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The Near-Contact Binary FU Ara: New Observations, a Photometric Study and Preliminary Elements

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Abstract A new CCD (*V*) light curve is presented for the semi-detached binary system FU Ara. The light curve, obtained in 2007, is the first one since the last 50 years. With our data we were able to determine six new times of minimum light and refined the period of the system to 0.8645049 days. A Wilson-Devinney analysis leads to a solution of a semi-detached configuration, composed of a main-sequence primary component of spectral type F5, fractionally smaller than its Roche lobe, and an evolved secondary component of spectral type K1 which fills its Roche lobe, and which is overluminous and oversized as compared with the main-sequence. The two components of FU Ara differ considerably in effective temperature. It is classified as an FO Virginis type of near-contact binary system. Assuming a reasonable value for the mass of the primary component, an estimate of the absolute elements of FU Ara has been made, on the assumption that the primary has a mass corresponding to its spectral type according to Svechnikov & Taidakova.

Key words: binaries: eclipsing — stars: fundamental parameters — stars: individual: FU Ara

1 INTRODUCTION

FU Ara was photographically discovered as a variable star by Swope (1936), she concluded that the star is an eclipsing binary. During 1954–1956 Cillié & Lindsay (1960) made a series of photoelectrical observations in *(B)* and *(V)* filters. From the observed primary minima they were able to derive the following ephemeris:

$$\text{Min.I} = \text{HJD}2426869.490 + 0.864500957 \times E. \quad (1)$$

Subsequently, Barani & Acerbi (2005) made an analysis of the photoelectrical observations of Cillié & Lindsay (1960) using the Differential Correction (DC) program by Wilson & Devinney (1971). They concluded that the star is a semi-detached eclipsing binary in which the primary component (more massive) is a main-sequence star and the secondary is a subgiant which fully fills its limiting lobe. The mass ratio of the system was found to be q = 0.399 and its inclination $i = 83^\circ.2$.

2 OBSERVATIONS AND DATA REDUCTION

FU Ara was observed in June 2007 at the International Amateur Sternwarte observatory (IAS) [1] located on the guest farm Hakos in Namibia. About 1850 CCD (*V*) filtered data points were obtained. The instrument used was a Celestron-11 telescope, equipped with a CCD ST-7 camera (KAF-400 chip), using a Johnson (*V*) filter. GSC 08741–00016 was used as a comparison star, which was located at α_{2000}=17:33:28.8, δ_{2000}

[1] see *http://www.ias-observatory.org/*

Table 1 Old and New Time of Minimum of FU Ara

JD(Hel.)+2400000	Method	Type	$Epoch_{(1)}$	$(O\text{-}C)_1$	$Epoch_{(2)}$	$(O\text{-}C)_2$	Ref.
26869.4900	pg	I	0.0	0	−31700.0	+0.0400	(1)
34973.3211 ± 0.0041	pe(B)	I	9374.0	−0.0009	−22326.0	+0.0022	(2)
34973.3226 ± 0.0086	pe(V)	I	9374.0	+0.0007	−22326.0	+0.0037	(2)
34989.3031 ± 0.0032	pe(B)	II	9392.5	−0.0122	−22307.5	−0.0091	(2)
34989.3074 ± 0.0032	pe(V)	II	9392.5	−0.0079	−22307.5	−0.0048	(2)
35270.2518 ± 0.0031	pe(B)	II	9717.5	−0.0262	−21982.5	−0.0245	(2)
35270.2522 ± 0.0045	pe(V)	II	9717.5	−0.0259	−21982.5	−0.0241	(2)
35710.3314 ± 0.0037	pe(B)	II	10226.5	+0.0224	−21473.5	+0.0221	(2)
35713.3330 ± 0.0033	pe(B)	I	10230.0	−0.0018	−21470.0	−0.0021	(2)
35713.3333 ± 0.0034	pe(V)	I	10230.0	−0.0015	−21470.0	−0.0021	(2)
54266.4779 ± 0.0021	CCD(V)	I	31691.0	+0.0881	−9.0	+0.0031	(3)
54268.6418 ± 0.0010	CCD(V)	II	31693.5	+0.0908	−6.5	+0.0058	(3)
54270.3695 ± 0.0010	CCD(V)	II	31695.5	+0.0895	−4.5	+0.0045	(3)
54272.5284 ± 0.0009	CCD(V)	I	31698.0	+0.0871	−2.0	+0.0021	(3)
54273.3925 ± 0.0009	CCD(V)	I	31699.0	+0.0867	−1.0	+0.0017	(3)
54274.2560 ± 0.0010	CCD(V)	I	31700.0	+0.0857	0.0	+0.0007	(3)

References: (1) Kholopov et al. (1985); (2) Cillié & Lindsay (1960); (3) This paper.

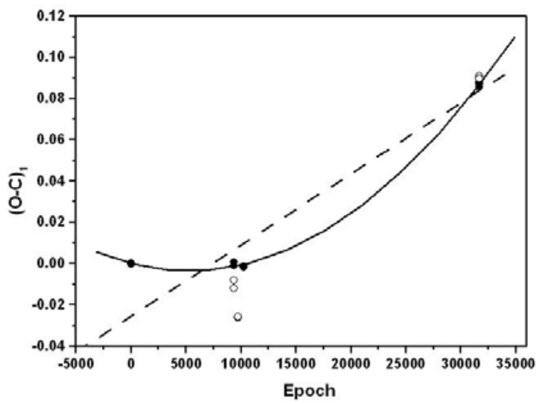

Fig. 1 (O - C) curve of the eclipsing binary FU Ara, showing the linear (dashed line) and quadratic (solid line) fit to the data. Filled circles represent the primary minima, and open ones, the secondary minima.

=–58:10:16. Its m_v=10.35; in spite of the fact that it is redder than FU Ara, it has the advantage of proximity to our variable star: in fact the distance is only 0.6 arcminutes. The Celestron-11 was operated on a German-type mounting, and it must be flipped when the star passes the meridian. Therefore it was easier to wait some hours and start the observation as soon as FU Ara reached the western part of the sky.

Due to the favorable desert climate at Hakos, the data could be collected in consecutive nights, but on one night there was a technical difficulty – shortage of electrical power. The images have been processed with the program C-Munipack [2] written by Ing. David Motl. The program also included aperture photometry.

The method by Kwee & van Woerden (1956) was used for the determination of the six new minima from our observations and the nine minima from the photo-electrical observations of Cillié & Lindsay (1960). The data are presented in Table 1. These minima, except a photoelectric (JD 35710.3314) one which was removed because of unreasonably large residual, permitted us to refine the orbital period to give:

$$\text{Min.I} = \text{HJD}2454274.2553(61) + 0.8645049(3) \times E. \quad (2)$$

[2] see *http://integral.physics.muni.cz/cmunipack/*

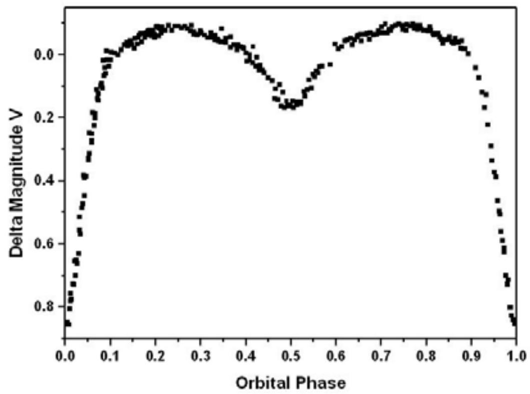

Fig. 2 CCD (*V*) light curve of FU Ara.

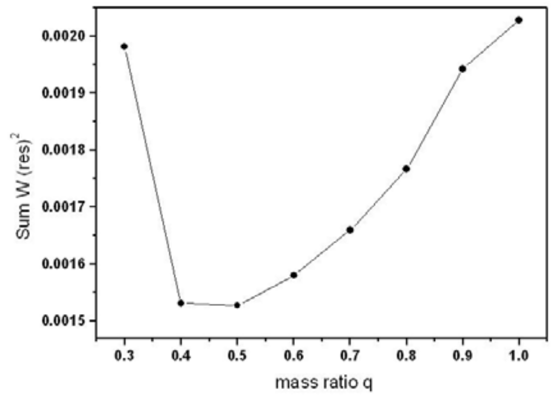

Fig. 3 $\sum(\mathrm{res})^2$ versus mass ratio *q* in Mode 5.

Period variation can be seen more clearly in the O-C diagram (Fig. 1), the phases of our observations were computed using Equation (2). The light curve in (*V*) filter of the individual observations is shown in Figure 2.

A quadratic ephemeris determined by a least squares fitting to all the minima gives:

$$\mathrm{Min.I} = \mathrm{HJD}2454274.2583(34) + 0.8645091(8) + 1.70(3) \times 10^{-10} E^2. \tag{3}$$

This ephemeris shows that the orbital period of FU Ara has increased. Using the coefficient of the square term of Equation (3), we calculate a period increase of $dp/dt = 1.44 \times 10^{-7}$ day yr^{-1}. However, the quadratic fit strongly depends on the first light epoch. More minima are needed to confirm this conclusion.

3 PHOTOMETRIC SOLUTION

Photometric analysis of the available (*V*) light curve (about 1850 individual points) of FU Ara was carried out using the 2003 version of DC program (Wilson-Devinney 1971; Wilson 1994; Wilson & van Hamme 2003). To start the analysis we used, as input parameters, the values obtained in the analysis of the old observations of Cillié & Lindsay (1960) made by Barani & Acerbi (2005). Convergence of the minimization procedure was obtained by means of multiple subsets (Wilson & Biermann 1976).

The calculations were started in Mode 2 - a detached configuration with no constrains on the potentials to test the semi-detached configuration (Leung & Wilson 1977). After a few iterations the solution converged to Mode 5 - a semi-detached configuration with star 2 accurately filling its Roche Lobe - the same configuration obtained by Barani & Acerbi (2005) in their analysis.

The fixed parameters we employed in Mode 5 were: the temperature of the primary component (star eclipsed at Min.I), T_1 = 6650 K; the bolometric albedos, $A_1 = A_2$ = 0.50 (Rucinski 1969); the gravity-darkening exponents, $g_1 = g_2$ = 0.32 for convective envelopes (Lucy 1967); the bolometric and wavelength-dependent limb darkening coefficients ($x_{1\mathrm{bolo}}, x_{2\mathrm{bolo}}, y_{1\mathrm{bolo}}, y_{2\mathrm{bolo}}, x_{1V}, x_{2V}$), using the square root law (LD = 3), taken from van Hamme (1993) for log g = 4.0 and solar abundances, and the Ω_2 potential. A fine surface grid, N1 = N2 = 30 , N1L = N2L = 25 and symmetrical partial derivatives for each of the adjustable parameters (ISYM = 1) were adopted during all calculations. The simple reflection model of Wilson (1990) was used with a single reflection (MREF = 1 , NREF = 1) . The third light was not allowed, l_3 = 0.0, circular orbit and synchronous rotation were assumed ($F_1 = F_2$ = 1).

The adjustable parameters employed were: the inclination *i*, the mean surface temperature of secondary component T_2, the non-dimensional surface potential Ω_1, and the monochromatic luminosity of the primary component L_1 (the black-body option was used in the computing code).

Since the spectroscopically determined mass ratio $q = m_2/m_1$ is not available, a search for a solution was made by fixing several values of *q* in the range between 0.3 and 1.0. A sufficient number of runs of the DC program was made until the sum of the residual $\sum(\mathrm{res})^2$ showed a minimum and the corrections to the parameters became smaller than their probable errors. The sum of the weighted square deviation $\sum(\mathrm{res})^2$

Table 2 Light Curve Solution of FU Ara for the 1954–1956 and 2007 Light Curves

Parameter	1954–1956	2007
i	83°.256 ±0°.013	82°.005 ±0°.086
T_1(K)	6650*	6650*
T_2(K)	4899 ± 7	4942 ± 8
f	–01.762 ± 0.002	–1.941 ± 0.005
Ω_1	3.1067 ± 0.0004	3.3414 ± 0.0012
Ω_2	2.6781*	2.8036*
$q = m_2/m_1$	0.39912 ± 0.0009	0.46284 ± 0.0033
$A_1(= A_2)$	0.50*	0.50*
$g_1(= g_2)$	0.32*	0.32*
$L_{1V}/(L_1 + L_2)$	0.835 ± 0.002	0.810 ± 0.026
$L_{2V}/(L_1 + L_2)$	0.135 ± 0.001	0.161 ± 0.010
X_{1V}	0.135*	0.099*
X_{2V}	0.688*	0.597*
L_3	0	0
Primary component		
r(pole)	0.3662 ± 0.0004	0.3439 ± 0.0014
r(side)	0.3800 ± 0.0004	0.3550 ± 0.0016
r(back)	0.3914 ± 0.0005	0.3651 ± 0.0018
Secondary component		
r(pole)	0.2825 ± 0.0003	0.2941 ± 0.0005
r(side)	0.2945 ± 0.0003	0.3069 ± 0.0006
r(back)	0.3272 ± 0.0003	0.3394 ± 0.0006
$\sum(\mathrm{res})^2$	0.00408	0.00150

* assumed parameters.

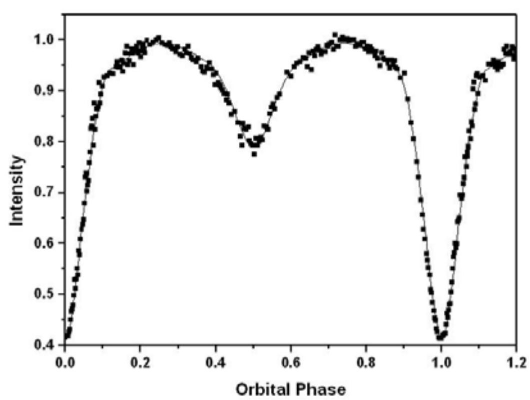

Fig. 4 Observational (points) and theoretical (line) light curves of FU Ara.

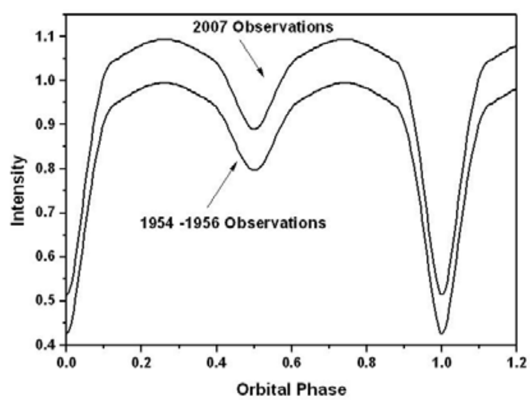

Fig. 5 A comparison of the features of the light curves of FU Ara in the different years, for convenience the 2007 data are shifted by 0.1 in intensity.

versus the mass ratio q is shown in Figure 3, a sharp minimum of $\sum(\mathrm{res})^2$ is seen between mass ratio 0.4 and 0.5. Then we used both q = 0.4 and q = 0.5 as the initial values of the mass ratio in two different DC procedures with q as additional free parameters. The best solution we obtained was one starting with q = 0.5 ($\sum(\mathrm{res})^2$ = 0.00150) rather than with q = 0.4 ($\sum(\mathrm{res})^2$ = 0.00153) and the synthetic light curve corresponding to this solution is shown by the solid line in Figure 4. We remark that the probable errors provided by the DC code are unrealistically small (Maceroni & Rucinski 1997).

Table 3 Estimated Absolute Elements for FU Ara

	primary		secondary	
	1954–1956	present work	1954–1956	present work
mass($M_\odot$)	1.34	1.34	0.54	0.62
radius($R_\odot$)	1.79	1.72	1.42	1.60
log($L/L_\odot$)	0.75	0.72	0.02	0.15

In Figure 5 we show a comparison of the fitted light curves, obtained with the parameters in Table 2, to the observations in the different years. We can see widely different minimum depths, which implies a significant difference in temperature between the two components. The primary eclipse is due to the transit of the cooler, less massive secondary component across the face of the hotter primary (Fig. 6).

The solutions for the detached configuration revealed the secondary filling the critical Roche lobe, so indicating that the semi-detached solution, near-contact binary star (NCBs), is correct. Figure 7 shows this configuration in the orbital plane.

Shaw (1994) divided the near-contact systems into two subclasses: (a) V1010 Ophiuchi systems, in which the primary component almost or completely fills its Roche lobe, while the secondary component is inside its Roche lobe. The light curve is then asymmetric with the primary maximum brighter than the secondary maximum, and both components are slightly evolved. (b) FO Virginis binaries, in which the primary component is inside the Roche lobe, and the secondary is close to, or filling its Roche lobe. The light curve then shows no asymmetry, and the components may be highly evolved. From the photometric solution of FU Ara, we find that the secondary component fills its Roche lobe and that there is no asymmetry in the light curve, so, FU Ara is very probably a new member of the FO Virginis subclass of near-contact binaries (NCBs). Most of this subclass have spectral types A or F for the primary and G or K for the secondary. The NCBs are considered to be evolutionary precursors of the A-subtype W UMa binaries (Qian 2002), inside the Thermal Relaxation Oscillation (TRO) model (Flannery 1976; Lucy 1976; Robertson & Eggleton 1977). Since the system is semidetached with the secondary filling its lobe, one can presume mass loss from this component. The slight increase in the orbital period of FU Ara may indicate that mass transfer is taking place, from the less massive to the more massive component.

4 THE EVOLUTIONARY STATE OF FU ARA

Without spectral types or individual masses of the system, it is difficult to obtain reliable absolute elements of the components. However, if we assume that the primary component is of spectral type F5 with temperature of T_1 = 6650 K (De Jager & Nieuwenhuijzen 1987), and obeys the spectral type-mass relation of Svechnikov & Taidakova (1984) for normal main-sequence stars, we can obtain approximate masses and dimensions of the components of FU Ara. From this assumption one obtains a mass of 1.343 $M_\odot$ for the primary component. The mass of the secondary component is then 0.621 $M_\odot$ from the mass ratio $m_2/m_1 = q$ = 0.46284. We used the well known formulae by Milano & Russo (1983) to estimate the absolute elements of FU Ara (Table 3),

$$M_c/M_\odot = qM_h/M_\odot, \tag{4}$$

$$R_h/R_\odot = [74.55(M_h/M_\odot)(1+q)P^2]^{1/3} r_h, \tag{5}$$

$$R_c/R_\odot = (r_c/r_h)(R_h/R_\odot), \tag{6}$$

$$L/L_\odot = (R/R_\odot)^2(T/T_\odot)^4. \tag{7}$$

The computed absolute elements of FU Ara are used to estimate the evolutionary status of the system by means of the H-R diagram.

A comparison of these data with the mass-luminosity data for main-sequence stars clearly demonstrates that while the primary component lies within the main-sequence band, the secondary component lies above it, being oversized and overluminous for its mass (Fig. 8). The system is therefore composed of a normal main-sequence primary component which lies well within its limiting Roche surface, and an evolved secondary component which fills its Roche lobe completely. The evolved secondary component strongly suggests that at some time in the past the binary has undergone a phase of mass reversal, and the present secondary is the remnant of the former primary component. An immediate conclusion strengthened by these

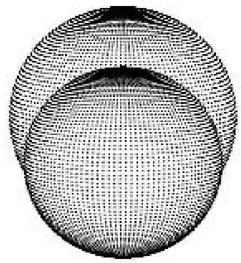

Fig. 6 Aspect of the system at 1.0 of orbital phase. The larger, more massive star is eclipsed.

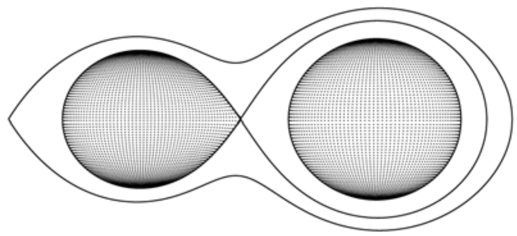

Fig. 7 Configuration of components of the system in the orbital plane according to our solution.

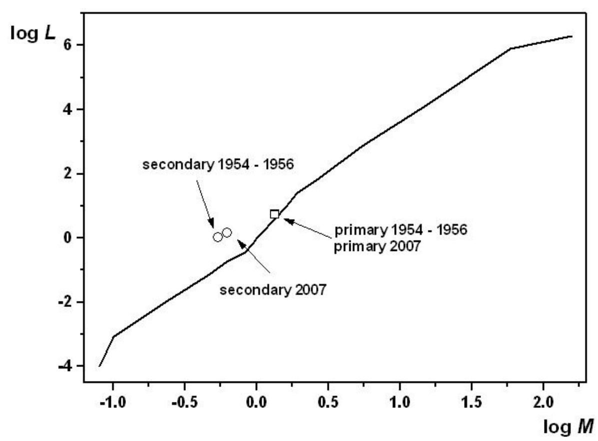

Fig. 8 Location of the primary and secondary components of FU Ara in $\log M$ vs. $\log L$ plot. The solid line shows the main-sequence.

results is that FU Ara is definitely a NCB of the FO Virginis subtype, rather than one of the V1010 Ophiuchi subtype. This is also in accordance with the photometric property of having equally bright maxima.

5 DISCUSSION AND CONCLUSIONS

We presented a new photometric study of the variable, FU Ara, which has been rather neglected for some 50 years. Our CCD photometric observations show a typical light curve of a β Lyrae variable star. A refined period and new ephemerides have been obtained. The increase in the period needs to be checked in the future with more data .

From the photometric solution of the (*V*) light curve, using the DC code, we conclude that it is a near-contact binary in which the secondary is a K1 spectral type, evolved star that fills its Roche lobe, and is overluminous and oversized for its mass (De Jager & Nieuwenhuijzen 1987). The primary component, an F5 spectral type star, lies within the main-sequence and well inside its limiting Roche surface. This configuration, as argued by Shaw (1994), is typical of the so-called FO Virginis near-contact systems, which include the other near-contact systems, RU UMi, DD Mon, and AV Hya (Qian 2000; Qian et al. 1997; Zhu et al. 2006). The primary (deeper) minimum occurs when the larger more massive star is eclipsed by its smaller, less massive companion.

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