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ORIGINAL ARTICLE

The intriguing orbital period variability of Y Leonis

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Abstract The orbital period variation of the oEA system Y Leo is revised by taking into account new times of minimum light covering an extended time base of 101.8 yr. A *multi-periodic* ephemeris was finally established by carefully approaching the problem of periodicity detection for the considered periodic components. A method relying on Monte Carlo simulations was applied. The problem of the long-term behaviour of the O–C curve was taken into account using *parabolic*, and *parabolic* + *periodic* ephemerides. The physical interpretation of the mathematical models describing both long- and short-term behaviour of the O–C curve was performed by considering different mechanisms: the conservative mass transfer, the light-time effect, and the orbital period modulation through the cyclic magnetic activity of the late spectral type secondary component in the system. The consequences of these interpretations are rather intriguing and emphasize the need of new and detailed observational studies on Y Leo.

Keywords Eclipsing binary stars · Stars individual Y Leo · Data analysis

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1 Introduction

The variable star Y Leonis (HIP 47178) is an A3 + K5 EA/SD eclipsing binary system (Giuricin et al. 1983). Recently, Turcu et al. (2008) discovered the oEA nature of Y Leo (see Table 1.1 of Turcu 2010b for an up to date list (September 2010) of oEA systems). The history of the studies on Y Leo resembles more or less that of other eclipsing binary systems. The continuous increase of the time base of the observational data allows to emphasize a more and more intricate shape of the O–C curve, which consequently led to various hypothesis invoked to explain the observed behaviour. Thus, Tsessevich (1958) observed a decrease of the orbital period. Few years later, Wood and Forbes (1963) established a cubic ephemeris, while Chiş and Pál (1964) concluded in their study that the orbital period displays jumps (explainable through the instability of the binary system and the hypotheses of mass transfer and mass loss) and irregular variations. Svechnikov et al. (1970) and Svechnikov and Surkova (1972) explained the observed period variation on the basis of mass loss and non-symmetrical mass ejection, respectively. Ghezloun and Svechnikov (1975) found evidence for the presence of a sinusoidal variation in the O–C curve with a period of about 57 years superposed on "*irregular (abrupt) variations*". They explained the periodic variation on the basis of a light-time effect due to a third body in the system having a mass of 0.65 M_{Sun}. Chiş (1976) rejected this hypothesis and considered that the observed period jumps could be understood through the theory of mass ejection and argued that this interpretation is in agreement with the evolutionary models of Refsdal and Weigert (1969). Rafert (1982) established two representations for the O–C curve: a parabolic one, and a superposition of a short periodic term (about 4.66 years) and a parabolic trend. Later, Chiş (1988) concluded that "*the system Y Leonis is actually* *in the phase of fast mass transfer*, *a little after the mass loss start*". In a recent paper Pop (2005) emphasized the multiperiodic behaviour of the O–C curve of Y Leo, the four involved periodicities being: 85.2, 8.606, 7.781, and 6.375 years. He also found some evidence for the presence of a low level stochastic variability of the orbital period, confirming thus the already mentioned opinion of Ghezloun and Svechnikov (1975). Pop (2005) argued that the longest periodicity could not be related to the presence of an unseen companion; he assumed that it could be related to the possible cyclic magnetic activity of the late spectral type secondary component of the system.

From a photometric viewpoint, the first investigation of Y Leo belongs to Johnson (1960). Later, Giuricin et al. (1980) reanalyzed Johnson's (1960) observations and concluded that Y Leo is an "*ordinary semi-detached system*, *probably free of complications*". Y Leo were also included in a target list of eclipsing binaries for searching extrasolar Trojan planets possibly existing at the Lagrangian points L_4 and L_5 (Caton et al. 2001; Davis et al. 2001), but until now no positive results have been reported. Yoon et al. (2004) found some Hα line profile variations in Y Leo. As they mentioned, these changes may be related to the presence of mass transfer phenomena in the system, or that of some gas streams etc. Recently, Turcu et al. (2011) published the results of a study of Y Leo light curve based on the analysis of 7217 CCD observations obtained during the 2009 observing season. Although, they found no strong evidence of mass transfer in the system, the occurrence of some photometric variability during primary minima related to the presence of some accretion structures cannot be ruled out. Furthermore, this photometric variability (occurring both at short and long time scale) could also be caused by the patterns of stellar activity of the cool, late type secondary component.

The present approach, which relies on a considerably long time base of 101.8 years, has as starting point the analysis of the alternating behaviour of the O–C curve of Y Leo. From the previous approach of Pop (2005) we took into account the coexistence of: (i) a long-term deterministic orbital period variation (cyclic or not), (ii) a short-term deterministic orbital period variability (maybe multiperiodic), and (iii) a short-term stochastic variability. As we know, the most invoked mechanisms for the observed alternating O–C curves are the light-time effect, and the cyclic magnetic activity of the late spectral type secondary component (e.g. Hall 1989, 1990). Apsidal motion cannot be involved, since the eccentricity of this binary system is zero. The presence of a secular trend, associated with mass transfer and/or mass loss phenomena, is also possible. Concerning the irregular variability already emphasized by several authors, we can take into account its presence, but without making, for the time being, any assumption about its nature.

2 Observational data

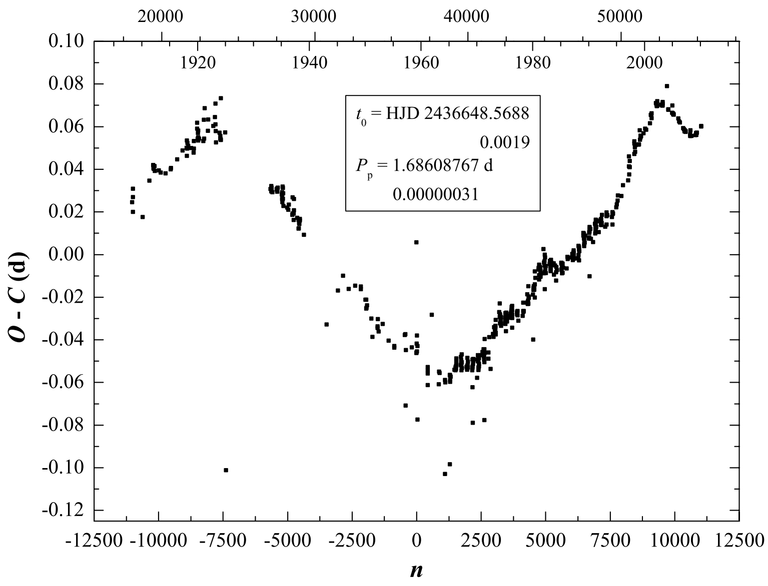
The present study of the orbital period variability of Y Leo relies on the 529 times of primary minimum light given in the Lichtenknecker-Database of the BAV (www.bav-astro.de/LkDB/). In addition, we included in our data set 15 new minimum light times, as follows: 2418737.2771 (v) (Graff 1914), 2431495.868 (pg) (Struve 1945), 2435876.303 (v) (Kordylewski 1958 quoted by Chiş and Pál 1964), 2438813.407 (v) (Hasler 1965), 2444335.426 (v) (Locher 1980), 2454905.5831, and 2454915.6988 (ccd) (Samolyk 2010), 2454509.35119, 2454541.38684, 2454600.39990, 2454912.32707, 2454944.36326, and 2454949.42150 (ccd) (Turcu et al. 2011), 2455232.68720 (ccd, Ir), and 2455232.68740 (ccd, V) (present paper). Thus, the total data number was 544 covering a timebase of 136.87 yr. Eight times of minimum light have been corrected, the new values being: 2418054.4185 (v), 2418113.434 (v), and 2418118.4962 (v) (Luizet 1917), 2418103.3105 (v) (Luizet 1908), 2436631.662 (pe), and 2436636.720 (pe) (Johnson 1960), 2438516.694 (v) (Baldwin 1964), 2445397.671 (v) (Williams 1993). Concerning these corrections, the following remarks have to be made: (i) Luizet's data are affected by HJD transforming errors; (ii) in case of Johnson's data, we found time conversion errors from Mountain Standard Time to JD; (iii) Baldwin's minimum—as given in the Lichtenknecker-Database of the BAV—has been corrected according to Baldwin's paper; (iv) in case of Williams (1993) minimum, most probably there is a one day time conversion error. The O–C curve of the whole data set, excepting the earliest time of minimum light, which is very probably an outlier, is given in Fig. 1, together with the corresponding elements of the linear ephemeris established by us, using the method mentioned in Sect. 3. The presence of many outlying data points is obvious, as well as the variability of the local scatter of the O–C residuals due, to the continuous improvement of the observing techniques and data processing methodology.

During the analysis and modelling of the O–C curve, we rejected 64 outlying data points, while during the averaging of the observed minimum light times corresponding to the same primary minimum, we decrease the number of data points by 77. The final data set consists of 403 times of minimum light covering 101.8 years.

3 Data analysis methods

In order to investigate the alternating behaviour of the O–C curve of Y Leo, we adopted a strategy joining the O–C curve modelling, and periodicity detection techniques in the amplitude spectrum through Monte Carlo simulations. In what follows we will review the main features of a high degree of generality ephemeris, which we found to be suitable

Fig. 1 The preliminary O–C diagram of Y Leonis. The scales of the top X axis are: years (*lower scale*), and HJD—2,400,000 (*upper scale*)



to describe the complex behaviour of the O–C curves of Algol binary systems (see Pop et al. 1996 for the case of RT Per, Pop 1998, 1999a for AB Cas, Pop et al. 2000 for that of ST Per, and Pop 2005 for Y Leonis). We have adopted this model because it is able to take into account the effect of different kinds of physical mechanisms occurring, sometimes simultaneously, in these binaries (Pop 1996; see also Pop 1998; Borkovits et al. 2005).

First of all, one has to establish the preliminary linear ephemeris in order to compute the O–C residuals. We used the method indicated by Pop (1999b) (see also Pop et al. 2003), the resulted values of initial epoch (t_0) and (*principal*) period (P_p) being finally improved through linear regression. This approach is justified within the theoretical frame of the pulse position modulation signals with natural sampling (Turcu and Pop 2003; Turcu 2005, 2010a; see also Spătaru 1965). Accordingly, one assumes that the temporal distribution of times of minimum light can be described by the following general ephemeris formula

$$t_n = t_0 + P_p n + \tau(n) + \varepsilon(n), \tag{3.1}$$

in which the orbital period P_p represents the sampling interval, n—the orbital cycles number, $\tau(n)$—the deterministic signal (secular trend due to mass transfer and/or mass loss, light-time effect, apsidal motion, modulation caused by magnetic cycle activity etc.), and $\varepsilon(n)$—the random (possibly Gaussian) noise related to various observational errors. The objective and rigorous character of this method (relying on optimization of P_p value through exhaustive search) allows us to avoid the problems arising from the dependence of the shape of the O–C curve on the considered ephemeris formula (in fact on the *assumed* orbital period value P_p) (e.g. Rovithis-Livaniou 2001).

Let $\Omega_1, \Omega_2, \ldots, \Omega_L$ be the "secondary" angular frequencies iteratively identified in the amplitude spectrum of the O–C curve, after removing the secular trend, where

$$\Omega_l = 2\pi f_{0l} = 2\pi(f_{sl}/f_p) = 2\pi(P_p/P_{sl}),\quad l = 1, 2, \ldots, L. \tag{3.2}$$

Note that they are dimensionless frequencies because time is expressed by means of the cycle number corresponding to the unperturbed principal period (P_p). We also shall assume that for each fundamental frequency Ω_l there exists $M_l - 1$ detectable harmonics. With these notations, the ephemeris describing the temporal repartition of minimum light times is

$$t_n = t_0 + \sum_{k=1}^{K} \tau_k n^k + \sum_{l=1}^{L} \sum_{m=1}^{M_l} \tau_{lm} \sin(\Omega_{lm} n + \Phi_{lm}), \tag{3.3}$$

where we obviously have $\tau_1 \equiv P_p$, and $\Omega_{lm} = m\Omega_l$. The values of the involved parameters are obtained through linear and then nonlinear least-squares fitting. The model fitting details have already been presented in our above mentioned papers. Note that this model implicitly assumes the additive character of the involved effects. For the simplicity's sake, we shall use the following notation: $P[K] + F[L]$; $[M_1], [M_2], \ldots, [M_L]$, where P refers to the polynomial term, while F refers to the sum of truncated Fourier series (see (3.3)). For all the fitted models, we computed the standard deviation of the corresponding residuals σ_{res} (see the last row in Tables 1–3).

An essential question in fitting the model to the observed times of minimum light is that of estimating the statistical significance of the adopted frequencies f_{0l} ($l = 1, 2, \ldots, L$). We approached this problem through the method proposed

Table 1 Parameters of the *parabolic* ephemeris of the O–C curve of Y Leo

	$t_0 = \text{HJD}2436648.5330$ ± 0.0013	
	$\tau_1 \equiv P_p = 1.68608726\ \mathrm{d\,c}^{-1}$ ± 0.00000016	
$\tau_2 = 1.019 \times 10^{-9}\ \mathrm{d\,c}^{-2}$ $\pm 0.026 \times 10^{-9}$		$\frac{1}{P_p}\frac{dP_p}{dt} = 2.619 \times 10^{-7}\ \mathrm{yr}^{-1}$ $\pm 0.068 \times 10^{-7}$
	$\sigma_{res} = 0.01731$ d	

Table 2 Parameters of the *parabolic* + *periodic* ephemeris of the O–C curve of Y Leo

	$t_0 = \text{HJD}2436648.5655$ ± 0.0048		
	$\tau_1 \equiv P_p = 1.68608809\ \mathrm{d\,c}^{-1}$ ± 0.00000030		
$\tau_2 = 1.1 \times 10^{-10}\ \mathrm{d\,c}^{-2}$ $\pm 1.0 \times 10^{-10}$		$\frac{1}{P_p}\frac{dP_p}{dt} = 2.8 \times 10^{-8}\ \mathrm{yr}^{-1}$ $\pm 2.6 \times 10^{-8}$	
$f_{01} = 0.0000543$ ± 0.0000021	$P_{S1} = 85.1$ yr ± 3.3	$\tau_{11} = 0.0499$ d ± 0.0047	$\Phi_{11} = 4.288$ rad ± 0.017
$2f_{01} = 0.0001086$	$P_{S1}/2 = 42.5$ yr	$\tau_{12} = 0.00359$ d ± 0.00056	$\Phi_{12} = 6.04$ rad ± 0.19
	$\sigma_{res} = 0.00627$ d		

by Pop (2005) (see also Pop et al. 2010), derived from the method of Kuschnig et al. (1997). Pop (2007) and Pop and Vamoş (2007) proved the ability of this method to detect low level periodic signals in the presence either of Gaussian noise, or Gaussian + autoregressive order one AR(1) noise. The method relies on the analysis of a given frequency domain of the amplitude spectrum of the standardized observed data, with the estimation of the mean amplitude (τ_{mean}), and of the amplitude of the highest peak ($\tau_{\max}$). The application of this method is based on Monte Carlo simulations with Gaussian noise, bootstrap resampling, and random permutations, is also able to detect the presence of significant amount of noise (correlated or not) in the analysed data.

In order to investigate the already mentioned stochastic variability phenomenon we applied the self-correlation method proposed by Percy et al. (1981) (see also Percy et al. 1993, 2003; Percy and Mohammed 2004). Operating in the *time domain*, this very simple and straightforward method proved to be a powerful tool in the study of such type of phenomena, being able to provide a "profile" of the respective variability.

4 Data analysis and results

As we already pointed out in Introduction, we first focused on the long-term behaviour of the orbital period variation. Taking into account the length of the observations time base, as well as the shape of the long-term variability of the O–C curve (see Fig. 1), we assumed that it has a deterministic character featured either by a parabolic trend, or by the superposition of a parabolic trend and a periodic or an arbitrary periodic variation. Concerning this parabolic trend, its physical significance in an Algol binary system is associated with the conservative mass transfer from the cool, low-mass secondary component towards the primary one. In this case, one has to expect a positive parabolic term in the fitted ephemeris, corresponding to the mass transfer phenomenon from the secondary component. This constraint is fulfilled in case of the parabolic trend (see Table 1), and in that of the superposition of the parabolic trend and an arbitrary periodic variation including the fundamental frequency (f_{01}) and its first harmonic ($2f_{01}$) (see Table 2). We immediately remark, that in the second case, the coefficient of the parabolic term in the ephemeris has no statistical significance. As it is well-known (e.g. Huang 1963; Pringle 1975), the mass transfer rate from the secondary

Table 3 Parameters of the *multiperiodic* ephemeris of the O–C curve of Y Leo

$t_0 = \mathrm{HJD}2436648.56918$ $\pm\,0.00029$			
$\tau_1 \equiv P_p = 1.686087833\ \mathrm{d\,c^{-1}}$ $\pm\,0.000000066$			
$f_{01} = 0.00005390$ $\pm\,0.00000031$	$P_{S1} = 85.65$ yr $\pm\,0.49$	$\tau_{11} = 0.05478$ d $\pm\,0.00023$	$\Phi_{11} = 4.3534$ rad $\pm\,0.0070$
$2f_{01} = 0.0001078$	$P_{S1}/2 = 42.82$ yr	$\tau_{12} = 0.00439$ d $\pm\,0.00035$	$\Phi_{12} = 0.439$ rad $\pm\,0.067$
$f_{02} = 0.00018394$ $\pm\,0.00000087$	$P_{S2} = 25.10$ yr $\pm\,0.11$	$\tau_{21} = 0.00788$ d $\pm\,0.00030$	$\Phi_{21} = 3.083$ rad $\pm\,0.035$
$2f_{02} = 0.00036788$	$P_{S2}/2 = 12.55$ yr	$\tau_{22} = 0.00191$ d $\pm\,0.00023$	$\Phi_{22} = 0.40$ rad $\pm\,0.11$
$f_{03} = 0.0004388$ $\pm\,0.0000021$	$P_{S3} = 10.521$ yr $\pm\,0.050$	$\tau_{31} = 0.00334$ d $\pm\,0.00022$	$\Phi_{31} = 1.645$ rad $\pm\,0.076$
$f_{04} = 0.0006039$ $\pm\,0.0000024$	$P_{S4} = 7.645$ yr $\pm\,0.031$	$\tau_{41} = 0.00253$ d $\pm\,0.00017$	$\Phi_{41} = 1.746$ rad $\pm\,0.082$
$f_{05} = 0.0005001$ $\pm\,0.0000025$	$P_{S5} = 9.231$ yr $\pm\,0.045$	$\tau_{51} = 0.00259$ d $\pm\,0.00021$	$\Phi_{51} = 3.558$ rad $\pm\,0.085$
$f_{06} = 0.0002555$ $\pm\,0.0000035$	$P_{S6} = 18.07$ yr $\pm\,0.25$	$\tau_{61} = 0.00232$ d $\pm\,0.00020$	$\Phi_{61} = 5.38$ rad $\pm\,0.11$
$\sigma_{res} = 0.00225\,\mathrm{d}$			

component in case of conservative mass transfer rate is given by (see also (3.3))

$$\dot{M}_2 = -\frac{1}{3}\frac{M_1 - M_2}{M_1 M_2}\frac{\dot{P}_p}{P_p}, \tag{4.1}$$

where

$$\frac{\dot{P}_p}{P_p} \equiv \frac{1}{P_p}\frac{dP_p}{dt} = \frac{P_p}{2\tau_2}. \tag{4.2}$$

Thus, we may conclude that, in case of Y Leo, we have either a value $\dot{M}_2 = -7.99 \times 10^{-8} \pm 0.21 \times 10^{-8}\ M_{\mathrm{Sun}}\,\mathrm{yr}^{-1}$, or a significantly lower one $\dot{M}_2 = -8.5 \times 10^{-9} \pm 7.9 \times 10^{-9}\ M_{\mathrm{Sun}}\,\mathrm{yr}^{-1}$, the present time base not allowing its reliable estimation. Such results are in agreement with the location of this relatively short-period Algol system in the $r - q$ diagram (r—the radius of the primary component in units of the binary separation, q—the mass ratio $q = M_2/M_1$) (Lubow and Shu 1975), as well as our recent results (Turcu et al. 2011). Consequently, we may conclude that Y Leo has no permanent accretion disk, and the mass transfer occurs either through a gas stream, or through a transient disk or an accretion annulus (e.g. Richards and Albright 1999). The presence of variable accretion structures (e.g. Richards 2004) seems also to be possible (Turcu et al. 2011).

In order to establish an overall description of the O–C curve of Y Leo, including the short-term variability too, we followed the same approach as described by Pop (2005). It is interesting to mention that because of the interplay between the intricate character of Y Leo orbital period variability and the available data window, we were not able to establish a simultaneous "*parabolic*" + "*multiperiodic*" fit to the O–C curve. The final model is of the $P1 + F6$; $2, 2, 1, 1, 1, 1$ type. The different stages of the prewhitening procedure of the O–C curve of Y Leo are displayed in Fig. 2, while the resulting fit is displayed in Fig. 3. The two long time gaps occurring during the first half of the observations time base, obviously led to severe constraints in the O–C curve modelling process. For all the frequencies appearing in Table 3, the null hypothesis was rejected at confidence levels higher than 99.9% (for tests with Gaussian noise the confidence levels were always 100%; see Fig. 4). To be more specific, the null hypothesis refers to the hypothesis according to which, the observed features of the respective amplitude spectra of the analysed O–C residuals are caused by the random character of the input data (simulated Gaussian noise, bootstrapping the input data, and random permutations of the input data; see Sect. 3) (see Fig. 4).

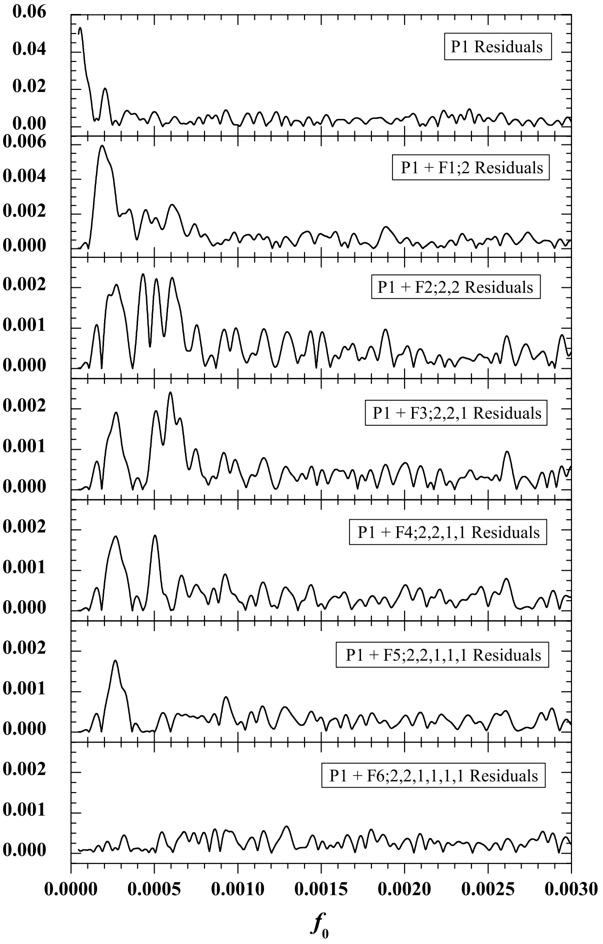
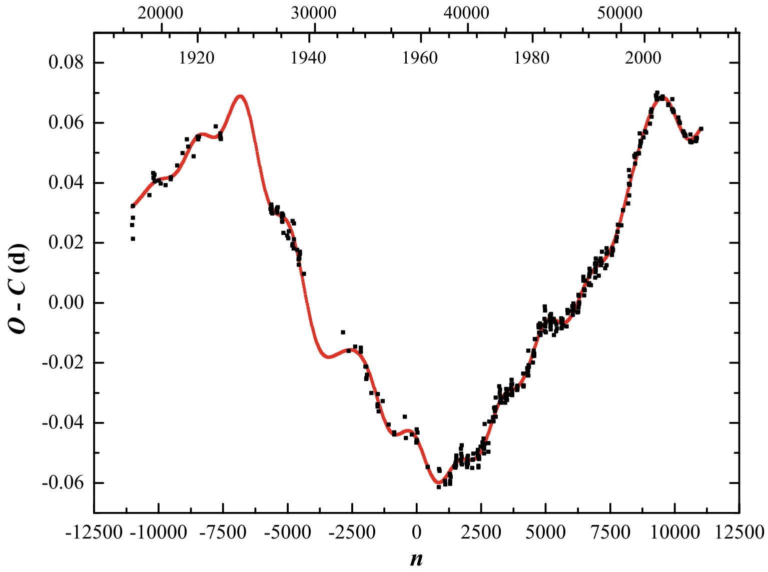


Fig. 2 Amplitude spectra corresponding to different stages of prewhitening of the O–C curve

Finally, we approached the problem of the already mentioned stochastic variability appearing in the O–C curve of Y Leo. The amplitude spectrum of the residuals obtained after removing the final model (Fig. 2), revealed a maximum peak situated at a (dimensionless) frequency $f_{07} = 0.001292$, the corresponding periodicity being $P_{S7} =$ 3.57 yr. The diagnosis of the time behaviour of the final residuals through the Monte Carlo type method, mentioned in Sect. 3 led us to the conclusion that we are dealing with *noisy* data (see e.g. Pop et al. 2010). More precisely, at confidence levels of about 99.99%, we are able to reject the different null hypotheses concerning the features of the *observed* amplitude spectrum, defined through Gaussian noise (see Fig. 4—remark the position of the *observed* point (the star) in the right extremity of the cluster of simulated data points, previously called *Gaussian Noise Syndrome* Pop 2005), bootstrap resampling, and random permutations. It also resulted that the above mentioned periodicity has no statistical significance; at most it may be treated as a *suspected* periodicity which need to be checked up in future studies (the respective null hypotheses may be rejected at confidence levels between 97.55% and 97.81%). A relatively close frequency value ($P_{S7} = 4.5$ yr) was obtained by applying the self-correlation method. In fact, it is rather a characteristic time scale of variability, this value corresponding to the first minimum in the self-correlation diagram (SCD) (see Fig. 5). The SCD does not display minima at multiples of this time scale. Thus, the self-correlation analysis of the final O–C residuals confirmed the lack of further significant periodicities. The level of the zeroth minimum in the SCD, which features the size of observational error, is 0.00223 d (compare with $\sigma_{res} = 0.00225$ d, in Table 3), if we take into account the centre of the first time bin (0.5 yr), or 0.00210 d, if we consider the extrapolated

Fig. 3 The final multiperiodic model of the O–C curve of Y Leonis



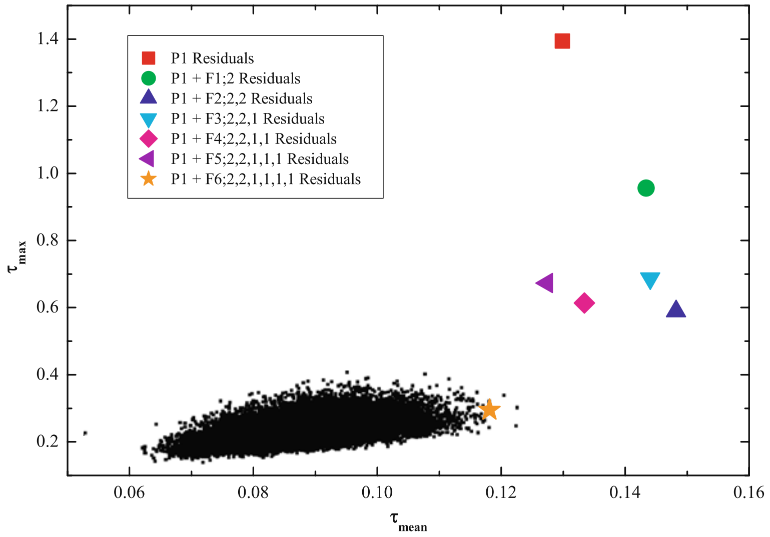


Fig. 4 The different stages of the prewhitening process in the plane (τ_{mean}, $\tau_{\max}$) with respect to the cluster of simulated data points

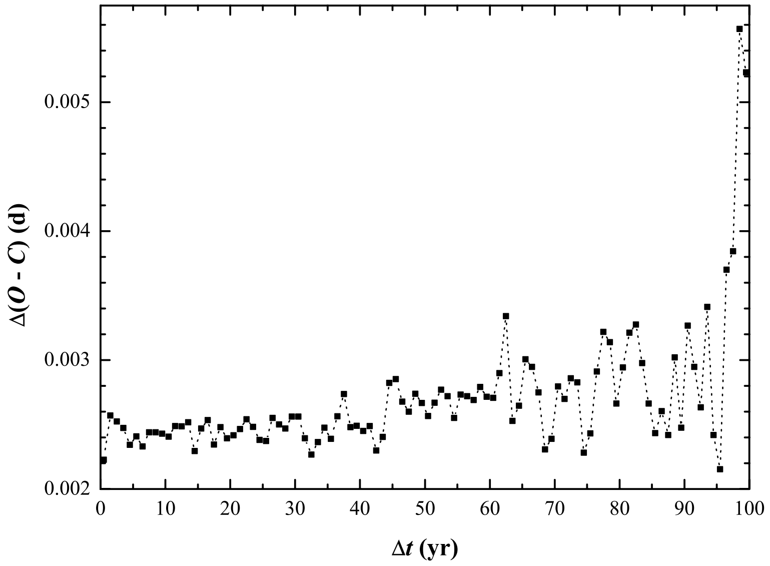


Fig. 5 Self-correlation diagram of the final O–C residuals

value for $\Delta t = 0$ yr. Examining the depths of the other minima appearing in the SCD, we found further evidence for the presence of some amount of irregular variability: within the interval of time lags between 0 and 95 yr, the deepest minimum level is slightly higher than that of the observational errors. The deep minimum which occurs at 95.5 yr, with a depth of 0.00215 d, may be a consequence of an incomplete prewhitening of the long-term trend in the O–C curve. Future studies have to clarify if this irregular orbital variability/modulation is a consequence of the already mentioned transient mass transfer, or a sign of the presence of some undetected periodicity(ies), or there is another cause.

Because of the complex behaviour of the Y Leo O–C curve, as well as of its amplitude spectrum, in order to take into account the established multiperiodic ephemeris, we will consider two well-known mechanisms invoked to explain the inferred orbital period modulations: (i) the hypothesis of Keplerian motion of the barycentre of the close binary due to the presence of an unseen third body in the system, and (ii) the hypothesis of magnetic cycles occurring in the cool, late spectral type secondary component.

4.1 The third body hypothesis

We investigated the consequences when taking into account this hypothesis by estimating the orbital parameters of the hypothetical companion for each periodic component in the multiperiodic ephemeris (see (3.3) and Table 3). In case of the first two periodicities we are dealing with arbitrary periodic modulations, which—in terms of the light-time effect hypothesis—corresponds to companions revolving on eccentric orbits around the barycentre of the system (e.g. Kopal 1978). In order to derive first guesses of the respective orbital elements, we applied the method proposed by

Table 4 Interpretation of the six periodicities as light-time effect related to Keplerian motions

P_s (yr)	$a \sin i$ (AU)	e ω (°) T_p (HJD)	$f(M)$ (M_{Sun})	$M_3 \sin i$ (M_{Sun})	K (km s^{-1})
85.65	9.634	0.1611 18.2 2448317.9831	0.1219	1.322	3.4
25.10	1.541	0.5271 335.6 2440723.8435	0.0058	0.410	2.2
10.521	0.578	0	0.0017	0.266	1.6
7.645	0.438	0	0.0014	0.249	1.7
9.231	0.448	0	0.0011	0.224	1.4
18.07	0.403	0	0.0028	0.314	2.5

Pop (1998, 1999a). The obtained values are given in Table 4, where: $a \sin i$—the projection of the semi-major axis of the close binary absolute orbit on the line of sight, i—inclination of the normal to the orbit plane on the line of sight, e—the orbital eccentricity, T_p—the time of periastron passage, $f(M)$—the mass function, M_3—the mass of the hypothetical companion, and K—the semi-amplitude of the radial velocity curve. We took into account the masses of Y Leo components derived by Turcu et al. (2011), i.e. $M_1 = 2.29\ M_{\text{Sun}}$, $M_2 = 0.74\ M_{\text{Sun}}$, and $i = 86.12°$.

4.2 The magnetic cycles hypothesis

In order to investigate the hypothesis of the modulation of Y Leo orbital period by the magnetic cycles of the secondary component (Hall 1989) via Applegate's (1992) mechanism, we considered each of the detected periodicities, and then we estimated the values of the physical parameters involved in Applegate's model: A_{O-C}—the semi-amplitude of the O–C curve, $\Delta P_p/P_p$—the amplitude of the orbital period modulation, ΔJ—the angular momentum transfer, $\Delta\Omega/\Omega$—the variable part of the differential rotation, ΔE—the energy budget required to transfer the angular momentum, ΔL_{RMS}—the *RMS* luminosity variation, and B—the mean subsurface magnetic field. In order to compute the values of these parameters we made use of the required physical parameters as given by Turcu et al. (2011): $M_2 = 0.74\ M_{\text{Sun}}$, $R_2 = 2.47\ R_{\text{Sun}}$, and $a = 8.625\ R_{\text{Sun}}$. We also estimated $L_2 = 0.988\ L_{\text{Sun}}$, and $I_s = 2.9001 \times 10^{54}$ g cm^2. The obtained results are displayed in Table 5. We have to note that, in case of arbitrary periodic modulations, we considered for the value of A_{O-C} the semi-amplitude of the full amplitude of the respective O–C curve component.

5 Discussion and concluding remarks

According to the above presented results, the interpretation of the multiperiodic orbital period modulation of the O–C curve of Y Leo either through the light-time effect, or through the hypothesis of magnetic cycles, faces some difficulties.

Thus, from the view point of the light-time effect hypothesis, the significance of the six detected periodicities becomes more clear if we represent the masses of the six hypothetical companions, as well as the semi-major axis of their absolute orbits around the system's barycentre with respect to the inclination values (Figs. 6 and 7). The following remarks have to be made:

(i) for all considered inclination values the longest orbital period companion has a mass value of at least 1.32 M_{Sun} (or 1.33 M_{Sun}, in case of coplanar orbits), and thus it might be perceived through its photometric perturbations;

(ii) for $i < 70°$, the mass of the most massive companion, if it is invisible, suggest that we are dealing with a neutron star, or even a black hole. Such a hypothesis obviously has to fulfil at least some age constraints from the viewpoint of stellar evolution. Furthermore, in the neighbourhood of Y Leo there are no signs of occurrence of violent stages of stellar evolution;

(iii) for $i < 36°$, the mass of the hypothetical companion corresponding to P_{S2} becomes higher than the mass of the secondary component of Y Leo, and consequently some photometric perturbations might be obvious, but this is not the case;

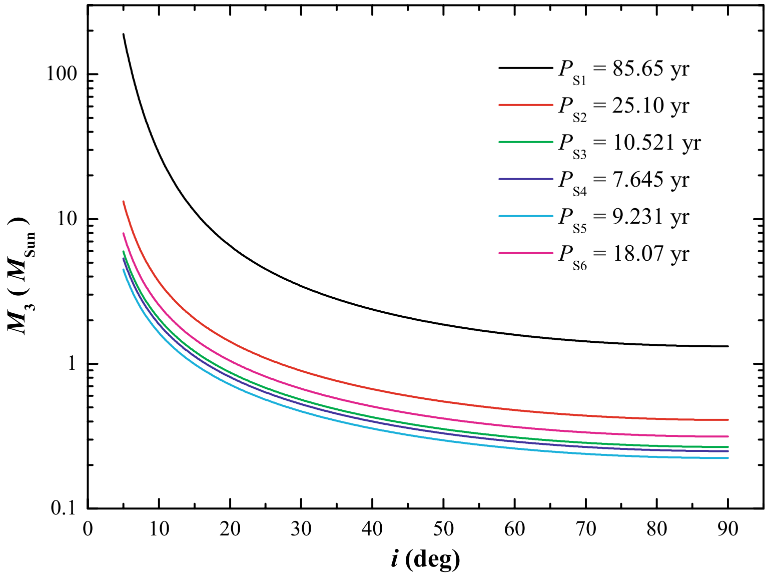


Fig. 6 (Color online) Hypothetical "third body" mass values for different inclination values corresponding to the six inferred periodicities

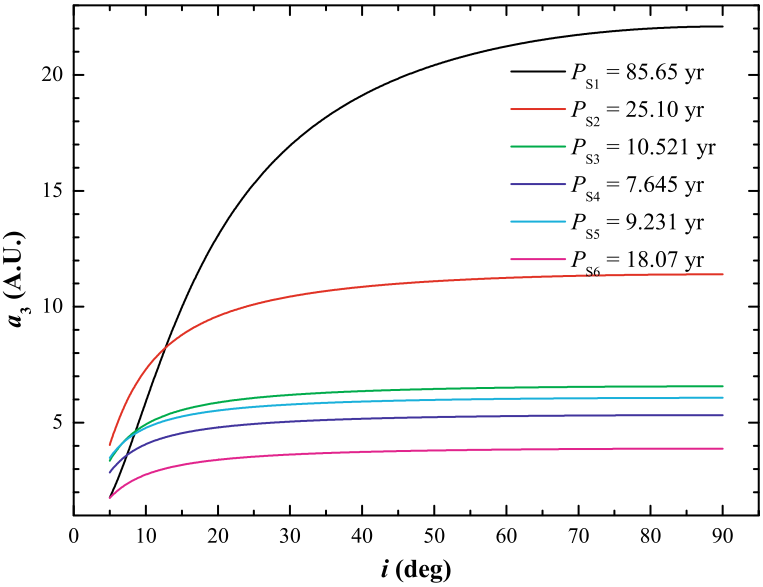


Fig. 7 (Color online) The values of the semi-major axis of the absolute orbit of the hypothetical "third body" corresponding to the six inferred periodicities, with respect to the inclination angle values

(iv) examining the amplitude spectrum of the $P1 + F2; 2, 2$ residuals (Fig. 2), we immediately observe the group of four close peaks, corresponding to P_{S3}, P_{S4}, P_{S5}, and P_{S6} (see also Tables 3 and 4). For $i > 53°$ the masses of the four corresponding hypothetical companions (Fig. 6) are situated in a very close domain, i.e. 0.2–0.4 M_{Sun}. According to the results displayed in Fig. 7, the values of the semi-major axes of the absolute orbits of these low-mass stellar objects corresponds—referring to our Solar system—to the area situated between the orbits of Mars and Saturn. Obviously, the problem of the stability of such a multiple stellar system has to be investigated;

(v) according to the K values given in Table 4, it is obvious that the detection of the presence of these hypothetical companions through radial velocity observations depends on the possibility to obtain enough precise data on Y Leo between primary and secondary maxima, at $V_{\max} = 10.16$ mag (Turcu et al. 2011).

In order to get a clue concerning the interpretation of the detected periodicities through the magnetic cycles hypothesis, we took into account the relation between the length of the modulation cycle in the O–C curve (assumed to coincide with the length of the hypothetical magnetic cycle) and the orbital angular velocity (supposing the synchronisation between the orbital motion and the rotation of the component stars $\Omega = 2\pi/P_{orb}$) found by Lanza and Rodonò (1999). Thus, from the data given in their Table 1, we obtained through linear least squares regression (see also (28)

Table 5 Interpretation of the six periodicities through Applegate's (1992) theory

P_s (yr)	A_{O-C} (d) $\Delta P_p/P_p$	ΔJ (g cm^2 s^{-1})	$\Delta\Omega/\Omega$	ΔE (erg)	ΔL_{RMS} (L_{Sun}, L_2)	B (kg)
85.65	0.05490 1.10×10^{-5}	8.74×10^{47}	4.66×10^{-3}	5.27×10^{41}	0.159 0.161	3.46
25.10	0.00854 5.85×10^{-6}	4.64×10^{47}	2.47×10^{-3}	1.48×10^{41}	0.153 0.155	4.66
10.521	0.00334 5.45×10^{-6}	4.32×10^{47}	2.30×10^{-3}	1.29×10^{41}	0.317 0.321	6.95
7.645	0.00253 5.70×10^{-6}	4.51×10^{47}	2.41×10^{-3}	1.41×10^{41}	0.476 0.482	8.33
9.231	0.00259 4.82×10^{-6}	3.82×10^{47}	2.04×10^{-3}	1.01×10^{41}	0.282 0.286	6.98
18.07	0.00232 2.21×10^{-6}	1.75×10^{47}	9.35×10^{-4}	2.12×10^{40}	0.030 0.031	3.38

from Lanza and Rodonò 1999)

$$\log P_{\mathrm{mod}}\,[\mathrm{yr}] = 0.021 - 0.362 \log \frac{2\pi}{P_{orb}[\mathrm{s}]}. \\ \pm 0.280 \pm 0.070 \qquad (5.1)$$

Taking into account the obvious presence of some outlying data points (see Fig. 2 of Lanza and Rodonò 1999), we applied a more suitable robust linear regression method, namely the mean median method proposed by Sârbu (1997); the following regression line equation was obtained

$$\log P_{\mathrm{mod}}\,[\mathrm{yr}] = 0.46 - 0.25 \log \frac{2\pi}{P_{orb}[\mathrm{s}]}, \\ \pm 0.53 \pm 0.13 \qquad (5.2)$$

where the parameters' uncertainties were estimated through the bootstrap resampling method. Using the orbital period value (P_p) given in Table 3, and (5.1), (5.2), we got the following predictions for the period of the magnetic cycles in the secondary component of Y Leo: 40.1 yr, and 35.6 yr. Thus, we may suppose that the second periodicity detected by us in the O–C curve of Y Leo ($P_{S2} = 25.10$ yr) could be associated with the magnetic activity. However, because of the large uncertainties of the regression line parameters, longer ($P_{S1} = 85.65$ yr) or shorter ($P_{S6} = 18.07$ yr) periodicities cannot be ruled out as related to magnetic cycles. On the other hand, examining the data listed in Table 5, we found that for P_{S1} and P_{S2} we have the best agreement with the requirements of Applegate's (1992) model.

Further information about Y Leo is supplied by IR and X-ray observations. Thus, from the IR observations performed within the 2MASS project (Cutri et al. 2003) we derived for Y Leo the following colour indices $(J - H) = 0.220$, and $(H - K_S) = 0.134$. The following oEA systems have similar spectral types to Y Leo: Y Cam (A9V + KV; Rodríguez et al. 2010), RZ Cas (A3V + K0IV; Rodríguez et al. 2004), AB Cas (A3V + KV; Rodríguez and Breger 2001), TW Dra (A5V + K1IV; Tkachenko et al. 2010), TZ Eri (Barblan et al. 1998), and AS Eri (A3V + K0IV; Mkrtichian et al. 2004). The IR colour indices $(J - H)$, and $(H - K_S)$ were also derived as follows: (0.240, 0.049), (0.205, 0.051), (0.162, 0.072), (0.220, 0.134), (0.276, 0.069), and (0.173, 0.060), respectively. It is interesting to note that, the values of $(H - K_S)$ index for TW Dra (which is the bright component of the visual binary ADS 9706) and Y Leo are identical, and they are also significantly higher than the corresponding values of the above mentioned systems. This IR excess could be in agreement with the above hypothesis concerning the presence of one or more, cool, low mass stellar companions. On the other hand, according to the *ROSAT All-Sky Bright Source Catalogue* (Voges et al. 1999), Y Leo has in its close vicinity, at an angular distance of 14.51″, the X-ray source 1RXS J093650.9 + 261405. A similar situation appears in the case of other oEA systems too. Thus, AS Eri has a X-ray source at 19.16″ (1RXS J033224.0 − 031839), while for RZ Cas and TW Dra, the X-ray source has practically the same position as that of the binary system in visible light (1RXS J024854.7 + 693804 and 1RXS J153350.2 + 635440, respectively). In case of Y Leo, the identification error of the X-ray source (12″, in X-ray domain) is practically the same as the angular separation in visible light. Consequently, it is possible that Y Leo may be identified with the X-ray source situated in its immediate neighbourhood. If so, a possible cause of the X-ray emission could be the mass transfer in the binary system Y Leo. At the same time, we have to emphasize that both IR excess and X-ray emission are symptoms of chromospheric activity (e.g. Hall 1989).

The present study on the variation of Y Leo orbital period revealed some intriguing aspects. What is the actual character of the long-term behaviour displayed by the $O–C$ curve? Does it really contain a long periodic component (P_{S1})? If so, is it related to the presence of an unseen high-mass stellar companion? Which periodicity (maybe P_{S2}?) is caused by the magnetic cyclic activity of the secondary component of Y Leo? Is the emphasized short-term (multiperiodic) orbital period modulation really caused by low-mass stellar companions? If one or more low-mass stellar companions are truly present in the system, then—having in view their convective atmospheres—do they have magnetic cycles too? In such a situation is/are its/their influence detectable in the $O–C$ curve? Obviously, answering these questions needs further observational and theoretical studies.

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