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Orbital Period Modulation in Chromospherically Active Close Binaries

Cafer İBANOĞLU
Ege University Science Faculty
Department of Astronomy, Bornova, İzmir, TURKEY
e-mail: ibanoglu@alpha.sci.ege.edu.tr

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Abstract

The orbital period changes in some chromospherically active close binaries have been interpreted as a consequence of magnetic activity. At least in two active close binaries a possible relationship between the orbital period modulation and activity cycle was suggested. The existence of a third companion in these binaries has also been proposed. The light-time effect which arises from orbiting around a third-body has been subtracted from all the O-C values and a cyclic change of the orbital period has been obtained. These cyclic changes seem to be connected with the total brightness variations at least in two samples, namely, V471 Tau and RT Lac. The lenght of the orbital period modulations and also activity cycle in these samples are nearly half that of the Sun.

1. Introduction

Variable stars reveal themselves with periodic or cyclic light variations. Among these stars the eclipsing variables are known to be the excellent laboratories for studying a wide variety of processes in stellar astrophysics. These stars present some information about tidal distortion, mass transfer or mass loss, angular momentum transfer or loss, magnetic activity and stellar evolution. The existence of sun-like active stars in close binaries have been revealed by Hall [1]. These binaries which contain at least a chromospherically active companion have been the subject of many investigations following their discovery. The existence of dark starspots is established in a wide variety of cool stars [2]. These spots cause periodic dimming of the star's light as it rotates. Doppler imaging technique developed by Vogt et al. [3] has been used to estimate the sizes and positions of spots on stars. The systems which have solar-like companion were named as RS Canum Venaticorum systems. They are characterized by solar-like activity. The signatures of this activity were observed not only in visible light but also X-ray, UV and radio spectral domains [4].

We assume that a spot on one of the chromospherically active stars appears at some latitude and stays there for the duration of its lifetime [5]. If the spot is located on the higher latitude than the co-rotation latitude it will reappear later than expected from the star's mean rotation due to the differential rotation. Therefore a spot's visibility phase would increase or decrease with time. The dimming of the total light due to the spot or spots would migrate through the light curve. Therefore we can measure the phases of spots with respect to the orbital period of a close binary system or a mean rotational period for a single star. The phases of the spots and light loss at these phases may present us some clues about the properties of the spots; namely, latitude, longtitude, radius and temperature with respect to the photosphere. To evaluate the spot parameters some methods were developed by Eaton and Hall [6], Budding and Zeilik [7], Kang and Wilson [8], Eaton et al. [9] and Henry et al. [10].

As it is known an interesting phenomenon in astronomy is the small but definite changes in orbital periods, rotation periods and pulsating periods. These changes are the clues of some changes in the physical conditions inside the stars. The types of period changes were summarized by Hall [11]. The timing of eclipses in close binaries can be obtained accurately with a few seconds deviations. When the differences between the observed and assumed ephemeris are obtained, over many orbits the orbital period changes of the order of $10^{-5} - 10^{-6}$ can be determined. Long term observations of close binaries have shown that the orbital period changes are common property in most of these binaries. Some systems show alternating period changes, i.e., increases followed by decreases. These period changes of alternating sign have been called as orbital period modulations which are common in RS CVn systems.

The aim of this study is to summarize the mechanisms of orbital period changes and to discuss the orbital period modulation studies made for close binaries in which at least one of the component stars has magnetic activity.

2. Types of Period Changes

We follow the classification schema made by Hall [11] for the orbital period changes.

2.1. Monotonic Period Changes

a) Mass Transfer: It is known that Roche lobe filling component in semi-detached binaries is transferring mass to its companion. We assume that the total mass and angular momentum are conserved during the mass transfer. Under these conditions it is expected that the orbital period will increase if the loser is less massive but will decrease if the loser is more massive component.

b) Mass Loss in a Wind or Shell: If one of the component in a close binary is too massive and is losing mass isotropically one would expect monotonic orbital period change. The

sign of the change will depend on the mode of mass loss. If the out-flowing mass is constrained by magnetic fields the orbital period will decrease. On the other hand magnetic braking is responsible for an increasing rotation period.
c) Gravitational Radiation: For the systems which include massive or a collapsed companion gravitational radiation causes loss of angular momentum. In these systems the orbital period will decrease monotonically.
d) Galactic Acceleration: The eclipsing binaries revolve around the center of the Galaxy in an elliptic orbit. Therefore the eclipse timings will show monotonic period changes. The sign of these changes will depend on the location of the binary in the Galaxy with respect to the Sun.

2.2. Periodic Period Changes

a) Apsidal Motion: It is known for a long time that the rotation of the line connecting the star's center causes a sinusoidal changes in both timings for primary and secondary eclipses. However, the displacements of primary and secondary eclipse are in opposite direction.
b) Third Body: If a star is physically bounded to another object and revolves around the center of mass we expect a time delay or advance in the periodic signals due to the finite velocity of the light. If the object emitting periodic light signals is an eclipsing binary the displacements of primary and secondary eclipses are in phase.

3. Cyclic Period Changes

Many eclipsing binaries which contain at least one late-type convective star show orbital period changes in both directions in a few decades. Since the components of these binaries are well inside their corresponding Roche lobes, and have similar masses with that of the Sun ,mass transfer and mass loss could not be the cause of these period changes. The orbits of these binaries are generally circular and displacements of primary and secondary eclipses are in phase, i.e., do not vary 180° out of phase as required for apsidal rotation. In the case of orbit around a third body the inferred mass of third body was too large that it will be visible in the composite spectrum and some changes in the velocity of the center of mass of the binary should be detected. Due to the lack of such evidence the third body orbit hypothesis was excluded. In addition third body and apsidal motion both require that period modulations be strictly periodic, but the observations show that this is not the case.

The idea for explaining the alternating orbital period variations in chromospherically active binaries has been suggested by Oliver and Rucinski [12] and later on by Hall and Kreiner [13]. In these suggestions a change in the radius of one star causes a change in rotation period. This change will be transformed to the orbit then the orbital period will change. A theory to explain these period changes as a consequences of possible magnetic cycle was first suggested by Matese and Whitmire [14]. They pursued the radius-change idea but they were not sure about the nature of radius changes. Later on

Van Buren and Young [15] suggested cyclical changes in one star's magnetic field would cause cyclical changes in the radius. A similar mechanism has been suggested by Van't Veer [16] for explaining the alternating period changes in W UMa and RS CVn binaries. He proposed that redistribution of the mass in the radiative core of one or both stars produces the changes in moment of inertia. Applegate and Patterson [17] realized that the orbital period would be changed at constant orbital angular momentum if the radial part of the gravitational acceleration varied.They have taken and examined the problem of time-variable magnetic field, angular momentum, rotation period and orbital period together.

The investigators have all assumed that magnetic field deforms the stars by distorting it away from the fluid equilibrium shape. On the other hand Marsh and Pringle [18] suggested that the energy required to make the deformation was larger than the luminosity of the star produced. Applegate [19] agrees with this idea and distortion away from hydrostatic equilibrium is ruled out. He proposes a mechanism to produce the period changes in active stars invokes the magnetic field to cause transitions between states of fluid equilibrium. This mechanism depends on the changes in the quadrupole moment which determines the angular momentum distribution within the star.

The most simple example of the distortion is the expansion and contraction of the active star as magnetic pressure changes. This is a very similar behaviour to that of pulsation in some stars. On the other hand the example of the transition may be a variable rotational oblateness. This variation in the oblateness is produced by the redistribution of angular momentum by a magnetic torque. When the magnetic field is vanished no deformations take place in the star's hydrostatic equilibrium; the shape of the star stops changing [19]. Applegate follows the below formulae to obtain the orbital period modulation in active close binaries.

We assume that in a close binary the mass and radius of active companion are M and R. The separation between the components is a and they revolve in circular orbits around the center of mass. The gravitational potential outside the active star is,

$$\phi(r) = -\frac{GM}{r} - \frac{3}{2}\frac{GQ}{r^3} \tag{1}$$

where Q is the gravitational quadrupole moment. We can obtain the quadrupole moment of the star by the formula given by Kopal [20, 21],

$$Q = \frac{2}{9}k_2\frac{\Omega_e^2 R^5}{G} \tag{2}$$

where k_2 is the apsidal motion constant which defines the density distribution within the star. The value of this constant depends on the physical parameters of the star and can be obtained from the tables given by Claret [22]. The parameter Ω_e is effective angular velocity and is related to centrifugal and magnetic tension forces:

$$\Omega_e^2 = \Omega^2 - \frac{B^2}{4\pi\rho s^2} \tag{3}$$

where s is the modulus of the vector distance from the rotation axis. On the other hand, the orbital period depends on the relative velocity on the orbit as $P = \frac{2\pi r}{\nu}$. The angular momentum is $J = \mu\nu a$, where μ is the reduced mass. The velocity on the circular orbit is, $\nu^2 = rg = \frac{GM_T}{r}$ where M_T is the total mass of the system. Therefore the relative velocity of a circular orbit $\nu^2 = \frac{rd\phi}{dr}$ is given by,

$$\nu^2 = \frac{GM_T}{r}[1 + \frac{9}{2}\frac{Q}{Mr^2}] \tag{4}$$

If we differantiate this equation we obtain,

$$2\frac{\Delta\nu}{\nu} = -\frac{\Delta r}{r} + \frac{9}{2}\frac{\Delta Q}{Mr^2} \tag{5}$$

On the other hand, if we assume that the angular momentum is conserved,

$$\frac{\Delta P}{P} = -2\frac{\Delta\nu}{\nu}, \qquad \frac{\Delta r}{r} = \frac{\Delta\nu}{\nu} \tag{6}$$

Combining these equations with equation (5) the following relation is obtained,

$$\frac{\Delta P}{P} = -9\frac{R^2}{a^2}\frac{\Delta Q}{MR^2} \tag{7}$$

The first equation indicates that when the active star is more oblate, $\Delta Q > 0$ gravitational field in the equatorial plane of the star will be stronger as it is clear from Eq. (1). To balance the gravity the centrifugal acceleration $\frac{\nu^2}{r}$ should increase. As we assumed the angular momentum fixed, then, ν_r should be constant. Therefore ν should increase while r decreases. The orbital period should decrease because the star moves faster. As it is seen the physics of the orbital period change due to the variation in the active star's quadrupole moment is very simple.

Applegate defines the transition as deformations in which the magnetic field causes the star to change from one fluid hydrostatic configuration to another. As we stated earlier the quadrupole moment of a rotating star is related to the distribution of angular momentum within the star. The quadrupole moment is determined by the angular momentum carried by the outer layers of the star. Because the moment of inertia is proportional to r^2 and the centrifugal acceleration increases towards these outer layers. Therefore the outer layers will turn faster than inside and they become more oblate. Whereas the inner zone will rotate slowly and it become less oblate. This different oblateness in a star will increase the quadrupole moment. Therefore the derivative will be positive.

Applegate takes a thin shell of mass, the moment of inertia of shell as $I_s = \frac{2}{3}M_sR^2$. Then, the derivative is

$$\frac{dQ}{dJ} = \frac{1}{3}\frac{\Omega R^3}{GM} \tag{8}$$

Combining this equation with those of Eq.(7) one obtains,

$$\Delta J = -\frac{GM^2}{R}\frac{a^2}{R^2}\frac{\Delta P}{6\pi} \tag{9}$$

This equation indicates that the orbital period decreases when the star's oblateness is increased. The energy required to transfer the angular momentum will be

$$\Delta E = \Omega_{dr}\Delta J + \frac{\Delta J^2}{2I_e} \tag{10}$$

where $\Omega_{dr} = \Omega_s - \Omega_*$ is the angular velocity of differential rotation, $I_e = \frac{I_s I_*}{I_s + I_*}$ is the effective moment of inertia. The quantities include asterisk correspond to the inner part of the star. Applegate takes the mass of the shell about 0.1 of the total mass and therefore $I_s \approx I_*$ and $2I_e \approx I_s$. If the angular momentum transferred to the outer shell is an amount of ΔJ, this shell will spin up by an angular velocity $\Delta\Omega = \frac{\Delta J}{I_s}$ which is given by,

$$\frac{M_s}{M}\frac{\Delta\Omega}{\Omega} = \frac{GM}{2R^3}\frac{a^2}{R^2}\frac{P^2}{4\pi^2}\frac{\Delta P}{P} \tag{11}$$

If the energy requirement is supplied by the nuclear luminosity of the star which will be variable with the RMS luminosity variation given by

$$\Delta L_{RMS} = \pi\frac{\Delta E}{P_{mod}} \tag{12}$$

where P_{mod} is the period of orbital modulation. The RMS torque required to periodically exchange ΔJ between the outer shell and the inner part of the star is

$$N = \pi\frac{\Delta J}{P_{mod}} = \frac{\pi}{3}\frac{GM^2}{R}\frac{a^2}{r^2}\frac{\Delta P}{P_{mod}} \tag{13}$$

Assuming this torque is supplied by a subsurface magnetic field it will be related to the magnetic field strength as,

$$N \sim \frac{B^2}{4\pi}(4\pi R^2)\Delta R \sim 0.1B^2R^3 \tag{14}$$

where $\Delta R = 0.1R$ is assumed. Then, we find the magnitude of the magnetic field as,

$$B^2 \sim 10\frac{GM^2}{R^4}\frac{a^2}{R^2}\frac{\Delta P}{P_{mod}} \tag{15}$$

If there is an observed orbital period modulation as cyclic character the amplitude of this modulation and the amplitude of the oscillation in the O-C diagram are related by

$$\frac{\Delta P}{P} = 2\pi\frac{O-C}{P_{mod}} \tag{16}$$

where P_{mod} is the modulation period. If we assume that active stars behave like the sun the orbital period modulation is expected to be fairly regular with a period of P_{mod}.

Table 1. The active binaries which indicate cyclic period changes.

Parameter	Algol	SS Cam	SV Cam	V471 Tau	RS CVn
P_{mod} (yr)	32	55	82	40	48
Semiamp. of $O-C$ (days)	0.03	0.1	0.015	0.0005	0.07
P_{orb} (days)	2.87	4.8	0.53	0.52	4.8
$\Delta P/P$ ($\times 10^5$)	1.6	3	0.3	0.2	2
ΔP (s)	4	13	0.14	0.09	8.3
ΔJ ($\times 10^{-48}$)	2.38	13.2	0.2	0.2	24
ΔL ($L_\odot$)	1.4	2.3	0.07	0.12	9.7
B (kG)	5.5	3.5	9	11	13

However we should bear in mind that the orbital period modulation should not be strictly periodic. The examples of the application are given in Table 1.

The model proposed by Applegate takes the orbital period modulations in the active close binaries as a signature of stellar magnetic activity. The luminosity variation should accompany to orbital period modulation with the same period. The relative phases of these variation are very important. Orbital period minimum should coincide with maximum quadrupole moment, i.e., outside spinning of the active star is the fastest. Therefore maximum luminosity should coincide with an $O-C$ curve minimum if the star's outside spins faster than its inside but should coincide with an $O-C$ curve maximum if the outside spins slower than inside.

The first test to the Applegate's model was the application to the CG Cygni by Hall [23]. He finds that the mean brightness outside eclipse and the period vary with the same cycle length, ~ 50 years. The orbital period increase occurs at maximum brightness reached by the system. Therefore the star's outside spins faster than its inside.

İbanoğlu et al. [24] studied throughly the long-term luminosity variations and period changes in the chromospherically active binary system V471 Tau. They have collected the data over an interval of 23 years. The mean brightness of the white dwarf-red dwarf eclipsing binary has regularly been increased about 0.2 mag in blue and yellow colours (See Fig. 1). The linear increament was extracted from the observed mean brightness and a cyclic change in the total luminosity of the system has been found as it is shown in Fig. 2. The averege period of these variations is about six years. On the other hand, the analysis of 154 timings of mid-eclipse has been made with assumption of the light-time effect. It means that the system revolves around a third component. The amplitude of the O-C curve is about 100 s (see Fig. 3). The analysis gave that the eclipsing pair orbits around a third-body with a period of 24.6 yr. The eccentricity of this orbit is about 0.614 and semi-major axis is about 3.84×10^7 km. The time delay due to orbiting around a third body was substracted from the O-C curve and a cyclic variation has been obtained and is shown in Fig. 4. The average amplitude of this variation is about 20 s with an average period of 5 years. The changes in the orbital period seem to be related to the system's

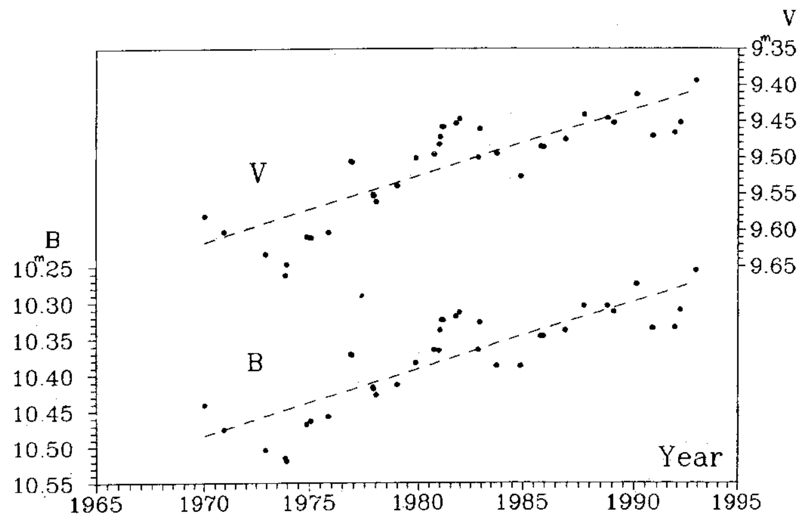

Figure 1. The variations in the mean brightness of V471 Tau in blue and yellow colours.

mean brightness variations. The closeness of the periods for the luminosity variations and the orbital period modulation has been taken as the evidence which support the theory developed by Applegate. The maximum of the O-C curve coincides with the maximum luminosity. This suggests that the outside spin of the chromospherically active companion should be slower than that of inside.

Another active system which has been observed for a long time is RT Lac. The system has been observing since 1978 at the Ege University Observatory. these observation show that the mean brightness of the system varies with an amplitude of about 0.16 mag in blue and 0.11 mag in yellow light (see Fig. 5). In the time interval between 1978 and 1992 the mean color of the system was also varied about 0.06 mag. All timings published so far have been collected and analysed by Keskin et al. [25]. Due to the sine-like changes of the O-C values as it is seen in Fig. 6. They have interpreted the O-C changes as the consequence of a light-time effect. The analysis indicate that the eclipsing pair revolves around a third body with a period of 80.71 yr. The separation between the eclipsing pair and the third body has been calculated to be approximately 176 times that of the separation between the eclipsing components. However, the lower limit estimated for the mass of the third body is about 1.77 solar masses. This value is larger than that of the massive primary component of the eclipsing pair. When the light-time effect has been subtracted from all the photoelectric times of minima, an existence of cyclic variation in the orbital period revealed itself (see Fig. 7). The minimum of the O-C curve coincides with the maximum light of the system. The period and the mean brightness of the system seem to vary with the same cycle lenght of about 12 yr. Since the light maximum coincides with the O-C curve's minimum, the outside spin of the more massive, active

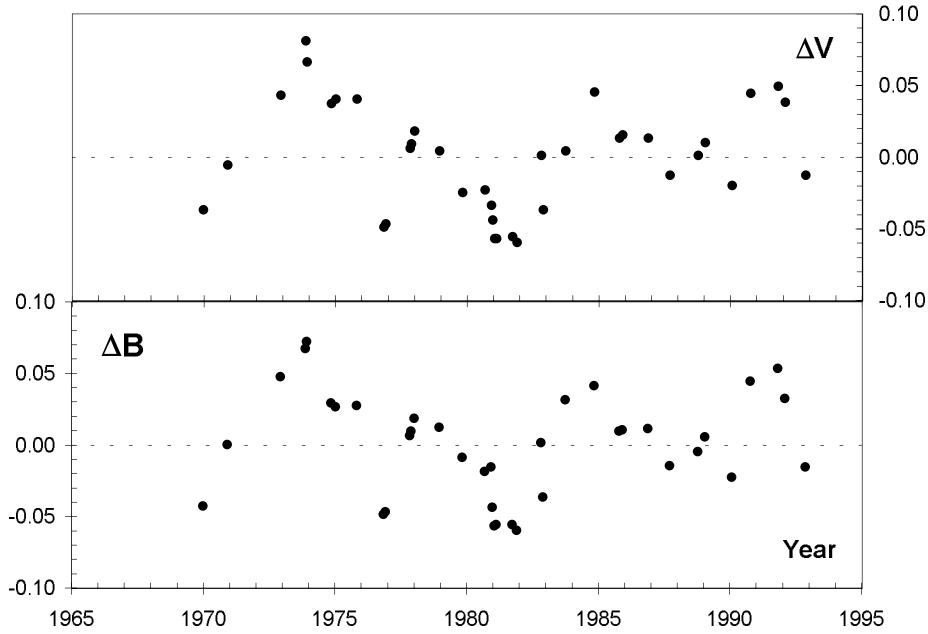

Figure 2. The cyclic changes in the mean brightness of V471 Tau.

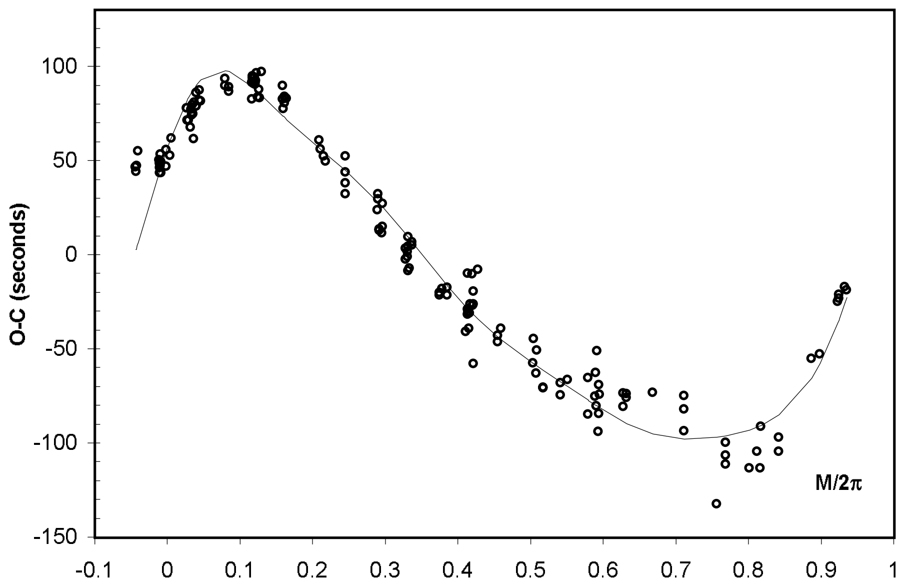

Figure 3. The O-C curve for V471 Tau. The solid line indicates the computed light time curve.

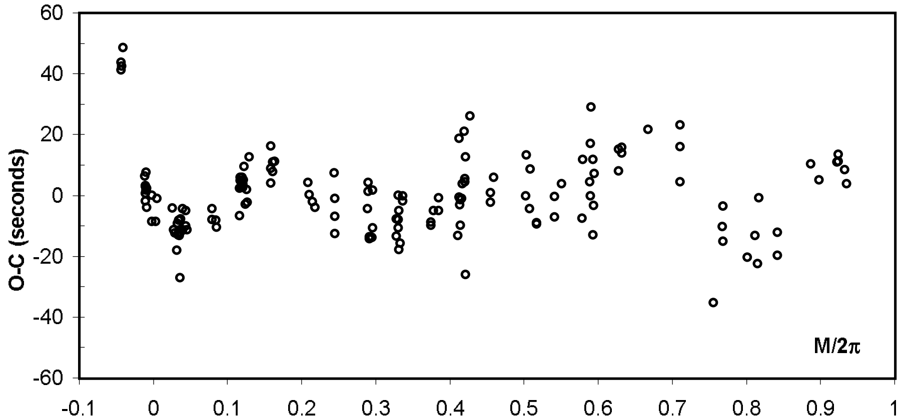

Figure 4. The O-C residuals from the third body ephemeris. The cyclic changes are clearly visible.

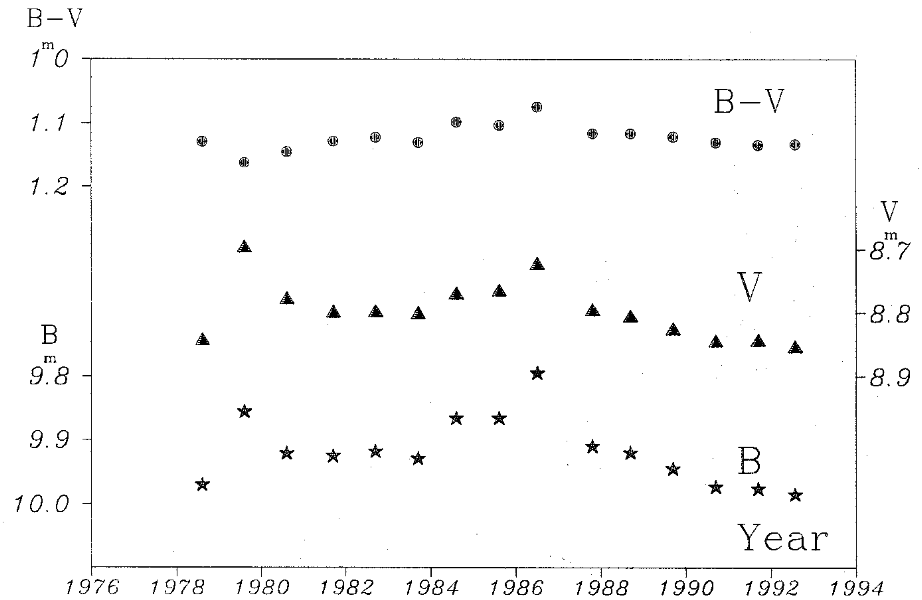

Figure 5. The mean luminosity and color variations of RT Lac between 1978-1992.

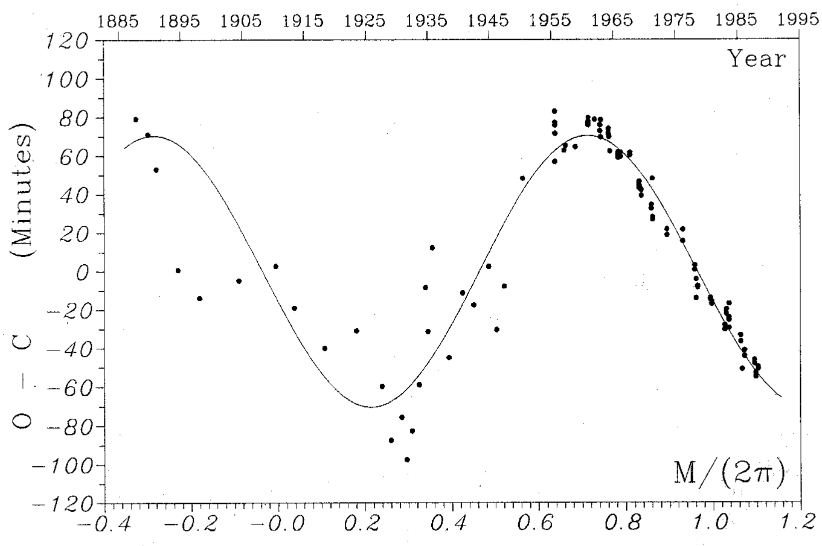

Figure 6. The light-time effect for the grouped photographic and for all the photoelectric times of minima of the system RT Lac.

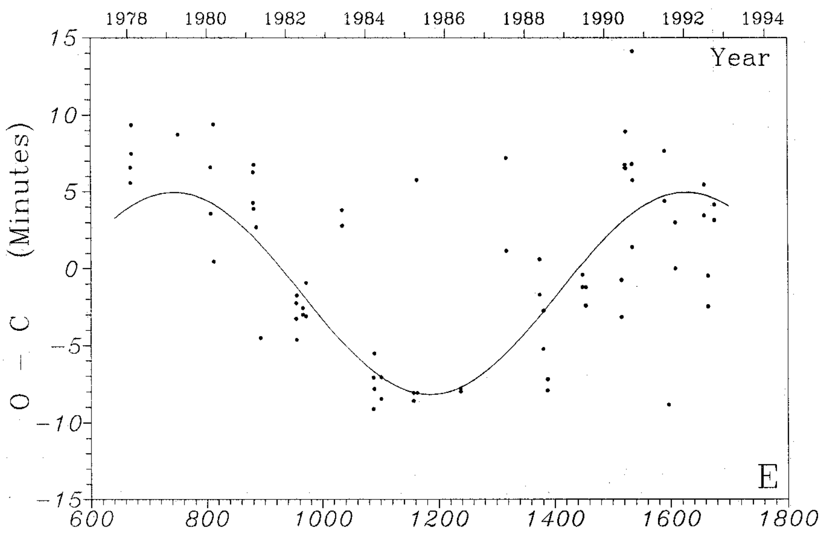

Figure 7. Deviations of the O-C values from the light-time effect of RT Lac.

star should be greater than its inside spin according the theory proposed by Applegate.

Recently, Lanza et al. [26] studied activity cycle and the period variations of AR Lac. They analysed the seasonal light curves of AR Lac covering 1976-1992 with two different approaches. The Maximum Entropy and Tikhonov principles were employed. Their analysis indicates that the spots are located on the photospheres of both components. The analysis could not give a significant evidence for an activity cycle on the primary. On the other hand, a possible modulation on a time scale of about 17 yr was suggested for the secondary star. The epochs of primary minima were collected and analysed by the same authors for the orbital period variations. They found an orbital period modulation with a period of ~ 35 yr, which is nearly twice the ~ 17 yr period for the modulation of the starspot area on the secondary component.

The mechanism of the orbital period modulations in active close binaries proposed by Applegate [19] relating the changes of the stellar internal rotation associated with a magnetic activity cycle with the variation of the gravitational quadrupole moment of the active component seems to fit at least for a few candidates. Further possible applications of the relationship between magnetic activity and orbital period modulation will not only highten the accuracy of the model but also give possibility for understanding the details of stellar magnetic dynamo.

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