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ECCENTRIC ECLIPSING BINARY STARS AS TEST OF GENERAL RELATIVITY: THE CASE OF EW ORIONIS

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The detached eclipsing binary EW Orionis (= BD +1°0976 = HD 287 727 = GSC 0104.1206 = HBV 421, $\alpha_{2000} = 5^{\rm h}20^{\rm m}9\overset{\rm s}{.}1$, $\delta_{2000} = +2°2'39\overset{''}{.}4$, $V_{max} = 9.9$ mag; Sp.: G0+G5) is a relatively well-known system having an eccentric orbit ($e = 0.08$) and an orbital period of $P_{orb} = 6.94$ days. It was discovered to be a variable star by Hoffmeister (1930), next visual observations were provided by Lause (1937), Gaposchkin (1953) and Kordylewski (1962). First photoelectric observations were obtained by Pierce (1951). Next moments of minima were determined by Busch (1976) using the photographic plates of the Sonneberg and Hartha Observatories. Radial velocities and two-colour V, R photometry of EW Ori were analyzed by Popper et al. (1986) and fundamental properties of the components were derived ($m_1 = 1.19\,{\rm M}_\odot, m_2 = 1.15\,{\rm M}_\odot, R_1 = 1.14\,{\rm R}_\odot, R_2 = 1.09\,{\rm R}_\odot$). EW Orionis is another important system for the study of the relativistic apsidal motion. The theoretically expected rotational velocity of the line of apsides caused by relativistic contribution could be $\dot\omega_{GR} = 0.0140°$ yr^{-1}, the classical contribution is $\dot\omega_{cl} = 0.00215°$ yr^{-1}.

Our photometry of EW Ori was carried out during two periods. The photoelectric measurements in standard V filter were made during January – March 1985 at the Tian-Shan Observatory of the Sternberg Astronomical Institute, Moscow, using a 50 cm reflector. The star BD +1°0923 = GSC 0104.1278 – noted also as star "*a*" by Busch (1976) – served as a comparison star. The current CCD photometry of EW Ori was carried out in March 1996 and February 1997 at the Ondřejov Observatory using a 65cm reflecting telescope with a CCD-camera (SBIG ST-6). The measurements were done using the standard Johnson V filter usually with 45 s exposure time. More details on our equipment and data reduction procedure see e.g. in Šarounová & Wolf (1997). The stars GSC 0104.1238 – listed also as star "*b*" by Busch (1976) – on the same frame as EW Ori served as the comparison star. The new times of primary and secondary minima and their errors were determined using different numerical methods and are presented in Table 1. The epochs were calculated according to linear light elements given by Busch (1976):

$$\text{Pri. Min.} = \text{HJD } 24\ 27543.350 + 6.9368515 \times \text{E}.$$

Table 1: Photoelectric times of minimum of EW Ori.

JD Hel.– 2400000+	Error [days]	Epoch	Observatory
28937.665*	0.005	201.0	Princeton
44916.8887*	0.0003	2504.5	McDonald
44947.8946*	0.0003	2509.0	McDonald
46096.15233	0.00005	2674.5	Tian-Shan
46113.2839	0.0007	2677.0	Tian-Shan
50147.2694	0.0005	3258.5	Ondřejov
50497.3691	0.0004	3309.0	Ondřejov

∗ *recalculated original data*

The apsidal motion in EW Ori was studied independently by means of an $O-C$ diagram and a light-curve analysis. For the study of the $O-C$ diagram we took into consideration all photoelectric times collected in Table 1 as well as moments published by Busch (1976). All photoelectric times of minimum were used in our computation with a weight of 10. The weight of first photoelectric measurements obtained by Pierce (1951) was reduced to 5 due to large scatter of these data. The visual and photographic times obtained by Busch (1976) were weighted with a weight of 1. A total 52 times of minimum light were incorporated in our analysis, with 37 primary eclipses among them. For the apsidal motion analysis we used a numerical method by Giménez & García-Pelayo (1983), which is a weighted least squares iterative procedure including terms in the eccentricity up to the fifth order.

Adopting the orbital inclination and eccentricity, derived from the light curve solution, of $i = 89.8°$ and $e = 0.079$ (Popper et al., 1986), the mean apsidal motion elements given in Table 2 can be determined. In this table P_s denotes the sidereal period, P_a the anomalistic period, e represents the eccentricity, $\dot{\omega}$ the rate of apsidal motion. The zero epoch is given by T_0, and the corresponding position of the periastron is ω_0. The corresponding value of the period of periastron rotation is found to be $U = 160\,000 \pm 40\,000$ yr. The $O-C$ diagram is given in Figure 1. The predictions, corresponding to the fitted parameters, are plotted as continuous and dashed lines for primary and secondary eclipses, respectively.

Residuals for the times of minimum of EW Ori with respect to the linear light elements. The continuous and dashed lines represent predictions for primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by circles and triangles, respectively. Larger symbols correspond to the photoelectric measurements with higher weight

For the light-curve analysis we used an improved iterative method of differential corrections developed for an analysis of light curves of eclipsing binaries with eccentric orbits (Khaliullina & Khaliullin 1984). Firstly we took into our calculation all photoelectric measurements and fixed the value of eccentricity at $e = 0.079$ (run I). In the second trial, the orbital period P_s was determined using all times of minima except the first photoelectric measurements of Pierce (1951) and the value of eccentricity was taken as an independent parameter (run II). Finally, in the third run, we took into consideration all photoelectric measurements for the period determination and all parameters were free

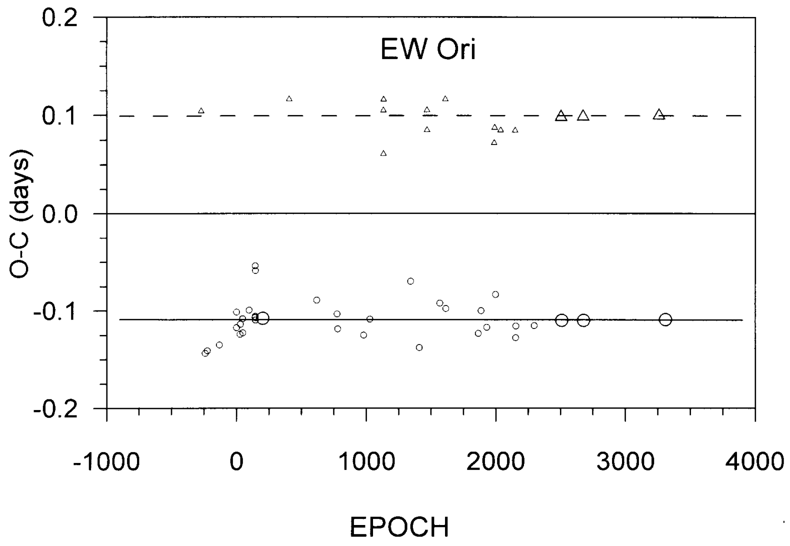

Figure 1.

during this calculation (run III). All results of this analysis are compared in Table 2.

We derived the apsidal motion elements using two independent methods on the current data set. Our results indicate that the apsidal motion rate in this system could be smaller than expected from theory. Surprisingly, the $O-C$ diagram analysis gives the rate of apsidal motion $\dot{\omega}_{obs} = 0.23°/100$ years, which is only 16 percent of the rate predicted by the General Relativity. Moreover, the second run of the light-curve analysis gives a negative value of $\dot{\omega}$. Resulting apsidal motion elements are also sensitive to the adopted weighting scheme. According to our light-curve analysis the spectral type of components should be F8 + G0.

Nevertheless, this system could be another eclipsing binary, which exhibits the discrepancy between observed and predicted rate of the apsidal motion. Another anomalous "slow" case of V541 Cygni was recently discussed by Wolf (1995) and Guinan et al. (1996) and was not yet explained satisfactorily. More high-accuracy timings of these eclipsing systems are necessary in the future to enlarge the time span for better analysis of the

Table 2: Apsidal motion parameters

	$O-C$ diagram	light-curve analysis		
		I	II	III
T_0	24 27543.4670 ± 0.0007		24 44913.2028	
P_s [days]	6.9368422 ± 0.0000012	6.9368428	6.9368446	6.9368428
P_a [days]	6.9368430 ± 0.0000012	–	–	–
e	0.079 (*fixed*)	0.079 (*fixed*)	0.067	0.063
$\dot{\omega}$ [° yr^{-1}]	0.00226 ± 0.00056	0.0097	– 0.0115	0.0189
ω_0 [°]	306.7 ± 0.4	306.9	315.3	319.1

apsidal motion.
For the present use we propose the following linear light elements for EW Ori:

$$\text{Pri. Min.} = \text{HJD } 24\ 50497.3691 + 6.936842 \times E$$
$$\text{Sec. Min.} = \text{HJD } 24\ 50147.2694 + 6.936842 \times E.$$

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