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Unexplored Eclipsing Stars with Elliptical Orbits

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This study presents parameters of several poorly studied eclipsing variable stars with elliptical orbits. The data were obtained from solution of our own long-term photometric observations.

The main goal of this work is to study the internal structure of stars. One of the ways of solving the problem is to measure the rotation speed of the apsidal line from observations of eclipsing stars with elliptical orbits. The rotation periods of the apsidal line can reach tens of thousands of years, and thus long series of observations of each star are required. In particular, our work has been going on for 35 years. Here we present a summary of our study.

The beginning of this study was first announced by Volkov and Volkova (2009), where the method of object selection was also described. The basis was the list of mainly northern stars obtained by Otero et al. (2006) from observations of ROTSE, ASAS, and Hipparcos. A number of stars were also selected that had previously avoided attention of observers due to difficulties of their observations: periods that are multiples of a day; eclipsing stars that are components of visual binary stars, etc.

We carried out observations with the 1.25-m and 60-cm reflectors at the Crimean Observatory of Sternberg institute; Zeiss-600 and Zeiss-1000 telescopes in the Simeiz INASAN observatory; 70-cm reflector of Moscow observatory of Sternberg Institute; 50-cm and 60-cm reflectors of Stará Lesná observatory, Slovakia. We mainly used CCD cameras, such as VersArray-512UV, VersArray-1300, ST-10XME, FLI PL09000; some others were also used, but not often. Observations were fulfilled in the Johnson–Cousins $UBV\ RcR\ IcI$ system. For bright stars, a UBV photometer designed by I.M. Volkov, with an EMI9789 photomultiplier, was used (Volkov and Volkova, 2007).

The methods of our observations are described in detail in earlier publications: Barabanov et al. (2021), Burlak et al. (2018), Volkov et al. (2021). Methods for processing observations and determining the relative and physical parameters of the systems are given in Volkov et al. (2010), Volkov et al. (2011), Bagaev et al. (2018).

Stellar temperatures were determined using Flower (1996) and Popper (1980) color index calibrations. Stellar magnitudes in the $UBVRI$ system were determined by normalizing to standards from Kornilov et al. (1991), Moffett & Barnes (1979).

Table 1 presents the main observational parameters of the stars under study. Interstellar reddening was determined from our UBV photometry. If there is an asterisk, the interstellar reddening was determined from the survey by Green et al. (2015).

The $B-V$, $U-B$, $V-R$, $R-I$ color indices corrected for interstellar reddening allowed us to determine spectral types of the components of eclipsing stars. In Table 1, we present only the $B-V$ index as the most important one. The data in this Table are accurate to one half of the last significant digit.

Modern ephemeris of eclipsing stars given in Table 1 allow observers to pre-calculate minima with a high accuracy.

Table 1: Basic observational parameters of the stars

Star	V	$B-V$	$E(B-V)$	Spectrum	Epoch HJD 2400000.0+	Period	Φ II
V871 Aql	12.51	1.06	1.19	B6V+B6V	52500.0229	2.952641	0.4451
V889 Aql	8.575	0.210	0.202	B9.5V+A0V	59060.3949	11.120760	0.3538
V645 Aur	9.72	0.01	0.11	B8V+B8V	52977.7382	10.8925082	0.7893
OO Cam	10.48	0.21	0.30*	B8V+A0V:	55873.6014	8.1190455	0.4892
V347 Cam	10.96	0.26	0.09	A6IV+A6V	55314.4168	9.4545582	0.6944
V361 Cam	10.81	–0.06	0.10	B3IV+B9.5V	58561.2482	8.6385638	0.4727
V409 Cam	10.71	0.47	0.13	F0V+A9IV	57800.4846	6.676482	0.5231
V422 Cam	11.10	0.62	0.11	G0V+G1V	57803.3008	17.8705606	0.4904
V498 Cam	11.64	0.57	0.04	F7V+F7V	57795.3229	12.1102647	0.5653
KX Cnc	7.20	0.585	0.00	F9V+G0V	54162.7372	31.2198585	0.6432
DR CMi	11.06	0.13	0.0	A5IV	56644.5759	23.770030	0.6685
V1066 Cas	10.81	0.28	0.29	A3IV+A0V	58896.2402	8.4649440	0.5564
V1110 Cas	10.33	0.69	0.24	F5+F5:	58958.34515	24.849451	0.7063
V1141 Cas	11.93	0.19	0.49	B2V+B3V	59129.2382	6.9094135	0.4550
V1162 Cas	10.72	0.43	0.2?	A0+A2:	59159.5948	29.0674505	0.2299
V750 Cep	11.26	0.68	0.76	B9V+A5V	58886.3278	18.8821656	0.438
V850 Cep	9.98	0.38	0.23*	A0	51475.7273	12.914975	0.590
V880 Cep	10.27	0.28	0.32	A0V+A1V	58655.4035	27.330125	0.539
V897 Cep	11.44	0.71	0.3?	KIII:	56235.5138	4.4871945	0.5118
V898 Cep	12.14	0.78	0.88	B9V+B9V?	55481.3576	2.8747704	0.6684
V921 Cep	11.69	0.87	0.61	F0IV+A8IV	58347.5032	13.7146644	0.4312
V922 Cep	11.41	0.42	0.5	B7V+B7V	55878.7002	3.57497303	0.5839
V944 Cep	10.92	0.95	1.03	B8V+B9V	58773.3625	6.56005423	0.5070
V1326 Cyg	11.44	0.22	0.23	B8V+B8V	55073.5052	16.681735	0.5302
V2544 Cyg	12.76	1.49	1.73	B2V+B2V	57927.3549	2.09381	0.5342
NS Dra	11.34	0.95	0.00	G5IV+K1III	58942.4806	50.54440	0.6321
V432 Dra	12.23	0.60	0.16	F5V+F5V	53278.3192	11.6281562	0.6985
UW Hya	13.19	0.53	0.0	F8V+F8V	47952.2502	2.11087916	0.5
IL Lac	12.47	0.26	0.35	B8V+B9V	55482.3025	7.395662	0.4354
V340 Lac	11.91	0.32	0.38	B9.5V+B9.5V	58350.5181	19.943091	0.7623
RU Mon	10.50	0.078	0.19	B8V+B9V	58921.1627	3.584690	0.3348
V501 Mon	12.31	0.501	0.22	A9V+F2V	52502.9358	7.0212043	0.4476
V521 Mon	10.055	0.135	0.249	B8V+B8V	59518.5547	2.970692	0.592
V2778 Ori	10.12	0.31	0.40	B6V+B9V	51629.65705	14.38759	0.4365
V751 Per	11.15	0.19	0.28	B8+B9	51508.6200	5.96134777	0.4487
V966 Per	13.08	0.06	0.24	B4V	54158.3045	4.3088431	0.3319
CR Sct	10.96	0.21	0.37	B5V+B5V	59365.5286	4.19235295	0.5112
V370 Sge	12.46	0.57	0.247	F0V+F2V	52734.9374	8.32628726	0.3790
EQ Vul	11.03	0.65	0.79	B6+B5III	60112.3244	9.297071	0.3214
V491 Vul	9.95	0.74	1.09	B0.5V	54648.4446	7.6697718	0.3348

Table 2: Relative parameters of the studied stars obtained from light curve solutions

Star	e	ω	i°	r_1	r_2	$\dot{\omega}_{obs}$ °/year	$\dot{\omega}_{theor}$ °/year
V871 Aql	0.156(4)	236.90(2)	89.80(1)	0.172(1)	0.180(1)	1.37(9)	2.07
V889 Aql	0.368(4)	127.01(1)	89.21(1)	0.056(3)	0.052(3)	0.014(1)	0.016(2)
V645 Aur	0.5733(8)	320.04(1)	89.71(1)	0.0612(1)	0.0582(2)	0.020(5)	0.047
OO Cam	0.103(3)	260.62(1)	87.52(1)	0.0606(35)	0.0716(31)	0.008(2)	–
V347 Cam	0.3110(1)	4.28(1)	87.59(1)	0.0728(1)	0.0441(5)	–	–
V361 Cam	0.128(3)	251.23(1)	89.49(1)	0.1339(7)	0.0544(3)	0.185	0.052
V409 Cam	0.043(2)	32.39(7)	84.92(1)	0.084(9)	0.105(6)	0.16(6)	–
V422 Cam	0.035(3)	243.86(4)	89.57(1)	0.0324(1)	0.0244(1)	–	–
V498 Cam	0.259(9)	67.47(2)	87.54(1)	0.063(5)	0.050(7)	0.020(3)	–
KX Cnc	0.4666(5)	63.80(1)	89.83(1)	0.0193(5)	0.0190(5)	0.0056(5)	
DR CMi	0.562(3)	65.85(1)	88.32(1)	0.0492(6)	0.0548(5)	0.011(7)	–
V1066 Cas	0.155(3)	55.34(1)	86.35(1)	0.1604(7)	0.0707(4)	0.193(4)	–
V1110 Cas	0.512(20)	54.10(4)	87.68(1)	0.040(14)	0.036(17)	0.0088	0.0036:
V1141 Cas	0.365(2)	259.58(1)	89.14(1)	0.1135(3)	0.0919(2)	0.15(3)	0.235
V1162 Cas	0.522(2)	142.94(1)	89.71(1)	0.0268(6)	0.0263(6)	0.00043:	0.0028
V750 Cep	0.278(2)	109.86(1)	89.99(4)	0.0501(2)	0.0306(1)	–	0.0050
V850 Cep	0.465(2)	74.20(1)	88.44(1)	0.0693(7)	0.0586(10)	0.010(3)	–
V880 Cep	0.320(6)	79.55(1)	88.34(1)	0.0393(6)	0.0272(9)	–	–
V897 Cep	0.034(8)	57.8(2)	82.15(1)	0.12(4)	0.14(4)	–	–
V898 Cep	0.2670(1)	359.02(1)	85.15(1)	0.140(9)	0.149(9)	4.6(10)	–
V921 Cep	0.469(2)	258.14(1)	89.68(1)	0.0868(2)	0.0699(2)	0.030(2)	–
V922 Cep	0.1325(1)	3.56(1)	89.64(1)	0.1000(7)	0.0984(8)	–	–
V944 Cep	0.179(2)	86.33(1)	84.62(1)	0.1931(4)	0.1049(3)	0.44(3)	0.70
V1326 Cyg	0.396(9)	276.3(1)	89.12(1)	0.0403(2)	0.0502(1)	0.014(7)	
V2544 Cyg	0.0827(9)	338.53(3)	85.97(1)	0.236(2)	0.190(3)	8.5(1)	8.9
NS Dra	0.349(9)	305.58(2)	88.09(1)	0.0245(3)	0.0674(8)	0.009(4)	0.0086
V432 Dra	0.377(1)	325.12(1)	89.19(1)	0.0389(4)	0.0388(4)	0.0265(10)	
UW Hya	0.0	–	87.01(1)	0.196(3)	0.197(2)	–	–
IL Lac	0.1089(8)	158.83(2)	89.81(1)	0.0734(2)	0.0668(2)	0.047(20)	0.032
V340 Lac	0.4261(1)	4.35(1)	89.62(1)	0.0333(3)	0.0352(2)	–	
RU Mon	0.398(2)	128.87(1)	89.10(1)	0.129(2)	0.129(2)	1.00(2)	0.86(3)
V501 Mon	0.137(2)	233.22(1)	88.27(1)	0.0854(4)	0.0678(6)	0.021(6)	0.024
V521 Mon	0.192(5)	45.15(3)	86.82(1)	0.2075(12)	0.1255(9)	1.85(7)	1.60
V2778 Ori	0.164(2)	127.28(1)	89.24(1)	0.0689(2)	0.0487(2)	0.18(3)	–
V751 Per	0.0809(1)	176.77(2)	88.72(1)	0.0942(2)	0.0761(4)	0.73:	0.05
V966 Per	0.2961(6)	206.52(1)	89.16(1)	0.1475(2)	0.1223(2)	0.68(2)	0.575
CR Sct	0.042(1)	65.7(1)	88.40(1)	0.1492(9)	0.1311(12)	0.57(1)	0.47(10)
V370 Sge	0.2189(4)	150.32(1)	89.02(1)	0.0945(1)	0.0756(1)	0.020(2)	0.025
EQ Vul	0.2906(6)	192.08(1)	88.88(1)	0.1543(6)	0.1282(6)	0.96(20)	–
V491 Vul	0.3372(9)	220.63(1)	89.99(1)	0.1115(2)	0.1018(2)	0.340(5)	0.31

The algorithm of light curve solution used to obtain parameters in Table 2 is described in Khaliullin and Khaliullina (1984). In Volkov (2023), an algorithm of taking into account pulsations of components was added to the program. Parameters' errors are given in parentheses. The last two columns of Table 2 present the apsidal rotation velocities obtained from observations and their theoretical values. Theoretical values are given only for those stars for which we consider the observed values to be reliable. It can be seen that, for some systems, there is a significant discrepancy between the theoretical and observed values. A possible explanation for this fact is lacking synchronism between the rotational and orbital moments. At this time, we do not have spectroscopic data on the axial rotation of the stars. Theoretical calculations are made under the assumption of synchronism at the periastron.

We obtained the absolute masses and radii of the components using the indirect method proposed by D.Ya. Martynov and described in Khaliullin (1985), Volkov et al. (2017). The results are presented in Table 3.

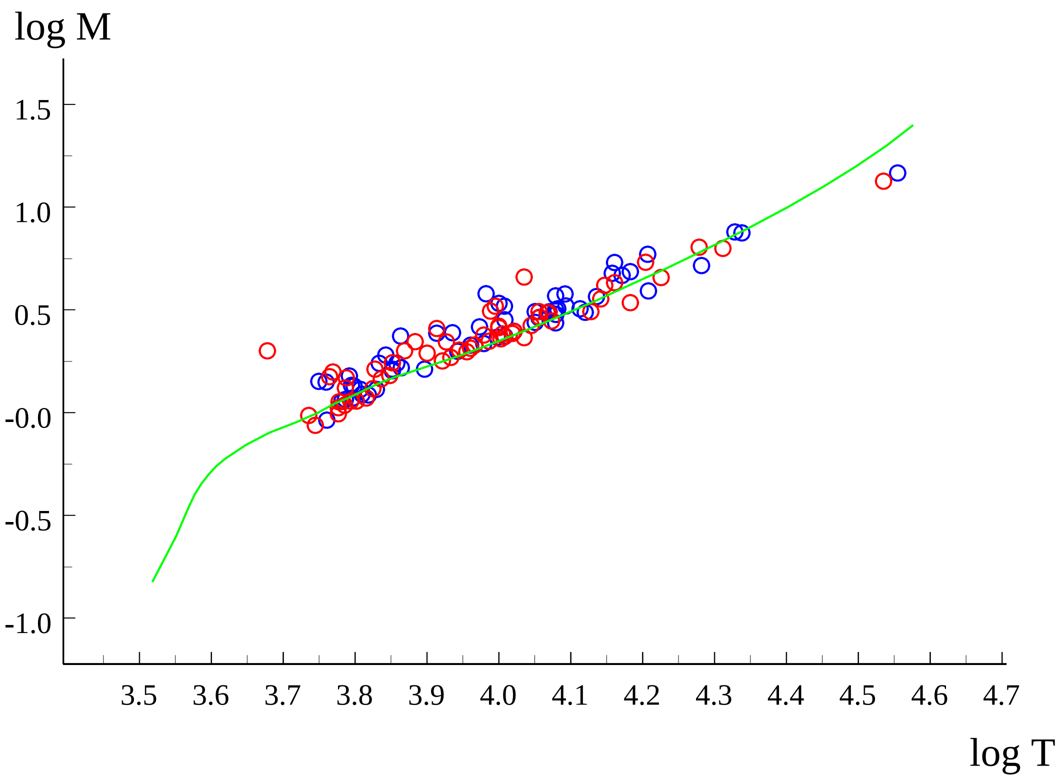

Figure 1. Dependence of mass on temperature according to the data from Table 3. Blue circles are the primary components, the red ones are secondary components. Green curve is the zero age main sequence, ZAMS.

We plotted the obtained data from Table 3 in the diagrams presented in Figs. 1, 2. They are similar to such diagrams constructed for other objects by other authors and to theoretical ones. We can conclude that the indirect method works satisfactorily, the obtained sizes and masses are close to real ones, and our data are suitable for use in studying the structure and evolution of stars.

Table 3: Absolute parameters of the stars obtained from light curve solutions

Star	T_1K	T_2K	M_1 $M_\odot$	M_2 $M_\odot$	R_1 $R_\odot$	R_2 $R_\odot$	$\log L_1$ $L_\odot$	$\log L_2$ $L_\odot$	$\log g_1$ cm/s^2	$\log g_2$ cm/s^2
V871 Aql	15500	15500	4.80	4.90	3.18	3.32	2.72	2.76	4.114	4.085
V889 Aql	10500	10120	2.49	2.42	1.97	1.84	1.58	1.46	4.245	4.275
V645 Aur	12000	11400	3.17	2.92	2.31	2.19	2.00	1.86	4.211	4.221
OO Cam	12000	9530	2.74	2.39	1.77	2.10	1.74	1.51	4.377	4.173
V347 Cam	7886	7950	1.97	1.55	2.08	1.26	1.18	0.75	4.095	4.426
V361 Cam	14852	11099	5.66	2.69	4.81	1.95	3.00	1.75	3.826	4.286
V409 Cam	7216	7399	1.74	2.00	1.94	2.43	0.96	1.20	4.104	3.967
V422 Cam	6453	5983	1.23	0.99	1.21	0.92	0.36	-0.017	4.359	4.510
V498 Cam	6198	6117	1.51	1.32	1.97	1.56	0.71	0.49	4.025	4.172
KX Cnc	6048	5994	1.138	1.131	1.057	1.043	0.127	0.099	4.446	4.455
DR CMi	8200	8200	2.44	2.57	2.93	3.26	1.55	1.64	3.892	3.822
V1066 Cas	9600	10000	3.80	2.64	5.21	2.29	2.32	1.68	3.584	4.137
V1110 Cas	6820	6725	1.74	1.63	2.16	1.95	0.96	0.84	4.009	4.070
V1141 Cas	21300	19000	7.59	6.39	4.21	3.39	3.51	3.22	4.069	4.184
V1162 Cas	9530	9140	2.17	2.06	1.72	1.69	1.34	1.25	4.301	4.295
V750 Cep	11240	8580	3.11	1.86	2.55	1.56	1.97	1.07	4.117	4.321
V850 Cep	8625	8454	2.45	2.21	2.68	2.27	1.55	1.37	3.971	4.071
V880 Cep	10200	9261	2.83	2.14	2.56	1.77	1.80	1.32	4.074	4.271
V897 Cep	5751	5819	1.41	1.50	2.01	2.22	0.60	0.71	3.981	3.921
V898 Cep	11376	11678	2.90	3.07	2.16	2.29	1.84	1.94	4.232	4.203
V921 Cep	7300	7650	2.36	2.22	3.47	2.80	1.49	1.38	3.730	3.890
V922 Cep	13197	13437	3.08	3.11	1.80	1.77	1.95	1.96	4.413	4.432
V944 Cep	12370	10200	5.16	3.13	5.76	3.13	2.84	1.98	3.629	3.943
V1326 Cyg	11238	11376	2.75	3.11	2.00	2.49	1.76	1.97	4.277	4.139
V2544 Cyg	21800	20500	7.5	6.3	3.90	3.13	3.49	3.19	4.130	4.247
NS Dra	5620	4767	1.42	2.00	2.12	5.83	0.61	1.20	3.935	3.206
V432 Dra	6587	6518	1.21	1.20	1.12	1.12	0.33	0.31	4.418	4.414
UW Hya	6158	6117	1.49	1.48	1.95	1.96	0.69	0.68	4.029	4.025
IL Lac	12008	11099	3.01	2.66	2.09	1.90	1.91	1.69	4.276	4.303
V340 Lac	10195	10011	2.32	2.34	1.72	1.82	1.46	1.47	4.333	4.288
RU Mon	12080	11736	3.21	3.07	2.35	2.35	2.02	1.95	4.202	4.183
V501 Mon	7319	6867	1.655	1.465	1.92	1.53	0.98	0.67	4.088	4.236
V521 Mon	14384	13867	4.77	3.58	3.65	2.21	2.71	2.21	3.992	4.303
V2778 Ori	12000	10000	3.71	2.60	3.17	2.24	2.27	1.65	4.006	4.152
V751 Per	11750	10500	3.10	2.49	2.31	1.87	1.96	1.58	4.201	4.292
V966 Per	15240	15240	4.86	3.43	3.32	2.74	2.74	2.58	4.082	4.096
CR Sct	16218	16218	5.30	4.97	3.54	3.12	2.89	2.78	4.063	4.147
V370 Sge	6964	7113	1.91	1.75	2.51	2.01	1.13	0.97	3.918	4.073
EQ Vul	14093	15488	6.34	6.35	6.69	5.56	3.20	3.20	3.588	3.750
V491 Vul	35900	34300	14.7	13.4	5.55	5.06	4.66	4.50	4.118	4.157

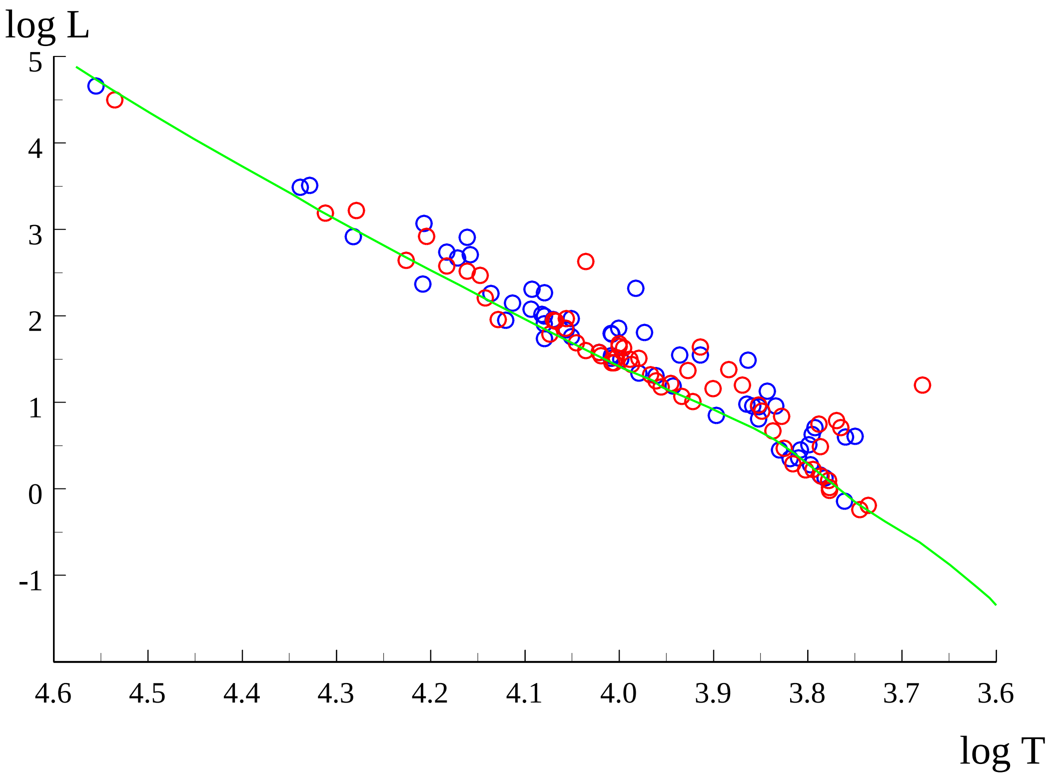

Figure 2. Dependence of luminosity on temperature (Hertzsprung–Russell diagram) according to Table 3. Blue circles are the primary components, red circles are the secondary ones. Green curve is the zero age main sequence, ZAMS.

The obtained rates of apsidal rotation, both theoretical and observed, cannot yet be considered final. In some systems, the eccentricity turned out to be insignificant and therefore determined with a large error. This significantly degrades the accuracy of the calculated value. In other systems, the longitude of periastron is close to 0° or 180°, which makes determining the observed value extremely difficult. V751 Per is a prime example of this case. Its periastron longitude is $\omega = 177°$, and small errors in determining the periods led to a clearly erroneous overestimation of the rate of apsidal rotation, see Table 2.

However, for some stars both values were determined with good accuracy. For V889 Aql, V2544 Cyg, V501 Mon, V521 Mon, V966 Per, CR Sct, V370 Sge, V491 Vul, the observations do not contradict theory.

For V645 Aur and V944 Cep, apsidal rotation is slowed down and the reason may be lacking synchronism between rotational and orbital moments, just as we discovered earlier in the systems EQ Boo (Volkov et al., 2011) and V490 Sct (Volkov and Kravtsova, 2022). In V1103 Cas (Volkov and Kravtsova, 2022), the lack of synchronism accelerates the apsidal motion.

We pay special attention to the fact that the rate of apsidal rotation for CR Sct given in Wolf et al. (2004), $\dot{\omega}_{obs} = 0.082(8)°$/year, is 7 times lower than ours and is definitely wrong. The error is probably due to the use of photographic observations, which are not accurate enough. In addition, the orbital eccentricity turned out to be two times lower than Wolf et al. suggest, which leads to an underestimate of the apsidal rotation rate by them.

The original observations in the V band on which this work is based are presented in the form of an electronic appendix to the html version of this paper, which contains headings with the name of the star and two columns: the heliocentric Julian date and the brightness of the star normalized to a constant level between minima. To get the real V magnitude of the star, one should add this value to the constant level between minima which is given in the second column of Table 1.

Original observations of some stars whose studies have already been published are added to this Table: BW Aqr (Volkov and Chochol, 2014), V1176 Cas (Bagaev et al., 2018), V798 Cep (Volkov et al., 2017), V541 Cyg (Volkov and Khaliullin, 1999), V2647 Cyg (Kravtsova et al., 2019), DI Her (Volkov, 2005), V577 Oph (Volkov and Volkova, 2010).

Currently, we continue observations of the objects, and the data presented in the Tables 1, 2, 3 may be refined over time.

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References:

Bagaev, L. A., Volkov, I. M., & Nikolenko, I. V. 2018, *Astron. Rep.*, **62**, 664

Barabanov, S. I., Potanin, S. A., Savvin, A. D., Volkov, I. M., Kravtsova, A. S., & Nikolenko, I. V. 2021, *INASAN Science Reports*, **6**, 92

Burlak, M. A., Volkov, I. M., & Ikonnikova N. P. 2018, *Contributions of the Astronomical Observatory Skalnate Pleso*, **48**, 536

Flower, P. J. 1996, *Astrophys. J.*, **469**, 355

Green, G. M., Schlafly, E. F., Finkbeiner, D. P., Rix, H. -W., et al. 2015, *Astrophys. J.*, **810**, 25

Khaliullin, Kh. F. 1985, *Astrophys. J.*, **299**, 668

Khaliullina, A. I. & Khaliullin, Kh. F. 1984, *Sov. Astron.*, **28**, 228

Kornilov, V. G, Volkov, I. M., Zakharov, A. I., Kozyreva, V. S., Kornilova, L. N. et al. 1991, *Tr. Gos. Astron. Inst. Sternb.*, **63**, 4

Kravtsova, A. S., Volkov, I. M., & Chochol, D., 2019, *Astron. Rep.*, **63**, 495

Moffett, T. J. & Barnes, T. G. III 1979, *Astron. J.*, **84**, 627

Otero, S. A., Wils, P., Hoogeveen, G., & Dubovsky, P. A. 2006, *Inform. Bull. Var. Stars*, No. 5681

Popper, D. M. 1980, *Ann. Rev. Astron. & Astrophys.*, **18**, 115

Volkov, I. M. 2005, *ASP Conference Series*, **335**, 351

Volkov, I. M. 2023, *Astron. Rep.*, **67**, 320

Volkov, I. M. & Chochol, D. 2014, *Contributions of the Astronomical Observatory Skalnate Pleso*, **43**, 419

Volkov, I. M., Chochol, D., & Kravtsova, A. S. 2017, *Astron. Rep.*, **61**, 440

Volkov, I. M., Chochol, D., Grygar, J., Mašek, M., & Juryšek, J. 2017, *Contributions of the Astronomical Observatory Skalnate Pleso*, **47**, 29

Volkov, I. M. & Khaliullin, Kh. F. 1999, *Inform. Bull. Var. Stars*, No. 4680

Volkov, I. M. & Kravtsova, A. S. 2022, *Astron. J.*, **164**, 194

Volkov, I. M. & Kravtsova, A. S. 2022, *Astron. Rep.*, **99**, 470

Volkov, I. M., Kravtsova, A. S., & Chochol, D. 2021, *Astron. Rep.*, **65**, 184
Volkov, I. M. & Volkova, N. S. 2007, *Astron. Astrophys. Trans.*, **26**, No. 1, 129
Volkov, I. M. & Volkova, N. S. 2009, *Astron. Rep.*, **53**, 136
Volkov, I. M. 2010, *ASP Conference Series*, **435**, 323
Volkov, I. M., Volkova, N. S., & Chochol, D., 2010, *Astron. Rep.*, **54**, 418
Volkov, I. M., Volkova, N. S., Nikolenko, I. V., & Chochol, D. 2011, *Astron. Rep.*, **55**, 824
Wolf, M., Harmanec, P., Šarounová, L., Zejda, M., Božyć, H., Hornoch, K., Kozyreva, V. S., Hynek, T., & Král, L. 2004, *Astron. & Astrophys.*, **420**, 619