Photometric investigation of near-contact binary FR Ori

R. Gális[1], L. Hric[2] & E. Kundra[2]

[1] Faculty of Sciences, University of P.J. Šafárik, Moyzesova 16, 041 54 Košice, The Slovak Republic (e-mail: galis@upjs.sk)

[2] Astronomical Institute of the Slovak Academy of Sciences, 059 60 Tatranská Lomnica, The Slovak Republic (e-mail: hric@ta3.sk, kundra@ta3.sk)

Abstract. An analysis of UBV photoelectric photometry for the eclipsing near-contact binary FR Ori using new observational data is presented. During four observational seasons were secured 106.4 hours of observations in 23 observational nights. The four new times of minima of the system FR Ori were determined from this photometric data. The analysis of the (O-C) diagram using method of weighted linear regression allowed to state new value of the orbital period 0.883162859 day and to construct new ephemeris for this eclipsing system. Detailed statistical analysis does not confirm the presence of intrinsic activity in this binary. The analysis of U, B and V light curves by the Binary Maker 2.0 gave the geometrical and physical parameters of the system.

1. Introduction

A new group, the near-contact binaries, with similar characteristics to the A type of W UMa eclipsing binaries, has been established by Shaw (1990). They have orbital periods less than one day, the components show tidal deformation and the facing surfaces are less than 0.1 orbital radius apart. Most of the systems have one component at or near its Roche lobe. The spectral type of the hot component is A or F, while that of the cooler one is a spectral type or two later. This similarity of features suggests that the near-contact binaries could be the missing link between detached binaries and W UMa systems, at least of A type. Evolutionary possibilities concerning the near-contact binaries have been discussed by Hilditch *et al.* (1988). On the basis of FR Ori parameters Shaw (1994) included this binary into the extended list of near-contact binaries.

FR Ori (HD 248406, m_{pg} = 11.0 – 11.9, spectral type A7) belongs to the classical β Lyrae type semi-detached binaries with orbital period of 0.88316217 days (Kholopov *et al.*, 1985). The star was discovered photographically by Hoffmeister (1934) to be a short period variable. Soloviev (1937) determined a period of the binary with considerable accuracy by using visual observations. He recognised that the right period is a half of the previously mentioned one. The object was observed photographically by Gaposhkin (1954) and visually by Szafraniec (1974). In the catalogue of GCVS (Kholopov et al., 1985) the following ephemeris of the eclipsing binary FR Ori is given:

$$Min\ I = HJD\ 2\,427\,862.159 + 0.^{d}88316217 \times E$$

The star is listed in the Catalogue of parameters for eclipsing binaries by Brancewicz & Dworak (1980). For the individual components e.g. the following physical and geometrical parameters are given:

$M_1 = 2.19\ M_\odot$	$M_2 = 1.30\ M_\odot$
$L_1 = 18.15\ L_\odot$	$L_2 = 3.43\ L_\odot$
$T_1 = 7980$ K	$T_2 = 6250$ K
$R_1 = 2.24\ R_\odot$	$R_2 = 1.60\ R_\odot$

The authors proposed the binary system to a detached one while the primary and secondary components fill their Roche lobes by 89 and 81% respectively. The separation of the components is equal to 5.88 $R_\odot$.

The first long-term photoelectric photometry during the years 1989 –1992 was secured by Zakirov (1994). He improved the ephemeris of the binary using those observations as follows:

$$Min\ I = HJD\ 2\,432\,508.4774 + 0.^{d}88316188 \times E$$

Swechnikov & Kuznecov (1990) derived the spectral type of the secondary component of this binary system as G3 IV. Zakirov (1996) studied selected stars of association Ori I on the basis of UBVR photometry. The close binary FR Ori is thought to be a member of this association. He showed that the decrease of the brightness during the primary minimum is the largest in U colour (1.05 mag) and the smallest in R colour (0.9 mag). The durations of both minima are the same (0.18 of orbital period). The ellipsoidal effect is manifested in all colours. The primary component is a MS star of spectral type A6 – 7 while the secondary one is a young star of spectral type K5 before MS. FR Ori seems to be a young binary and very probably this is the reason of contradiction in geometrical parameters determinations. Mass-ratio is q = 0.41. The secondary component nearly fills up the corresponding Roche lobe and possible mass transfer can be the source of unstable processes in the system. Nevertheless changes of the orbital period have not been detected.

2. Observations

FR Ori was observed using the Cassegrain (0.6m) telescopes equipped with a single channel photoelectric photometer and a the digital converter as well as the Newton (0.5m) telescope equipped with CCD SBIG ST-10MXE at the observatories of the Astronomical Institute of the Slovak Academy of Sciences, Stará Lesná and Skalnaté Pleso for 22 nights during 4 observational seasons. A set of Johnson's UBV(R) filters was used. One observational run was taken at the Kryonerion Station of the National Observatory of Athens, Greece, where the Cassegrain telescope (1.2 m) with the same single channel photoelectric photometer and filters were used.

Table 1. Observational information for FR Ori.

Julian Date - 2400000	Date	Obs.	Obsrv.	Duration [h]	Phase interval	Comp.	Ext. Coeff.				Note
							U	B	V	O.K.	
51923	1/13/01	SL	Hr,Ga	2.7	0.48 - 0.58	$S_1(S_2,Ch,S_5)$	0,440	0,100	0,072	No	1
51924	1/14/01	SL	Hr,Ga	5.7	0.35 - 0.56	$S_1(S_2,Ch,S_5)$	0,896	0,495	0,350	No	
51926	1/16/01	SL	Hr,Ga	9.5	0.57 - 0.92	$S_2(S_1,Ch,S_5)$	0,772	0,391	0,237	No	
51957	2/16/01	SL	Hr,Ga	7.3	0.72 - 0.99	$S_1(S_2,Ch,S_5)$	0,768	0,440	0,275	Yes	
51975	3/6/01	SL	Hr	4.0	0.15 - 0.30	$S_2(S_5)$	0,392	0,239	0,084	No	1
52167	9/14/01	Kr	Hr,Pk	0.5	0.91 - 0.93	$S_2(Ch,S_5)$	0,608	-0,129	-0,261	No	1
52197	10/14/01	SP	Sc	5.4	0.73 - 0.93	$S_2(Ch)$	0,595	0,365	0,233	Yes	
52251	12/7/01	SL	Ga	5.2	0.90 - 0.09	$S_2(S_5)$	0,816	0,454	0,322	Yes	
52252	12/8/01	SL	Ga	4.4	0.00 - 0.16	$S_2(S_1,Ch,S_5)$	0,535	0,384	0,169	No	
52343	3/9/02	SL	Hr, Ga	2.4	0.89 - 0.98	$S_2(S_1,S_5)$	0,726	0,385	0,236	Yes	
52345	3/11/02	SL	Hr, Do	3.5	0.09 - 0.22	$S_2(S_5)$	0,573	0,187	0,065	No	
52597	11/18/02	SL	Hr, Do	6.8	0.57 - 0.82	$S_2(S_5)$	-0,860	-1,642	-1,742	No	1
52617	12/8/02	SL	Hr, Do	5.7	0.27 - 0.48	$S_1(S_5)$	0,556	0,271	0,129	Yes	
52618	12/9/02	SL	Do	4.9	0.35 - 0.53	$S_1(S_5)$	1,052	0,607	0,420	No	
52620	12/11/02	SL	Do	6.8	0.55 - 0.80	$S_1(S_5)$	0,289	-0,023	-0,067	No	
52682	2/11/03	SL	Hr, Do	1.4	0.81 - 0.86	$S_1(S_5)$	0,749	0,436	0,360	No	1
52685	2/14/03	SL	Hr, Do	3.3	0.06 - 0.18	$S_1(Ch)$	0,892	0,629	0,359	No	1
52692	2/21/03	SP	Ku	5.7	0.95 - 0.16	$S_2(Ch)$	0,754	0,479	0,295	No	
52698	2/27/03	SL	Hr, Do	2.2	0.91 - 0.99	S_2	0,765	0,382	0,265	Yes	
52703	3/4/03	SP	Sc	1.1	0.41 - 0.45	$S_2(Ch)$	5,073	4,188	4,643	No	1
53345	12/5/04	SL	Ga	1.4	0.45 - 0.50	$S_2(S_1)$	-0,317	-0,159	0,056	No	1
53409	2/7/05	SL	Ga,Kn	8.7	0.77 - 0.09	S_2	-	-	-	-	2
53410	2/8/05	SL	Ga,Kn	7.8	0.90 - 0.19	S_2	-	-	-	-	2

Observatory: SL - Stará Lesná, Kr – Kryonerion, SP – Skalnaté Pleso.
Observers: Hr - Hric, Ga - Gális, Pk –Petrík, Sc – Schalling, Do – Dobrotka, Ku – Kuziel, Kn - Kundra.
The column O.K. indicates using the seasonal ext. coefficients (No) or the ext. coefficients for given night (Yes).
Notes: 1 –the dispersion is very large, unusable, 2 – CCD observations.

The method of the differential photometry was used for the photometric observations. The comparison and check stars were chosen from the general catalogue of the photometric data – GCPD (Mermilliod *et al.*, 1997). As comparison star (S_1) we used HD 038623 (Deutschman *et al.*, 1976) and as check star (*CH*) HD 248018 (Johnson & Morgan, 1935). Since both stars are far from the variable the stars GSC 00715-00098 (S_2) and GSC 00719-00690 (S_5) close to the variable were chosen as the comparisons. The new comparisons had not published UBV magnitudes therefore we performed the cross measurements of all comparison stars during 5 nights and resulting values are follow: S_2 (U = 11.328 ± 0.011, B = 11.272 ± 0.004, V = 10.964 ± 0.006) and S_2 (U = 14.658 ± 0.212, B = 12.939 ± 0.006, V = 11.556 ± 0.004). The mutual comparison of resulting values suggests that all comparison stars are not variable on a short as well as long-time scale respectively.

Seasonal extinction coefficients have been used in the reduction of observations except in the case of very good atmospheric conditions, when the coefficients of the running night have been adopted. The individual observational nights are described in the Table 1, with the listed Julian date, date, observatory, observers and duration of observation, phase interval, used comparison stars, final extinction coefficients and notes. The total duration of observation is 106.4 hours. After the statistical evaluation of the quality of the individual observational nights, eight nights were not used in the subsequent analysis. The mean error of observations in B and V is the same ($<\sigma_V>$ = 0.022 mag, $<\sigma_B>$ = 0.022 mag) and the mean error in U colour is rather larger ($<\sigma_U>$ = 0.053 mag).

The phase diagrams of the light curves for individual filters are displayed in Fig. 1. The individual observational runs are distinguished by colour of symbols.

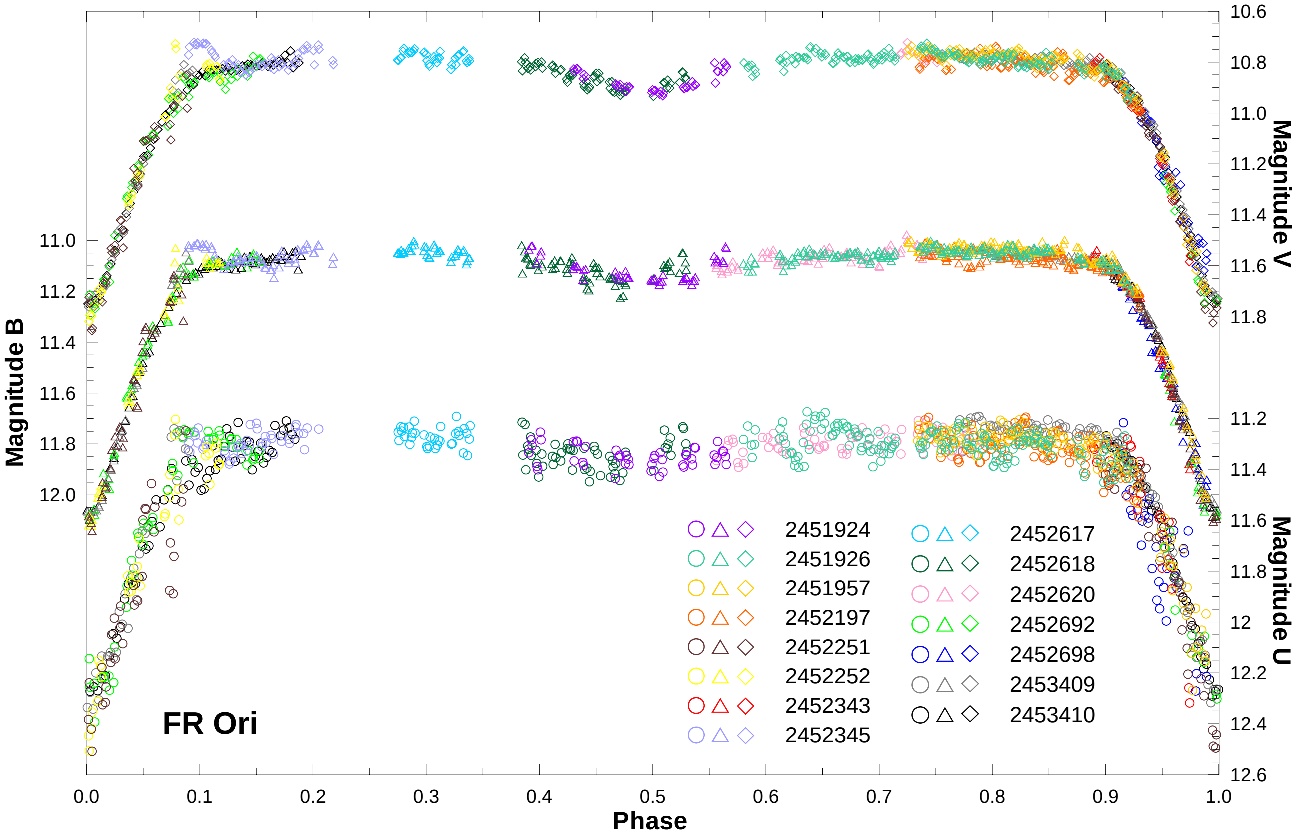

Fig. 1. Phase diagram of the light curve of FR Ori in U, B and V colours

3. Statistical analysis of observational material

The rather homogeneous covering of the light curves in all colours justifies performing the statistical analysis of mean errors of individual observational points. The whole phase interval was divided into 20 subintervals with a width of $\Delta f = 0.1$, while all intervals were overlapped with the shift in phase ($\Delta f = 0.05$). Polynomials of higher orders have been used for fitting, while the character and the shape of the light curves have been taken into account. The graphical representation of the previous statistical analysis is shown in Fig. 2.

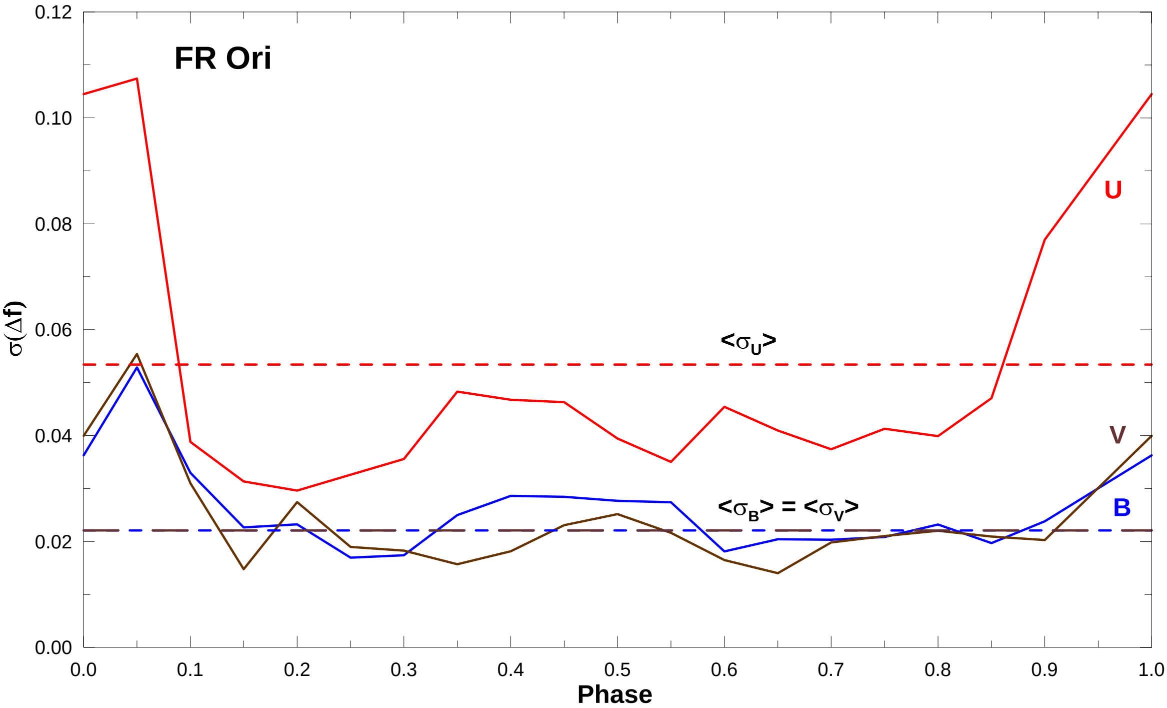

Fig. 2. The phase dependence of mean error of one observational point.

In order to evaluate these results, it is inevitable to compare $\sigma(\Delta f)$ with the mean errors of observational points of all data ($<\sigma_V> = 0.022$ mag, $<\sigma_B> = 0.022$ mag and $<\sigma_U> = 0.053$ mag). One can see in Fig. 2 that the largest differences between $\sigma(\Delta f)$ and $<\sigma>$ are pronounced in all three colours around the primary minimum $\Delta f = (0.9 - 1.1)$. However, such behaviour is not a real representation of the observational point scatter, because on the descending as well as on the ascending branch of the primary minimum, the brightness of the star changes very quickly.

In this case the small error in time produces a large error in magnitude determination. It is impossible to evaluate this influence, therefore these results will not be taken into account during the evaluation of $\sigma(\Delta f)$ dependence. In the phase interval $\Delta f = (0.9 - 1.1)$ the values $\sigma(\Delta f)$ are very similar to $<\sigma>$, which can be explained by the random scatter in the frame of observational fluctuation. We can conclude that detailed statistical analysis does not confirm the presence of intrinsic variations of light curves as manifestation of activity in this binary.

4. Times of minima. The (O - C) diagram

The observations of FR Ori show that the ephemeris published in the literature does not agree. This behaviour has drawn our attention to the analysis of times of minima. We have determined new times of minima from our own photometric data. The primary minima were detected four-times, two-times by photoelectric photometer (Dec. 7. 2001, Feb. 21. 2003) and twice by CCD camera (Feb. 7. 2005, Feb. 8. 2005).

There were derived times of secondary minima too (Jan. 13. 2001, Jan. 14. 2001, Dec. 9. 2002). Due to large scattering of this data (the secondary minima of FR Ori are very flat) the errors of times of minima were large and these minima were not taken into account.

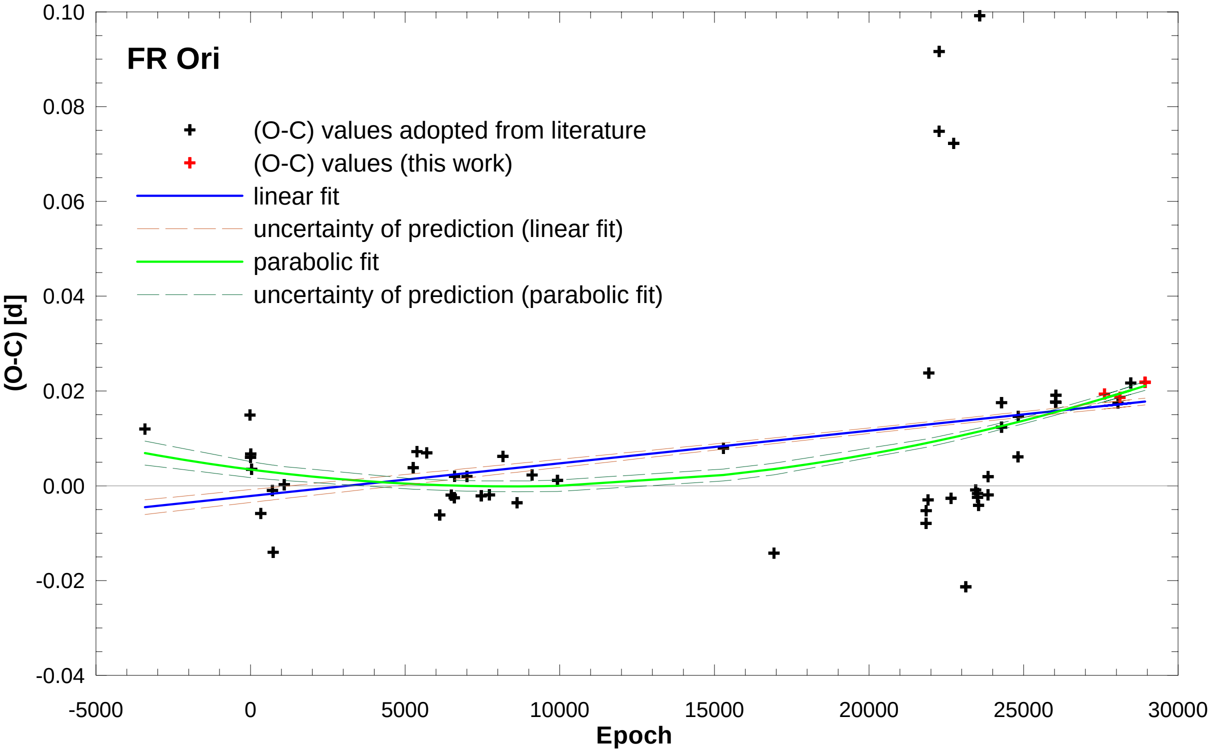

Fig. 3. (O-C) diagram of all available times of minima of FR Ori (The ephemeris from GCVS (Kholopov *et al.* 1985) was used for determination of (O-C) values).

All the available photoelectric, photographic as well as visual times of primary minima have also been adopted from literature. In this way, 54 times of minima have been collected and are displayed in Fig. 3. Our times of minima are depicted by red crosses in this diagram. For (O-C) diagram we have used the ephemeris published in GCVS by (Kholopov *et al.*, 1985).

We have obtained the new ephemeris by analysis of all data by the method of weighted linear regression. The times of minima were determined by various methods or by unknown method, therefore in the first step were computed weights for particular methods. The (O-C) data were fitted by linear orthogonal polynomial:

$$(O-C) = (0.0105 \pm 0.0030) + (7.62 \pm 2.90)10^{-7}\,(E - 15348.62)$$

and the standard deviation of the time of minimum was derived for given type of observation. The weights for particular observational methods were loaded like inverted values of root squares of its corresponding standard deviations. For 38 visual observations the weight had the value 16, for 6 photoelectric times of minima 56 and for 6 CCD times of minima 112. For times of minima determined by unknown methods together with one photographic minimum we obtained the weight 13. Input data and weights were used for linear and parabolic fit by the method of weighted linear regression. The formula for linear fit is follows:

$$(O-C) = (0.0124 \pm 0.0005) + (6.88 \pm 0.58)10^{-7}\,(E - 21080.79)$$

The formula for parabolic fit with the same weights:

$$(O-C) = (1.24 \pm 0.05)10^{-2} + (6.88 \pm 0.58)^{10^{-7}}\,(E - 21080.79) +$$
$$+ (50.02 \pm 8.91)10^{-12}(E^2 - 30480.35\,E + 110909552.07)$$

The linear weighted fit is in Fig. 3 depicted by blue line and parabolic fit by green line. The dashed lines represent the uncertainty of prediction of linear and parabolic fit. Because the sum of residual squares for parabolic (0.4679) and linear (0.4844) fits are comparable it is not necessary to use the polynom of higher order. We proposed that the period do not change and therefore we derived new value of the period as well as the new ephemeris:

$$\text{Min I} = \text{HJD } 2452251{,}58502 + 0{,}883162859 \times \text{E [d]}$$
$$\pm 21 \qquad\qquad \pm 59$$

For more precise analysis of (O-C) diagram in the future the new observational data are inevitable.

5. Physical and geometrical parameters of the system

We used normal points of phase diagram to derive the photometric elements of the binary system of FR Ori by code Binary Maker 2.0 (Bradstreet, 1993). The normal points we obtained by averaging of phase diagram points in corresponding subintervals of phase and magnitude by method of running averages. Thus we obtained 176, 191 and 178 normal points in U, B and V filters respectively.
The magnitudes were converted to the intensities by Pogson equation. As the unit intensity the value from maximum I (around the phase 0.25) of FR Ori brightness was adopted.

The simulation of phase diagram by code of Binary Maker 2.0 (Bradstreet, 1993) has essence in influence of Roche geometry on the surface star brightness distribution. The input parameters of the analysis are mass ratio q, potentials Ω_1, Ω_2, effective wavelength λ, effective temperatures T_1, T_2, gravity exponents g_1, g_2, limb darkening coefficients X_1, X_2, bolometric albedo coefficients A_1, A_2 and inclination i. For the components of FR Ori were derived gravity exponents $g_1 = 1.0$, $g_2 = 0.32$ (Lucy, 1967) and bolometric albedo coefficients $A_1 = 1.0$, $A_2 = 0.5$ (Rucinski, 1969). The limb darkening coefficients X_1, X_2 were derived by interpolation of values published by van Hamme (1993). We interpolated values for surface gravity and effective temperature in given filter. The model was computed in effective wavelengths λ_U=370nm, λ_B=440nm, λ_V=550nm. The optimised parameters were mass ratio q, potentials Ω_1, Ω_2, temperatures T_1, T_2 and inclination i.

Consequently the absolute parameters of the system were derived. From obtained effective temperatures of components we derived by Lang (1992) the mass of the primary component $M_1 = 1.84\ M_\odot$. Following mass ratio $q = 0.411$ we derived the mass of the secondary component $M_2 = 0.75\ M_\odot$. Using the third Kepler law and our orbital period we derived the mutual distance of the components $a = 5.3\ R_\odot$.

From the relative volumes of components which are results of solution by code of Binary Maker 2.0 (Bradstreet, 1993) in cylindrical coordinates we derived the values of volume radii of the components $r^{obj}{}_1 = 0.333$ and $r^{obj}{}_2 = 0.266$. From known mutual distance of the components and volume radii we derived real radii of the components $R_1 = 1.8\ R_\odot$, $R_2 = 1.4\ R_\odot$. The radius of the secondary component of FR Ori is 1.75-times larger as the radius of MS star of the same spectral type. Using masses and radii of the components we derived densities of the components $\rho_1 = 473.3$ kg m^{-3}, $\rho_2 = 383.3$ kg m^{-3}.

The solution of light curve of FR Ori was started with the parameters published by Zakirov (1996). We performed the analysis simultaneously in filter B and V. The light curve shown in filter U in spite of normalisation short-term variations, therefore U filter was improper for analysis. We used it only for checking of results obtaining by solution of light curves in B and V filters. These results are listed in Table 2.

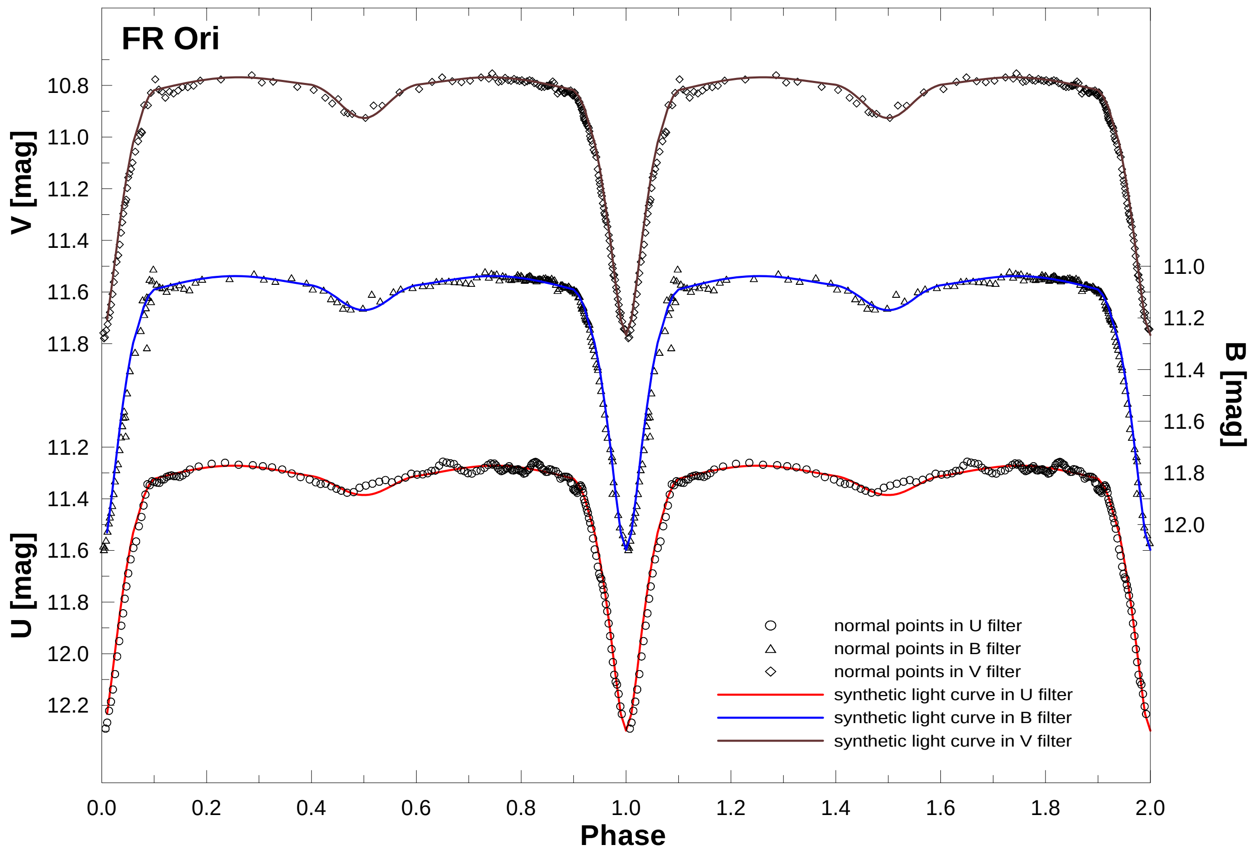

Fig. 4. The synthetic light curves of FR Ori with corresponding normal points.

Short-term variations in filter U mentioned Zakirov (1996) too and he explained them on the assumption that the secondary component of FR Ori is very young. The resulting synthetic light curves of FR Ori are depicted in Fig. 4. The model of FR Ori in phase 0.25 is shown together with inner and outer critical surfaces in Fig. 5.

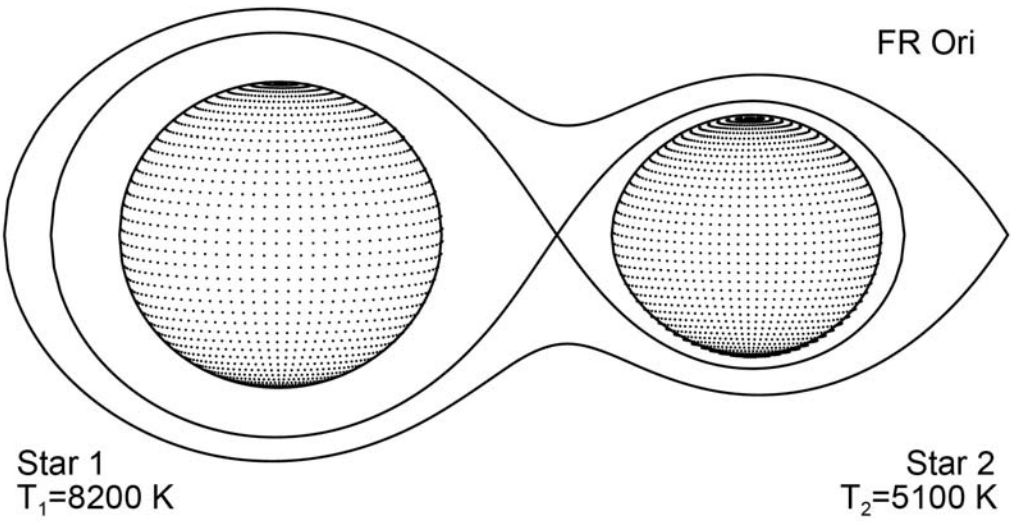

Fig. 5. The model of FR Ori.

Luminosities of the primary and secondary components were calculated from obtained effective temperatures using Stefan-Boltzmann law. The values are L_1 = 12.5 L⊙ and L_2 = 1.8 L⊙. Moreover the absolute bolometric magnitudes for the primary component $M^{bol}{}_1$ = 2.00 mag, and for the secondary component $M^{bol}{}_2$ = 4.57 mag were calculated.

Using the bolometric correction for the primary (-0.15) and secondary (-0.37) of given temperature (Lang, 1992) we determined the values of absolute visual magnitudes $M^V{}_1 = 2.15$, $M^V{}_2 = 4.94$ and the total absolute visual magnitude of the binary $M_V = 2.07$. The value of interstellar absorption was derived by the equation $A_V = (3.30 + 0.28(B\text{-}V)_0 + 0.04\, E_{B\text{-}V})\, E_{B\text{-}V}$ (Lang, 1992). The value $E_{B\text{-}V}$ for the direction where FR Ori lies was determined from the charts of distribution $E_{B\text{-}V}$ published by Fitzgerald (1968). Because the published value of distance of FR Ori is 530 pc by Brancewicz & Dworak (1980), we selected the chart up to 500 pc. In the direction of FR Ori given by galactic coordinates L = 197.49, B = -8.84 is the value $E_{B\text{-}V} \leq 0.1$. The colour index $(B\text{-}V) = 0.24$ was determined during the secondary minimum, when only primary component is visible. The coefficient of interstellar absorption used for calculation of distance has then the value $A_V = 0.33$.

Table 2. Geometrical and physical parameters of FR Ori

Parameter	Primary comp.	Secondary comp.
Mass-ratio	0.411	
Inclination	84°	
Ω potential	3.469188	2.878919
Inner Critical Surface	2.700448	
Outer Critical Surface	2.450348	
Temperature [K]	8200	5100
Gravity exponent*	1.0	0.32
Limb darkening coef. in U*	0.544	0.976
Limb darkening coef. in B*	0.598	0.824
Limb darkening coef. in V*	0.515	0.698
Albedo coefficient*	1.0	0.5
Volume	0.154608	0.078777
Mean radius	0.333	0.266
Radius r (back)	0.340	0.280
Radius r (side)	0.333	0.262
Radius r (pole)	0.325	0.254
Radius r (point)	0.345	0.293
Luminosity in U	0.9658	0.0342
Luminosity in B	0.9474	0.0526
Luminosity in V	0.9187	0.0813
* - fixed, adopted from literature		

In such manner was determined the distance of binary 472 pc that is lower than the distance published by Brancewicz and Dworak (1980) (530 pc). Using the value of interstellar absorption determined by Zakirov (1996) $A = 0.51$ we would get lower distance of FR Ori.

Evolution state of particular components of eclipsing binaries of W UMa type and some near-contact binaries were studied by Hilditch *et al.* (1988). They used diagrams mass versus radius *M-R*, mass versus luminosity *M-L*, HR diagram and diagram of total angular momentum J (more exactly the parameter $J/M^{5/3} \sim q(1+q)^{-2}\, P^{1/3}$, where $M = M_1 + M_2$) versus mass ratio q. Such diagrams constructed on the basis of the data published in their paper are depicted in Figs. 6, 7, 8 and 9.

The primary component of the system occurs in the region between ZAMS and TAMS. From the diagrams M-R and HR follows that it occurs behind ZAMS. The secondary component occurs out of region MS stars, behind TAMS. The star already left the main sequence and aims to the giant branch. The star radius determined in this paper is 1.75 times larger as the radius of MS star of the same spectral type.

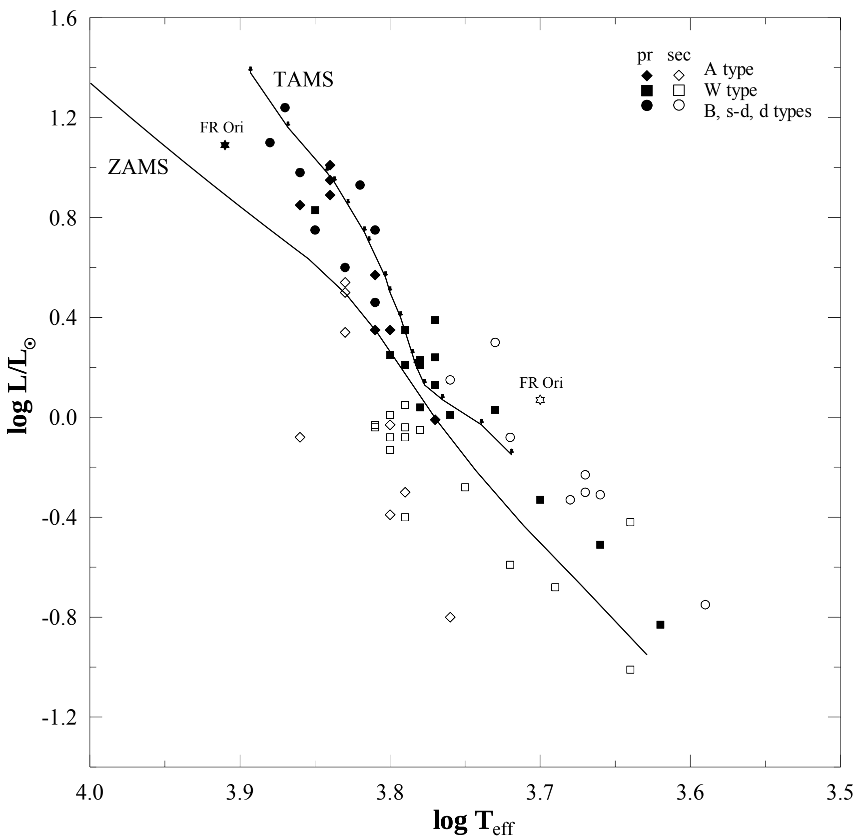

Fig. 6. HR diagram (Hilditch *et al.* 1988) and the position of primary and secondary components of FR Ori in this diagram.

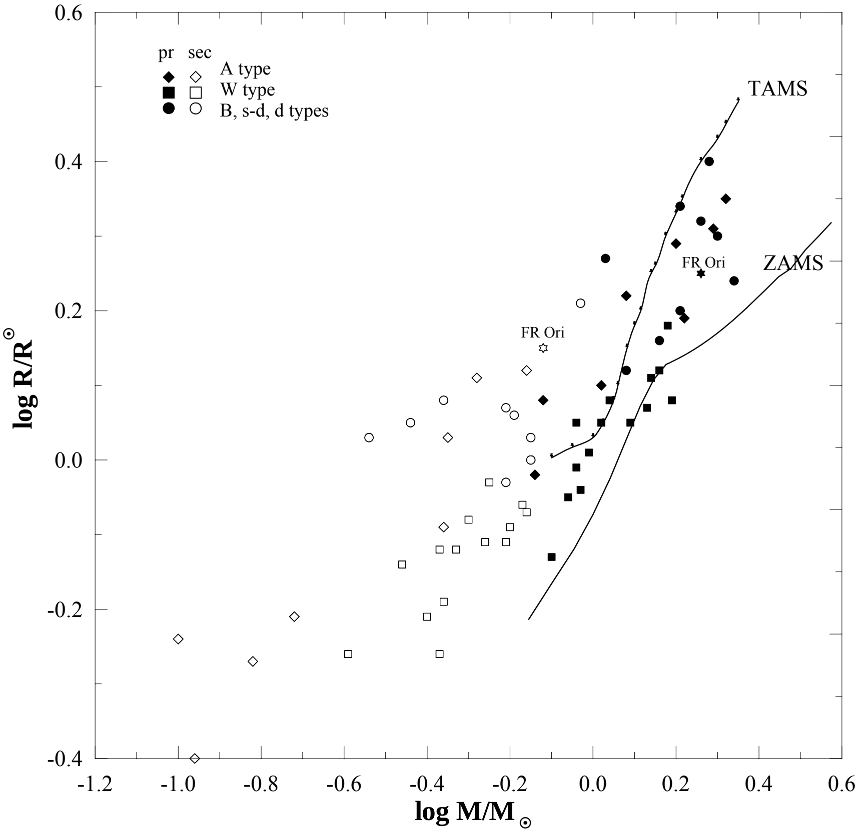

Fig. 7. M-R diagram (Hilditch *et al.* 1988) and the position of primary and secondary components of FR Ori in this diagram.

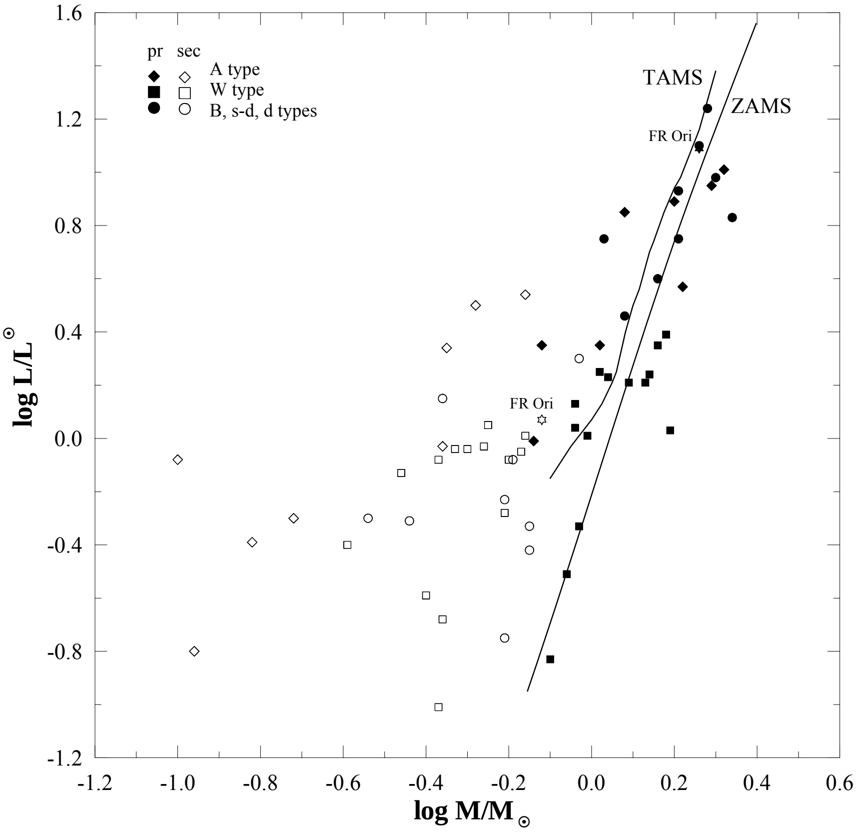

Fig. 8. M-L diagram (Hilditch *et al.* 1988) and the position of primary and secondary components of FR Ori in this diagram.

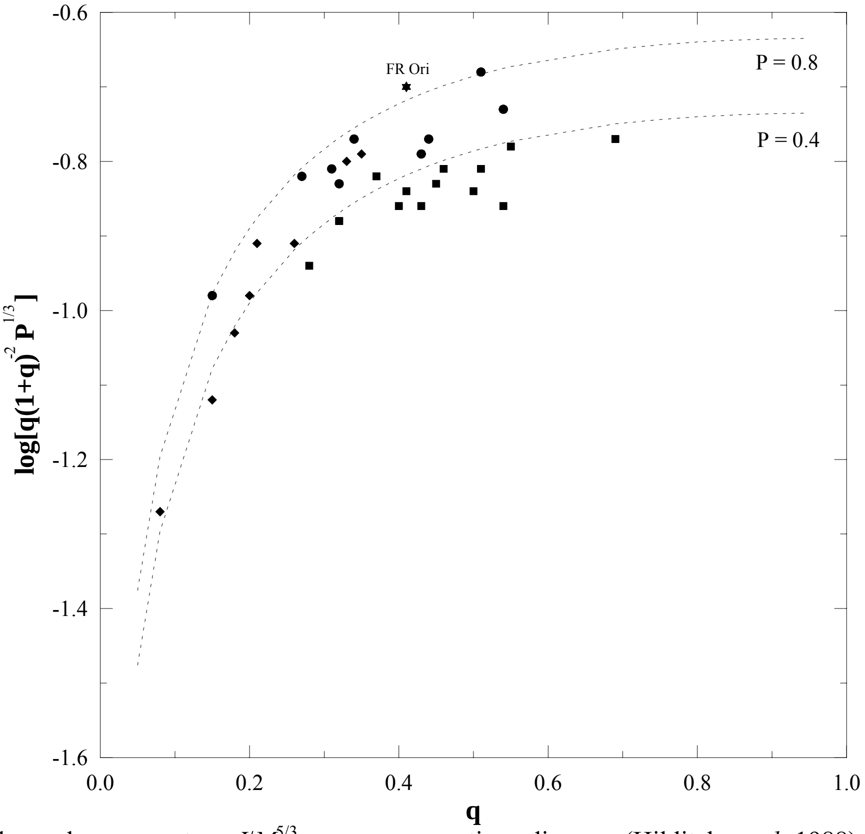

Fig. 9. Total orbital angular momentum $J/M^{5/3}$ versus mass ratio q diagram (Hilditch *et al.* 1988) and the position of primary and secondary components of FR Ori in this diagram.

In the diagram of angular momentum dependence versus mass ratio FR Ori lies in upper part. It means that the loss of angular momentum has not occurred yet, for example by magnetic braking and so the contact has not happened yet (Hilditch *et al.* (1988). They consider in their paper the evolution of stars with the similar characteristics as eclipsing binary FR Ori has. By mass transfer from more massive component (primary component FR Ori) to its companion the binary system becomes semidetached system where the secondary component fills its Roche lobe. During the next evolution the system evolves from near-contact configuration up to contact configuration A type of W UMa eclipsing binaries. Such evolution can tend to the formation of fast rotating massive star. Presently it seams that the system FR Ori is in the detached state of evolution.

6. Conclusion

In this paper were reduced the new photometric data for eclipsing near-contact binary FR Ori. The observational material was undergone the detailed statistical analysis, which showed that the quality of observed data in filters B and V is comparable and higher than the quality in filter U. Detailed statistical analysis does not confirm the presence of intrinsic activity of this binary in recent evolutionary state. From the observations were determined four new times of minima. These were together with published minima used to construct (O-C) diagram. By the analysis of this diagram the period of the system was precise (0.883162859 days) and the new ephemeris was derived.

By analysis of the light curves the new geometrical and physical parameters of particular components of studied system were derived. Consequently by using of photometric elements the absolute parameters of eclipsing binary FR Ori were determined. The analysis shows that the primary component occurs on MS in the region between ZAMS and TAMS. The secondary component is more evolved, it left the MS and tends to the giant branch. FR Ori is near-contact system. Any component does not fill the critical Roche lobe and therefore presently probably the mass transfer does not occur.

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