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Period changes of the sample of eclipsing binaries with active chromospheres

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In this work we present results derived from analysis of the O-C behaviour of ten eclipsing binary systems: AR Lac, CG Cyg, HP Aur, MM Her, RS CVn, RT And, SV Cam, V471 Tau, WW Dra and CF Tuc. It was proved on the basis of moments of minima compiled from the literature and new ones determined from recent observations, that these binaries show long term (19-91 years) modulations of their orbital periods, clearly visible in their O-C diagrams. Two possible explanations for this effect are considered: (1) the light-travel time effect due to the presence of a third body orbiting the eclipsing systems; (2) the Applegate mechanism predicting period modulation by changes in the distribution of angular momentum as a star goes through its activity cycles. It was found that in the case of four systems the existence of a third star, orbiting the binary, is a more plausible explanation of observations.

Key words: stars: binaries: eclipsing, stars: magnetic field, stars: chromospheres

INTRODUCTION

The incentive for this research is the not as yet fully resolved problem of the long term orbital period modulation observed for some eclipsing binaries. We have tried to test two commonly considered explanations of this phenomenon for each system in the studied sample, to ascertain which one is more plausible for a particular system: the light-travel time effect or the Applegate mechanism.

A sample of nine eclipsing binaries meeting the following criteria has been created: (1) their orbital periods show a long term modulation in their historical, well covered O-C diagrams [10]; (2) they have the evident chromospheric activity [4]; (3) their absolute parameters are known; (4) their orbital periods are between 0.5 and 8 days; (5) systems are bright enough to allow good accuracy observations using small (50 cm in diameter) telescopes in the Northern hemisphere. CF Tucani was added to this sample as it was recently studied by Dogru et al. [3] and both hypotheses considered in the present work were applied for this system by the authors. The physical parameters of components were compiled from the literature and listed in Table 1 along with references to the original papers. As can be seen, components of most binaries are in general the main sequence solar like stars with just one exception, V471 Tau, the secondary component of which is a white dwarf.

OBSERVATIONS

To enhance the catalogue of historical times of minima by Kreiner et al. [10] we performed photometric observations of primary minima of these systems using the 50 cm Cassegrain Telescope of the Astronomical Observatory of the Jagiellonian University equipped with Andor DZ 936-BV CCD Camera (minima derived at this site are marked by 'OAUJ' in Table 2). In addition we used the 60 cm Telescope at the Mount Suhora Observatory of the Pedagogical University in Krakow equipped with an Apogee Alta CCD Camera at the primary focus (denoted by 'Suhora'). For CF Tuc, which is invisible from our geographical latitude, we used data from the All Sky Automated Survey (ASAS) and additional observations were done at a private observatory in South Africa (CPTSA). Images were corrected for bias, dark and flat field using the `IRAF` package. After extracting magnitude differences between the target and comparison stars, minima times were derived making use of the Kwee van Woerden [11] method. The results are presented in Table 2. Formal errors listed in Table 2 are those given by the Kwee van Woerden method. The errors given by this method are likely to be underestimated (see e.g. [2]). Therefore, we tried to do an independent estimation of errors by the least square fitting of out data with the second order polynomial. It turned out, however, that uncertainties determined with this approach were com-

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parable to those derived with the Kwee van Woerden algorithm.

ANALYSIS

We supplemented the historical timings with those derived from new observations to draw an O-C diagram for each system. The O-C behaviour was analysed assuming two hypotheses: the light-time effect due to the presence of a third body in the system and the Applegate mechanism.

We applied Petr Zashe's `Matlab LITE` procedure [15] which uses the simplex algorithm to search for orbital parameters of the companion and the lower mass limit of the third body. From the preliminary computations it turned out that two selected systems, HP Aur and RT And, actually do not exhibit significant period modulations. Consequently they were discarded from further computations. The procedure applied was as follows: first, the O-C values were calculated with a linear ephemeris for each system taking into account all available minima times. Then, we used minima times values as input data for the `LITE` code, and final computations resulted in the determination of the lower limit of the hypothetical companion mass. Results are presented in Table 3 and in Figures 1 and 2 (solid lines represent the final solutions while dashed ones show the quadratic term fits). As it can be seen, for all cases the models fit the data very well. For two systems, CG Cyg and SV Cam, the Zashe's code returns unrealistically small errors, and we believe that for binaries having companions with very small masses, as the two above mentioned, the procedure of errors estimation in the code needs some improvement.

There is another explanation for cyclic period changes for which a third body is not necessary. An alternative model was proposed by Applegate [1] who argued that the star changes its shape during activity cycles. When magnetic field lines are perpendicular to the stellar surface, angular momentum transfer from the core to the envelope is more effective than when magnetic lines are parallel to the rotation axis. The star becomes more oblate which changes the quadruple momentum of the gravitational potential. Stars move closer to each other and as a result the period of the binary system decreases. However, when magnetic field lines are parallel to the rotation axis, the star becomes spherical and a period increase is observed. Such changes of shape consume part of the star's energy supplies. Consequently the luminosity should also vary with shape changes during the activity cycles. Since we selected stars with active chromospheres, the Applegate mechanism could be applied to these systems. Based on Applegate's work, we calculated the changes in luminosity and magnetic field strength which, as an alternative, could also explain period variations. The results are also given in Table 3.

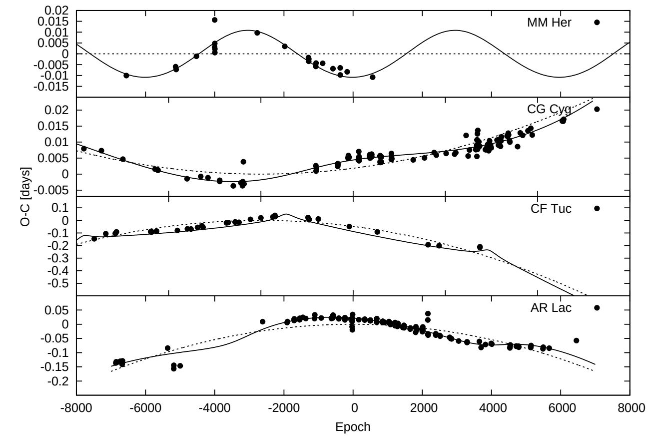

Fig. 1: `LITE` solution part 1.

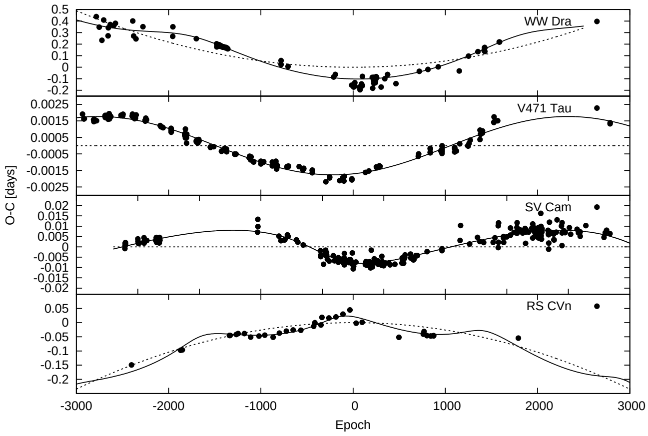

Fig. 2: `LITE` solution part 2.

RESULTS AND CONCLUSIONS

Two systems, HP Aur and RT And, initially selected for exhibiting large period changes, turned out not to have any cyclic O-C behaviour. The large period change of HP Aur resulted from the use of an inaccurate period to calculate its ephemeris. This became obvious immediately after plotting its O-C diagram which showed a clear linear trend. After correcting the period, we derived an improved ephemeris to be:

$$HJD_{min} = (2455473.510435 \pm 0.0002) + 1.42282E$$

Using these light elements for ephemeris calculation, the scatter does not exceed ± 0.006 of the orbital period and shows no trace of any periodic trend. On the other hand, RT And shows large O-C deviations. However, after subtracting a parabola, which can be interpreted either as mass loss from the system or mass transfer between components, we could not find any periodic variations, unless the subtracted

Table 1: Absolute parameters of analysed sample of binaries

system	references	P_{orb} (days)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	R_1 ($R_\odot$)	R_2 ($R_\odot$)
CG Cyg	[7]	0.631143114	0.97 ± 0.04	0.8 ± 0.03	1.00 ± 0.03	0.83 ± 0.03
RT And	[6]	0.6289294	1.24 ± 0.03	0.92 ± 0.02	1.26 ± 0.015	0.90 ± 0.013
SV Cam	[8]	0.59307167	1.47 ± 0.06	0.87 ± 0.06	1.38 ± 0.05	0.94 ± 0.06
V471 Tau	[12]	0.52118373	0.93 ± 0.07	0.84 ± 0.05	0.96 ± 0.04	0.0107 ± 0.0007
AR Lac	[16]	1.983188	1.12 ± 0.02	1.26 ± 0.02	1.53 ± 0.03	2.68 ± 0.05
HP Aur	[9]	1.442281192	0.950 ± 0.011	0.801 ± 0.010	1.050 ± 0.012	0.821 ± 0.009
MM Her	[5]	7.960326	1.21 ± 0.02	1.30 ± 0.02	1.59 ± 0.12	2.85 ± 0.13
RS CVn	[14]	4.797695	1.41 ± 0.04	1.44 ± 0.03	1.99 ± 0.12	4.00 ± 0.12
WW Dra	[13]	4.6297094	1.36 ± 0.08	1.24 ± 0.08	2.12	3.90
CF Tuc	[3]	2.7975004	1.11 ± 0.01	1.23 ± 0.01	1.63 ± 0.02	3.60 ± 0.02

parabola was a part of some very long-period sine-like curve.

In three systems V471 Tau, CG Cyg and SV Cam, third body masses approximate the limit for brown dwarf mass, so the luminosity of third bodies would be very low compared to the luminosity of the binary systems. For these systems the Applegate mechanism is also effective to describe the observed behaviour, hence future observations are required to establish which explanation is correct.

In order to explain the cyclic behaviour of AR Lac within the LTE hypothesis, its third body mass needs to be approximately one solar mass. Such a star should be easily detectable (but it is not) if the inclination of the companion's orbit is close to 90 degrees or co-planar. Although the amplitude of period changes is large, it can also be accounted for within the Applegate mechanism assuming its enhanced version (solid body rotation of the star). Due to the long period of MM Her (almost 8 days), the Applegate mechanism requires a non-physical rate for luminosity transfer. Therefore, we argue that in this case the LTE is the most probable explanation for observed O-C changes. Although the companion is a main sequence star, it can not be detected easily as its contribution to the total light of the system would be very small.

Analysis of O-C diagrams for the three systems CF Tuc, RS CVn and WW Dra resulted in the lower limit of mass of their companions to be at or above the neutron star mass limit. If so, in these systems the third body could be invisible in optical wavelengths despite its high mass. In all three systems the Applegate mechanism can produce amplitude variations much smaller than observed. For CF Tuc our solution (with new minima times) is in a very good agreement with that published by Dogru et al. [3].

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Table 2: Recent minima times

system	minimum time [HJD]	error [days]	band	comparison star	observer	observatory
CG Cyg	2455419.56229	0.000040	R	TYC 2696-2207-1	D. Koziel-Wierzbowska	OAUJ
	2455419.56238	0.000071	V		D. Koziel-Wierzbowska	OAUJ
	2455447.33251	0.000021	b		S. Zola	Suhora
	2455464.37402	0.000034	y		D. Jableka	OAUJ
HP Aur	2455473.51042	0.000049	y	GSC 02401-01128	D. Jableka	OAUJ
RT And	2455288.38929	0.000042	y	HD 236062	S. Zola	OAUJ
	2455352.54302	0.000054	V		T. Szymanski	OAUJ
	2455447.51157	0.000010	b		S. Zola	Suhora
	2455473.29617	0.000014	y		D. Jableka	OAUJ
SV Cam	2455357.53096	0.000104	V	3UC 345-010529	A. Kuzmicz	OAUJ
	2455417.43346	0.000094	V		T. Szymanski	OAUJ
	2455474.36877	0.000031	y		A. Kuzmicz	OAUJ
	2455480.30028	0.000119	b		S. Zola	Suhora
	2455644.579509	0.000031	R		D. Jableka	OAUJ
V471 Tau	2455478.38513	0.000300	y	BD+16 515	D. Jableka	OAUJ
	2455480.46993	0.000200	b		S. Zola	Suhora
CF Tuc	2454816.63376	0.001060	V			ASAS
	2455566.397988	0.000746	R	HD 5499	S. N. de Villiers	CPTSA
	2455566.392616	0.000687	V		S. N. de Villiers	CPTSA
WW Dra	2455650.519467	0.000018	V	BD+60 1691B	D. Jableka	OAUJ
	2455687.557411	0.000045	y		D. Jableka	OAUJ

Table 3: The results derived from O-C analyses: lower mass limit of a companion, amplitude, period and eccentricity of third body orbit and luminosity changes needed for the Applegate mechanism to work.

		LITE			Applegate
System	$M_3 \sin i$ $[M_\odot]$	P_3 [years]	A[days]	e	$\Delta L_{RMS}[L]$
AR Lac	0.9011 ± 0.0026	39.3946 ± 2.5067	0.0262 ± 0.0028	0.3542 ± 0.1656	0.39
CF Tuc	3.5627 ± 0.1647	19.6860 ± 2.1882	0.0435 ± 0.0068	0.1575 ± 0.1108	9.98
CG Cyg	0.07290 ± 0.00001	31.4153 ± 5.7904	0.0027 ± 0.0007	0.1906 ± 0.2229	0.20
MM Her	0.3473 ± 0.0033	31.4210 ± 16.5404	0.0103 ± 0.0043	0.1983 ± 0.6432	83.8
RS Cvn	1.7381 ± 0.0485	19.959 ± 1.2010	0.0264 ± 0.0059	0.3220 ± 0.3851	7.84
SV Cam	0.22410 ± 0.00001	43.3733 ± 0.7852	0.0081 ± 0.0002	0.3903 ± 0.0585	0.10
V471 Tau	0.0742 ± 0.0003	36.1185 ± 0.5611	0.0017 ± 0.0001	0.0000 ± 0.037	0.03
WW Dra	2.6232 ± 0.0729	91.6323 ± 1.0757	0.1009 ± 0.0171	0.2976 ± 0.6675	11.4