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Study of the period changes of X Trianguli

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Abstract. In the present study the (O-C) diagram of the eclipsing binary X Tri is used to study its orbital period behaviour. From our analysis, which is based on the description of the (O-C) diagram using weighted, high-order polynomials, it is shown that the period changes of X Tri (at least those after 1949) can be explained as due either to magnetic activity cycles or to a third companion on the subgiant G3IV cool secondary component. The elements of this hypothetical third body were computed and from their values it was found that it cannot coincide with the already known, visual companion. Moreover, if the period variations of X Tri are coming from the magnetic activity of the subgiant component of the binary, the subsurface magnetic field was found to be equal to 8.77 kG.

Key words: stars: binaries: close – stars: binaries: eclipsing – stars: individual: X Tri

1. Introduction

X Tri is a semi-detached eclipsing binary, member of the JDS 3257, with a visual companion of 13th magnitude at an angular separation of 7 arcsec (Hall & Weedman 1971; Chambliss 1992). As early as 1932, Gadomski noticed that the period of X Tri was variable; this was later confirmed by many investigators (e.g. Odinskaya & Ustinov 1951; Lange 1957; Mallama 1975; Rovithis-Livaniou & Rovithis 1996). Frieboes-Conde & Herczeg (1973) were the first to include X Tri in a list of 14 systems with possible light-time effect, in their effort to explain its period variations; while according to Rafert (1982) there is no evidence for apsidal motion in the system. In the present study, the (O-C) diagram of X Tri is used to study its orbital period variations and it is analyzed using the Kalimeris et al. (1994a) method.

2. The data and their treatment

Searching in the literature we found 984 times of minimum light for X Tri, most of which are visual; specifically: 917 visual, 22 photographic and 45 photoelectric ones. Moreover, most of them correspond to the system's primary minimum, which is easily observable, because its difference from the maximum light is more than 2 magnitudes and the falling from the maximum to minimum light is rapid.

2.1. The (O-C) diagram

Using all available times of minimum light, we formed the (O-C) diagram of X Tri, which is presented in Fig. 1. Most of these data can be found in Pop's et al. table (1996); (all 984 times of minimum light used in the present analysis are available from the authors to the interested readers). The C's in Fig. 1 are based on the light elements given by Mallama (1975):

$$MinI = 2422841.7827 + 0^d.97153633 \cdot E \qquad (1)$$

In order to minimize the observational errors and get more accurate results in the following analysis, we form *normal* points. So, till HelJD 2433334 (which corresponds to the year 1949), where there exist only visual data, 16 such normal points were formed out of 256 individual visual ones. After 1949 all visual points were excluded as having much lower accuracy than the other ones. Moreover, normal photographic and photoelectric points were also formed: 4 out of 22, and 22 out of 45, respectively. The result is the (O-C) diagram of X Tri presented in Fig. 2, where the RMS error (representing the standard deviation of the diagram) has been reduced to about 32 per cent in comparison with its previous value (produced if we work with the original points). We analyzed the (O-C) diagram of X Tri, based on normal points, using the first continuous method proposed and developed by Kalimeris et al. (1994a). For this purpose, we described the (O-C) diagram presented in Fig. 2, applying a piece-wise, least-squares approximation, with two high-order, weighted polynomials ($p_{asc}(E)$ & $p_{desc}(E)$) for the ascending and descending branches, respectively, connected together by a spline interpolant at E=10800. Each one of the polynomials has the form:

$$p(E) = \sum_{k=0}^{N} a_k (\frac{E}{S_c})^k \qquad (2)$$

The elements of the polynomials used are listed in Table 1, while the solid line in Fig. 2 represents them. Then, the period $P(E)$:

$$P(E) = P_e + p_w(E) - p_w(E-1) \qquad (3)$$

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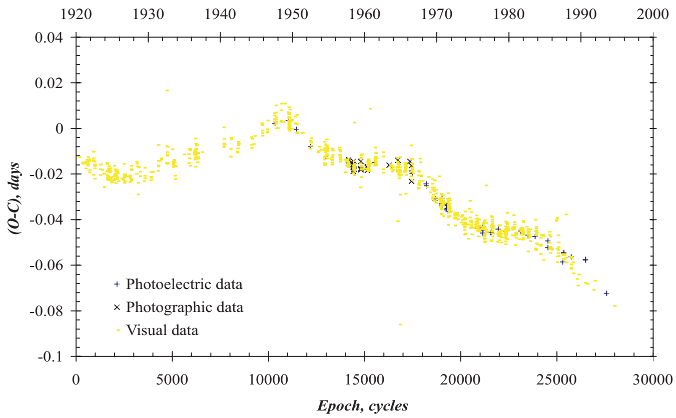

Fig. 1. The (O-C) diagram of X Tri based on all available data. The C's have been caclulated using Mallama's ephemeris formula (see text).

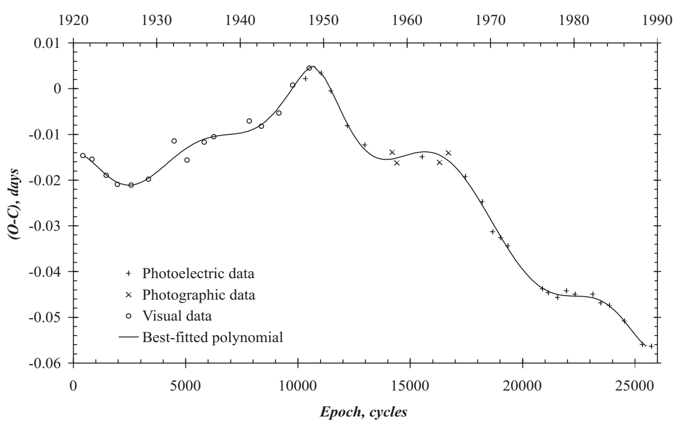

Fig. 2. The (O-C) diagram of X Tri based on the normal points. Solid line stands for the best fitted least-squares polynomials.

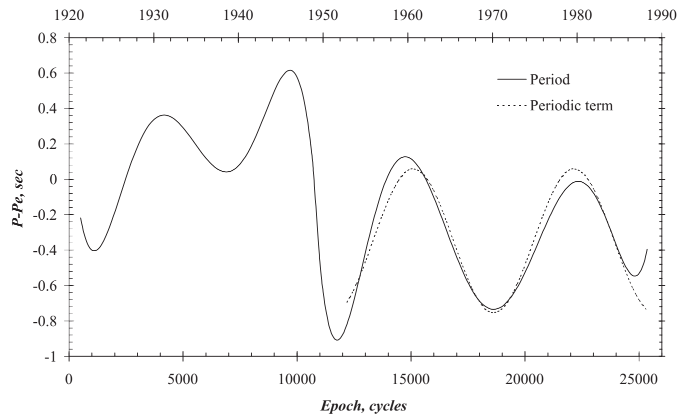

Fig. 3. The period $P(E)$ of X Tri. Dotted line stands for the periodic term.

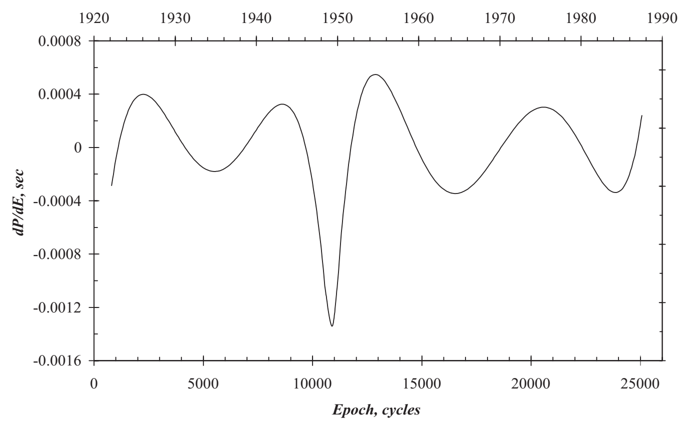

Fig. 4. The rate of change of the period $P(E)$ of X Tri.

Table 1. Elements of the best-fitted polynomial shown in Fig. 2. All quantities are in days, except S_c which is dimensionless.

Element	ascending branch	descending branch
a_0	-0.015	-54.72753
a_1	0.039	232.99582
a_2	-0.934	-416.22533
a_3	4.344	404.66085
a_4	-8.056	-231.41329
a_5	6.654	77.90813
a_6	-2.031	-14.31149
a_7		1.1078
S_c	10000	10000
RMS error	$1.044{\cdot}10^{-4}$	$6.278 \cdot 10^{-4}$

was computed and is shown in Fig. 3, where P_e is the ephemeris period and $p_w(E)$ is the best-fitted polynomial approximation. From Fig. 3 the wave-like behaviour of the period is immediately revealed. Moreover, in Fig. 4 the rate of change of the $P(E)$ function is shown, while in Fig. 5 the Fourier power spectrum of the period $P(E)$. From the latter, a single periodicity is traced corresponding to $P = (18.75 \pm 0.07)$ yr with amplitude $\Delta P = (0.406 \pm 0.002)$ s.

Although the ascending branch's error is less than that of the descending one (as is easily noticeable from the data of the Table 1), this is only a result of its better polynomial description and has nothing to do with the observational errors. We do know that more reliable results are coming using the much more accurate photoelectric data.

2.2. The right-hand branch of the (O-C) diagram

The descending tendency characterizing the right-hand branch of the (O-C) diagram of X Tri might correspond to a real period variation or not. According to Batten (1973) such a tendency in an (O-C) diagram might be the result of a false ephemeris period used, P_e, which is larger than the real one. A linear, weighted, least-squares description of this tendency can produce an improvement to Mallama's ephemeris, which is:

$$MinI = 2422841.8253 + 0^d.97153241 \cdot E \quad (4)$$

If this revised ephemeris, given by the foregoing formula (4), is used to calculate the C's values (corresponding to times after Hel.JD 2433334), the (O-C) diagram of X Tri changes form and takes the shape presented in Fig. 6. The solid line in this figure stands for the best-fitted polynomial, which differs from the $p_{desc}(E)$ only in the values of the constant (which now

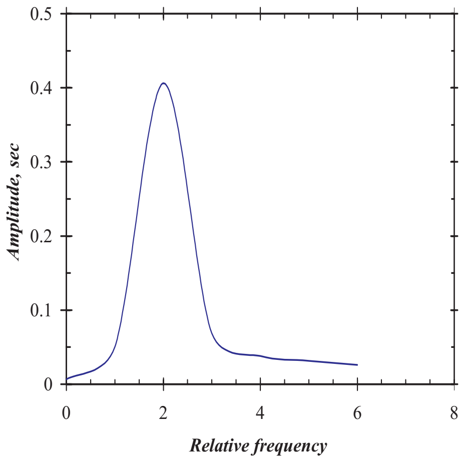

Fig. 5. The Fourier power spectrum of $P(E)$.

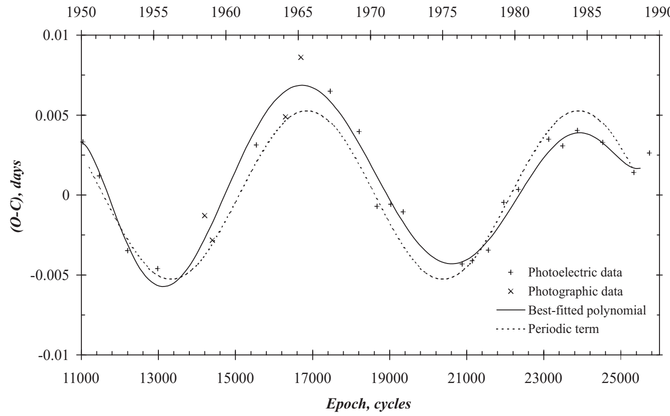

Fig. 6. The *new* (O-C) diagram of X Tri corresponding to times after Hel.JD 2433334 as calculated using the improved ephemeris. The periodic term is also shown (dashed line).

is $a_0 - 0.04438$ days) and of the linear element (which now is $a_1 + 4.014 \cdot 10^{-6} \times S_c$ days).

It is worthwhile to repeat here that, although the *new* (O-C) diagram of X Tri is absolutely different now, since its shape depends on the ephemeris used, the period $P(E)$ does not change form; it remains invariant, independently of the ephemeris used (details can be found in Kalimeris et al. 1994b).

3. Periodic mechanisms

From the *new* and almost sinusoidal shape of the (O-C) diagram of X Tri, one can easily see the presence of a periodic mechanism acting in the system and causing the observed orbital period variations. Two are the possible periodic mechanisms, which with their action could produce the observed period variations in X Tri: namely, a light-time effect and/or magnetic activity cycles.

3.1. Light-time effect

Light-time effect, produced by the presence of a third companion in the vicinity of a binary system has been examined in the past by Irwin (1959) and recently by Mayer (1990). Its influence to the (O-C)differences can be easily calculated by the following equations:

$$\tau(E) = \frac{a \sin i}{c}[\frac{1-e^2}{1+e\cos u}\sin(u+\omega)] \tag{5}$$

$$\tan\frac{E_c}{2} = \sqrt{\frac{1-e}{1+e}}\tan\frac{u}{2} \tag{6}$$

$$\frac{T_0 + P_e E - T_p}{P} = \frac{M}{2\pi} = \frac{E_c - e\sin E_c}{2\pi} \tag{7}$$

where a is the semi-major axis of the binary's mass centre as it revolves around the mass centre of the triple system; i and e are the inclination and the eccentricity of this orbit, respectively; u, E_c and M stand for the real, eccentric and the mean anomaly, respectively; P is the period of revolution; T_p is the time of periastron passage and ω is the longitude of periastron, while T_0 is the initial epoch.

The period of revolution P of the hypothetical third companion is taken equal to the detected periodicity $P = (18.75 \pm 0.07)$ yr of amplitude $\Delta P = (0.406 \pm 0.002)$ s.

The $P(E)$'s curve shape suggests a circular orbit (i.e. e=0), while the amplitude of the harmonic variation gives us a clue regarding the amplitude of the light-time effect, with the help of equation:

$$a \sin i = c\frac{\Delta P}{\sqrt{2(1-\cos f)}} \tag{8}$$

where $f = (2\pi P_e/P)$.

On the other hand, the assumption of zero eccentricity makes things even simpler, since:

$$\tau(E) = \frac{a \sin i}{c}\sin(fE+\phi) \tag{9}$$

where

$$\phi = \frac{2\pi(T_0 - T_p)}{P} + \omega \tag{10}$$

Following the foregoing described procedure, we got the solution given in Table 2, for a circular orbit, light-time effect. The light-time curve, computed from Eq. (9), is shown in Fig. 6 as a dotted line.

This is a first approximation to a possible elliptical orbit, for which additional elements can be found, if we solve for ϕ from the following set of equations:

$$A = \frac{a \sin i}{c}[(1-\cos f)\cos\phi - \sin f \sin\phi] \tag{11}$$

$$B = \frac{a \sin i}{c}[\sin f \cos\phi + (1-\cos f)\sin\phi] \tag{12}$$

where A, B are the cosine and sine amplitudes of the harmonic term found by Fourier transform of the period $P(E)$. Eq. (10), then, gives

$$T_p - \frac{\omega}{2\pi}P = (65.2 \pm 0.2) yr \tag{13}$$

Table 2. Physical and orbital elements of the hypothetical third body. Values marked with asterisk are under the assumption $i_3 = i$.

Element	value
$a \sin i$ (AU)	0.913 ± 0.006
P_3 (yr)	18.78 ± 0.07
f_m ($M_\odot$)	2.17 ± 0.05
a (AU) *	0.914 ± 0.006
a_3 (AU) *	10.1 ± 0.1
M_3 ($M_\odot$) *	0.316 ± 0.002
L_3 ($L_\odot$) *	0.018 ± 0.001)
$M_{bol,3}$ *	9.09 ± 0.03

which relates the time of periastron passage T_p with the longitude of periastron ω.

The influence of the light-time effect to the period $P(E)$ comes immediately from the equation:

$$P_{light}(E) = P_e + \tau(E) - \tau(E-1) \quad (14)$$

In Fig. 6 one can compare this influence (dotted line) with the period $P(E)$ (solid line). In fact, $P_{light}(E)$ coincides with the periodic term traced by Fourier transform in the period $P(E)$.

3.2. Magnetic activity cycles

The basic idea that changes in the orbital period of a binary system are the result of magnetic activity of one of its members, can be found in many searchers (e.g. Matese & Whitmire 1983; Applegate & Patterson 1987; Hall 1990; Applegate 1992). In particular the latter suggested that the internal angular momentum of the active star is periodically exchanged between different shells of its convective zone during the active cycle. In the case of X Tri, which consists of two A3 V & G3 IV components (Shaw & Kusler 1973; Batten et al. 1989), only the subgiant, cool, secondary component is capable of sustaining an Applegate-type mechanism.

Recalling Applegate's formalism, we consider the traced periodicity found in the power spectrum of $P(E)$ to be the modulation period P_{mod}, that is $P_{mod} = (18.75 \pm 0.07)$ yr. Moreover, assuming that the characteristics of the system are: $M_1 = 2.3M_\odot$, $R_1 = 1.71R_\odot$ for the primary and $M_2 = 1.2M_\odot$, $R_2 = 1.96R_\odot$ for the secondary component (Mezzetti et al. 1980), and that there is no energy storage in the outer layers of the active cool star, the required value for angular momentum transfer ΔJ, in order to reproduce the observed orbital period changes, the energy required to transfer this ΔJ, the RMS luminosity variations ΔL_{RMS} yield by the energy transfer and the magnetic field strength B that sustains the whole mechanism were computed and are given in Table 3.

The ΔL_{RMS} found, is comparable to the luminosity $L_2 = 2.818L_\odot$ of the secondary component. In Fig. 7 one can compare the observations (circles), taken from Olson & Etzel (1993) work, together with the estimated periodic term we have traced. Although we need more observational points to be certain about the existence of the magnetic circulation mechanism, our estimate meets the observations pretty good.

Table 3. Magnetic circulation elements

Element	value
ΔJ ($kg \times m^2 \times s^{-1}$)	$(-6.14 \pm 0.04) \times 10^{40}$
$\Delta\Omega$ (s^{-1})	$(2.07 \pm 0.01) \times 10^{-7}$
ΔE (joule)	$(2.5 \pm 0.6) \times 10^{34}$
ΔL_{RMS} ($L_\odot$)	0.35 ± 0.09
B (kG)	8.77 ± 0.09
ΔM_{bol}	0.49 ± 0.01

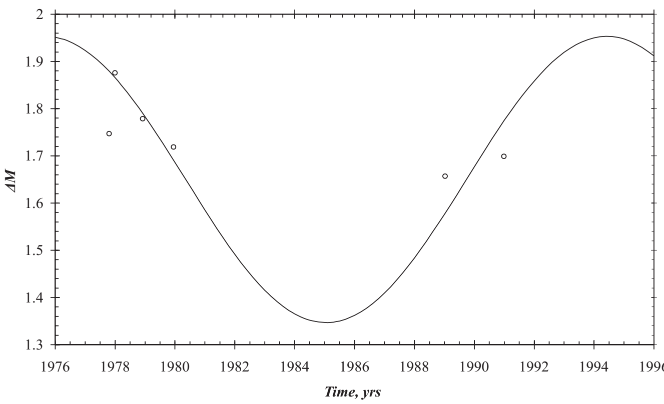

Fig. 7. The observed magnitude variability of X Tri vs. time. Solid line represents the estimated periodic term resulting from a magnetic circulation mechanism.

Moreover, the effective moment of inertia, I_{eff} was computed under Applegate's (1992) assumption that $M_{shell} = 0.1M$, since the age and hence the general internal structure of the secondary cool subgiant are poorly known. In general, the procedure described in the case of the RS CVn's-type binary SZ Psc (Kalimeris et al. 1995) was followed.

4. Non periodic mechanisms

Around 1949 (i.e. HelJD 2433334), X Tri exhibited a rapid continuous decrease in its period of the order of -0.505 s.

This period change could be explained as mass transfer from one component towards its mate. X Tri is an Algol-type binary and its secondary component is expected to have filled its corresponding Roche lobe, and the mass to flow from this star towards the primary, through the inner Lagrangian point L_1. But, since mass transfer from the the less to the more massive star is known to produce period increase, mass transfer cannot explain this observed period variation of X Tri.

Another possible mechanism is the mass loss from the system. If the decrease in period is due to mass going out the binary star, then the estimated mass loss is $\Delta M = -1.05 \cdot 10^{-5} M_\odot$

Finally, if we adopt the mass and angular momentum loss mechanism, as developed by Tout & Hall (1991), the observed period decrease leads to an amount of mass $\Delta M = -5.37 \cdot 10^{-6} M_\odot$, which leaves the system as stellar wind and rotates at an Alfven radius $R_A = 1.49R_2$.

5. Conclusion

In the present investigation of the orbital period variations of X Tri all kind of data (photoelectric, photographic, visual) have been taken into account. Normal points were considered to minimize the observational errors, especially that of the visual observations, from which the ascending branch of the (O-C) diagram of X Tri obtained. Otherwise, this part would not have been considered at all, because of the large observational errors.

In the subsequent analysis and description of both branches using high-order polynomials (Kalimeris et al. 1994a), we have got a better polynomial fitting for the ascending branch; however, the information it carries is less reliable than that of the descending one. For this reason, the *new* (O-C) diagram of X Tri is based only on the observational material obtained after 1949 (Fig. 6).

Moreover, we found a periodic term, which might be the result of a third body in the system, or of magnetic activity.

As regards the presence of a third body (light-time effect) we found that it fits pretty well not only the new (O-C) diagram of X Tri, but also its period $P(E)$ itself. The fact that the light-time curve does not fit the original (O-C) diagram (Fig. 1), does not mean that there is no light-time effect in the system. Assuming that the hypothetical third companion circulates at the same plane as the binary does (i.e. $i_{binary} = i_3 = 87.5\,\mathrm{deg}$) and that it is a ZAMS star, its mass of $M_3 = (0.316 \pm 0.002)\ M_\odot$ and luminosity $L_3 = (0.018 \pm 0.001)\ L_\odot$ reveals a body of M3-M4 spectral type and of $V_3 = 19.1^m$, adopting the parallax of X Tri to be 0.001 arcsec (Brancewicz & Dworak 1980). Therefore, it is a faint body, very difficult to be observed, with a difference of $\Delta V \sim 10.6^m$ from X Tri. Moreover, its angular separation from the binary is, also, very small: only 0.011 arcsec, adopting again the same value for the X Tri's parallax. Thus, it cannot coincide with the observed, visual companion of X Tri, which is 7 arcsec away from the binary.

Regarding the magnetic activity, and assuming that only the secondary component is capable of sustaining such activity circles, we give an estimation of the corresponding elements (Table 3). Moreover, the published light curves of X Tri are not adequate, as a result of the difficulties in its observation, which are mainly arised from the value of its orbital period, which is close to one day, and less from the presence of the visual companion. But even so, making use of the limited available data (Olson & Etzel 1993), it was shown that its magnitude variation, seems to follow the detected periodic term, for the time interval 1976-1996.

Finally, an attempt has been made to explain the rapid continuous decrease in the period of X Tri around 1949. Our estimations show that the mass transfer cannot cause the observed period variation, assuming that X Tri is an Algol-type system. Moreover, an estimation of mass and mass & angular momentum loss has been made.

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