and the period should be increasing, while all the previously measured period values [34–50] are not lower than those we have derived. This can be taken as evidence against the hypothesis that the system's period is varying, and that the times of minima exhibit variations due to the light-time effect.

5. MASS OF THE THIRD BODY

In the general case, accurately determining the mass of a body in a binary, and especially a multiple, system can require a dedicated, complex study. There is no sense in carrying out such estimates in the framework of our current study, since the orbital period of the third body has not been accurately determined, and is longer than the time covered by the Kepler observations. Moreover, we were not able to derive the orbital inclination of the third body relative to the orbital plane of the system. Therefore, we have obtained a simple lower limit for the third body's mass.

Since the orbital period of the third body is much longer than the orbital period of the central binary, we can use Kepler's third law to obtain a simple mass

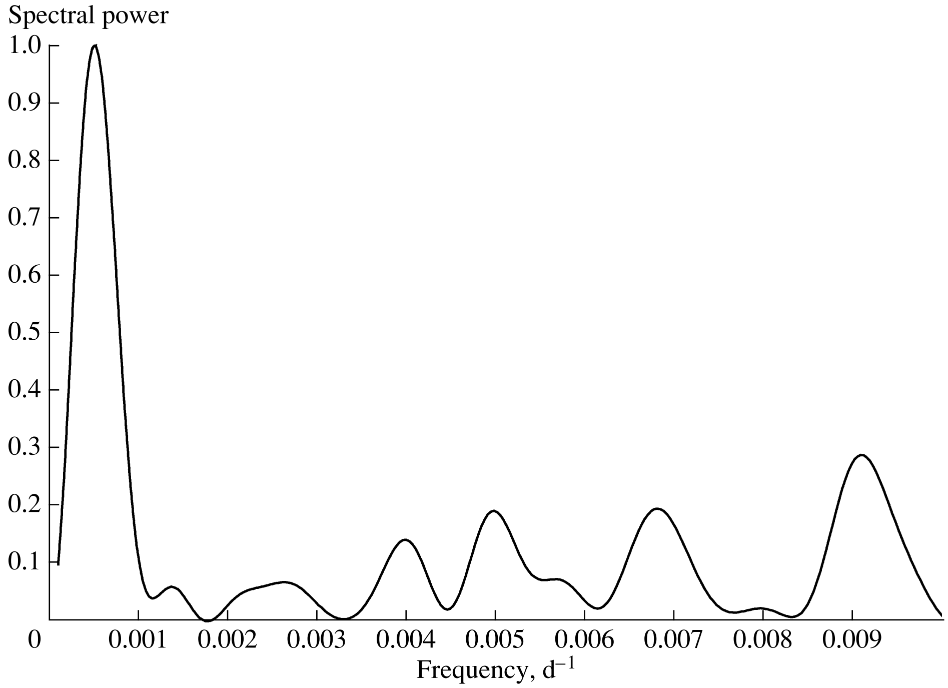

Fig. 4. Same as Fig. 3 on a larger scale, for the part at low frequencies.

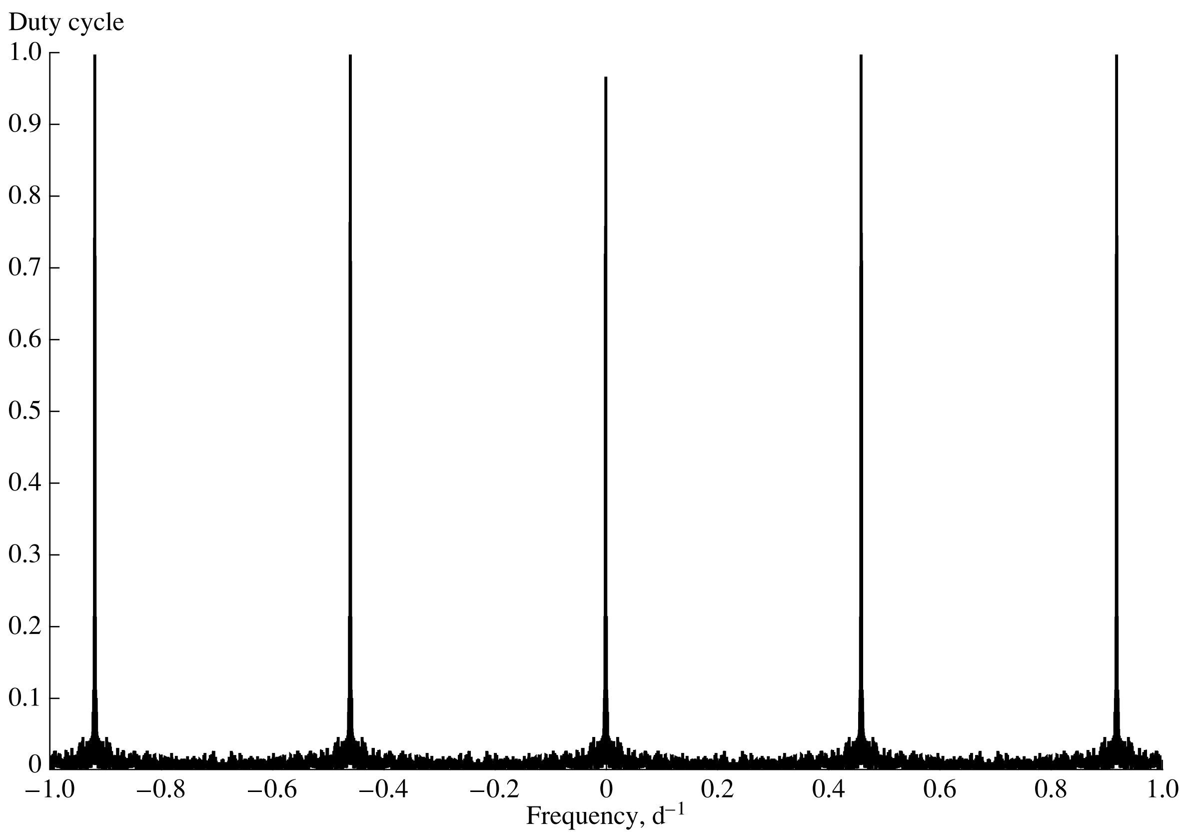

Fig. 5. Duty cycle as a function of the signal frequency.

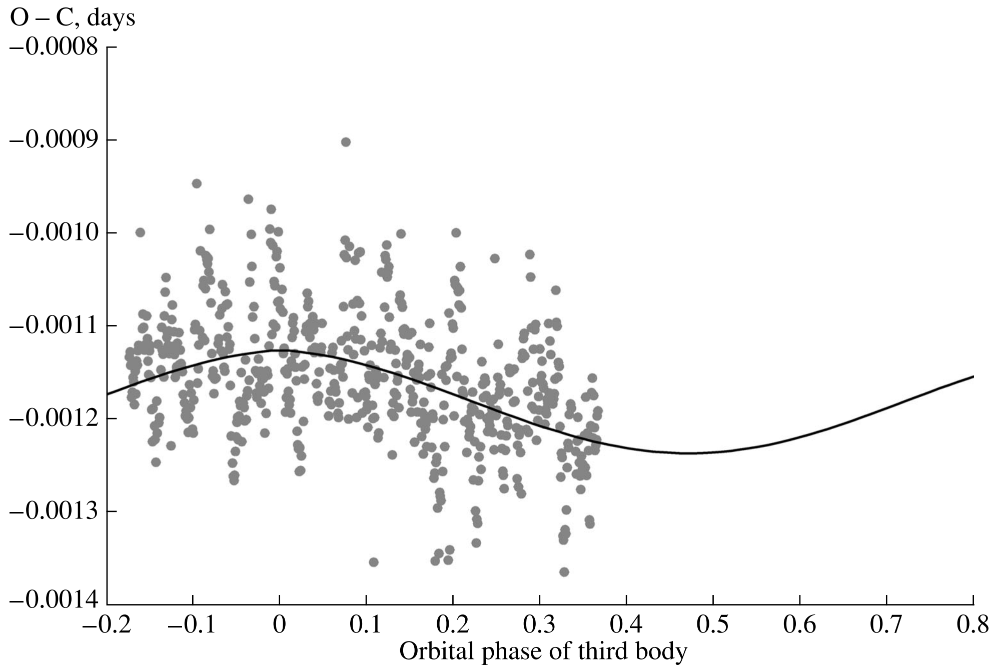

Fig. 6. Light-time effect for the third body. The ephemeris (1) was used in the calculations. See Table 4 for the period and amplitude of the light-time effect. The solid curve shows the theoretical curve, and the gray circles the observations.

estimate[10]:

$$P_{orb} = 0.1\frac{a^{3/2}}{M^{1/2}}, \quad (4)$$

where P_{orb} is the orbital period of the third body in days, a the semi-major axis of the third body's orbit in solar radii, and M the combined mass of the two components of FL Lyr and the third body in solar masses.

The sum of the component masses in the FL Lyr system is $\approx 2\ M_\odot$ [21]. The orbital period of the third body with the ephemeris (1) is $\gtrsim$7 years. According to (4), the semi-major axis of the orbit of the third body is $\gtrsim 1100\ R_\odot$. The semi-amplitude of the light-time effect with the same ephemeris is 2.4 s. During this time, light traverses half the distance of the periodic shift of the FL Lyr binary due to the third body; i.e., the semi-major axis of the orbit of the FL Lyr system about the center of mass of the FL Lyr—third body system is approximately 1 $R_\odot$. Thus, the ratio of the third body's mass to the mass of the FL Lyr binary is ≈1/1000. We thus get the simple estimate for the third body's mass $2\ M_\odot/1000 \approx 2M_J$. If the orbital period of the third body proves to be longer than our estimate, the estimated mass of this body will be lower; at the same time, the orbital inclination of the third body will increase its estimated mass. Note that the orbital planes for all eight known exoplanets in orbits around binaries are very close (within 1°) to the orbital planes of their parent binaries. Thus, our rough estimate of the planet's mass may prove to be close to the actual mass of this planet.

[10] The orbital period of the third body is 7 years or more, compared to the 2-day orbital period of FL Lyr; stable orbits admitting application of Kepler's third law (for rough estimates, since there will definitely be perturbations of the third body's orbit) would begin with an orbital period of 20 days [11].

6. CONCLUSIONS

We have analyzed Kepler light curves for the eclipsing binary FL Lyr and detected the light-time effect, indicating that the system probably contains a body with a mass of about two Jupiter masses, with an orbital period around the close binary of ≥7 yrs. Confirmation of this planet's existence will require long-term photometric observations of FL Lyr with an accuracy no worse than that of the Kepler data; otherwise, it will be necessary to analyze the radial-velocity curve of the system over a long time and with very high accuracy.

The times of minima we have derived from the light curve of FL Lyr (Table 3) can be used in further studies of the system.

Discoveries of planets in close binary systems in recent years mean that the formation of two stellar

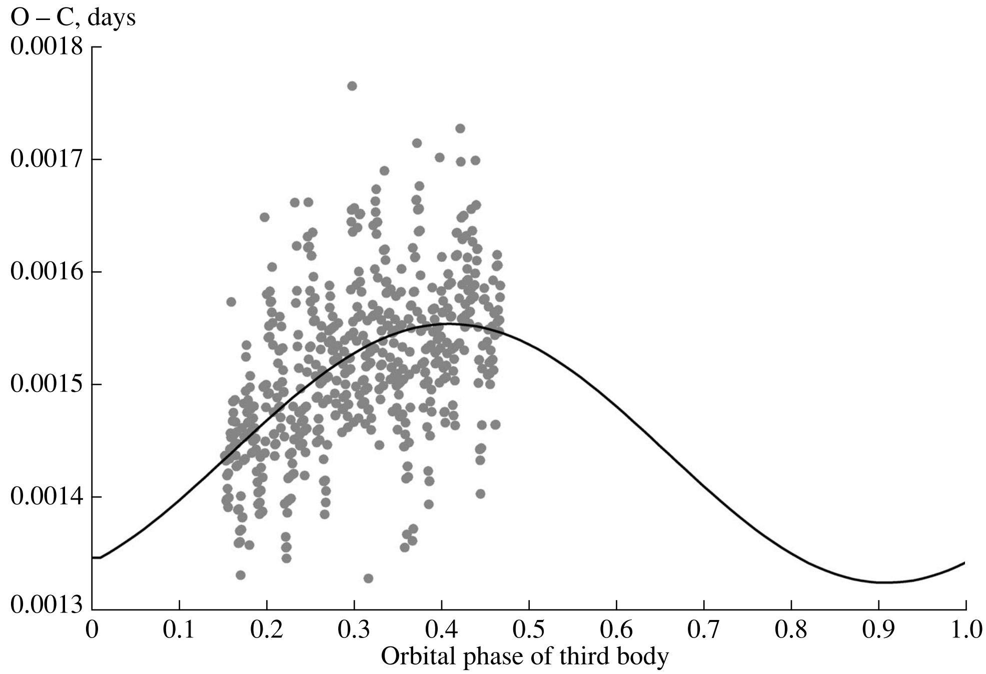

Fig. 7. Same as Fig. 6 using the ephemeris (2).

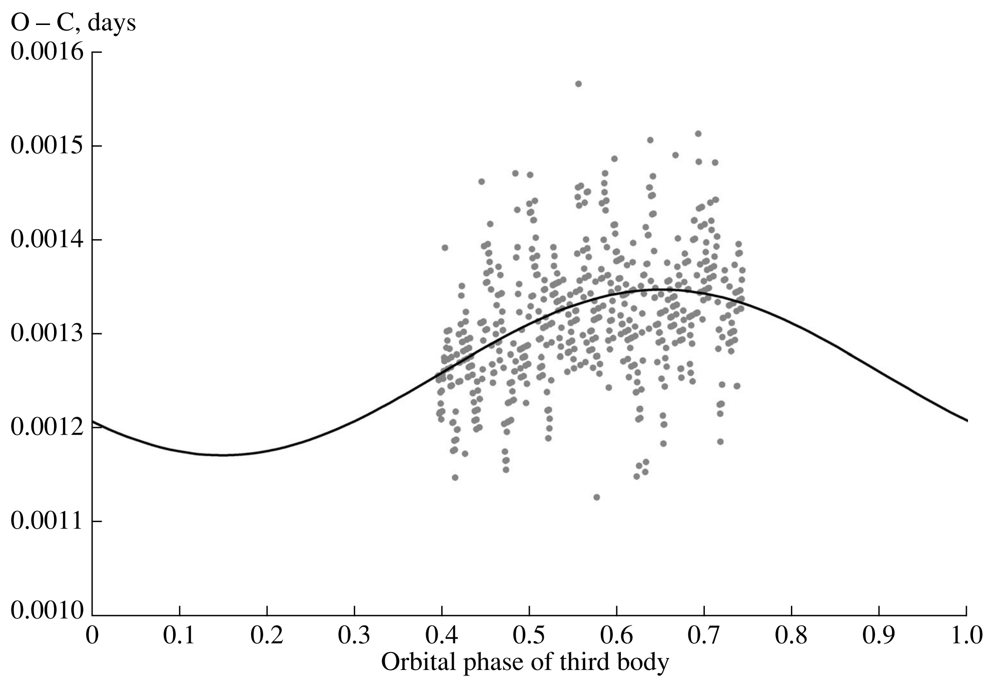

Fig. 8. Same as Fig. 6 using the ephemeris (3).

components during the collapse of a rotating protostellar cloud does not completely resolve the problem of the inevitable angular-momentum excess in protostellar clouds. The formation of planets in circumstellar accretion–decretion disks remains necessary to completely resolve this problem. As a result, the components of wide, as well as close, binary systems could have planets around them. This means that most stars can possess planetary systems, so that the formation rate of planetary systems could be close to the star-formation rate (see, for instance, the recent paper [51]). This rate for the Milky Way would thus be several planetary systems per year.

ACKNOWLEDGEMENTS

The authors thank A.I. Zakharov, S.E. Leontyev, and V.N. Sementsov, who developed software for the computation of photometric elements of eclipsing binaries.

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Translated by N. Samus'