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The RS CVn binary XY UMa as a member of a triple system

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Abstract. New minima of the short period RS CVn binary system XY UMa taken in 1997-98 follow the light-time orbit with a 30.5 years period. An inferior conjunction of the third body with mass 0.23 ± 0.03 $M_\odot$ occurred in 1979. It is suggested that the light-curves of XY UMa taken in 1978-79 were affected by the eclipse of the binary system by a dusty envelope of the protostellar object responsible also for the observed infrared excess. There is no correlation between the long-term brightness variations of the system and the minima times in the O-C diagram, so its explanation by the Applegate mechanism proposed recently by Erdem & Güdür (1998) is brought into question.

Key words: binaries: eclipsing – stars: individual: XY Uma – stars: pre-main sequence – stars: magnetic fields

1. Introduction

XY UMa (HD 27143, BD +55 1317, G3 V + K5 V) is the most active member of the RS CVn short period group (P = 0.47899 days).

Pojmanski & Geyer (1990) explained the deviations of the minima times from a linear ephemeris by a light-time effect. They proposed either a 25 or 40 year orbital period for a third body to get a nearly perfect correlation between the light-curve asymmetry and the O-C residuals from a light-time fit.

Hilditch & Collier Cameron (1995) and Jeffries et al. (1995) have collected brightness estimates of XY UMa since 1976 and 1955, respectively. They showed that the whole system has been getting brighter since about 1961. Jeffries et al. (1995) explained this effect by a magnetic cycle at least 40 years long and attributed the short-term, year-to-year changes of the light-curve asymmetry to variability of low-latitude spots that are obscured during primary eclipse. On the other hand, Maceroni et al. (1990) prefer a 3.5 - 4 years periodicity of a magnetic cycle, found by Geyer (1980) as a "spot cycle". He published XY UMa observations only in graphical form. Due to the fact that printing errors have crept in and been propagated, we give Geyer's data in Table 1.

Table 1. Differential V magnitudes (XY UMa - SAO 27139) at brightness maxima (Geyer, 1980).

Date	$V_{Max\ I}$	$V_{Max\ II}$
Feb. 8, 1975	0.19	0.10
Mar. 1 - 8, 1976	0.12	0.10
Dec. 25, 1976 - Feb. 27, 1977	0.02	0.15
Dec. 19, 1977	0.22	0.18
Jan. 6, 1979	0.20	0.28

Erdem & Güdür (1998) fitted times of the primary minima simultaneously by a quadratic ephemeris and the light-time effect or sinusoidal fit, respectively. The long-term period increase was explained by mass loss from the system (Hall & Kreiner, 1980). Erdem & Güdür put in question the light-time orbit with the period 32.5 years and preferred the Applegate (1992) gravitational coupling mechanism with the 31.1 year period of the magnetic cycle of the primary component as an explanation of the O-C residuals.

The spectroscopic elements of the primary component were determined by Rainger et al. (1991) as K_1 = 119.5 ± 2.0 km s^{-1}, V_0 = -9.2 ± 1.5 km s^{-1} and f(m) = 0.082 ± 0.004 $M_\odot$. Erdem & Güdür (1998) determined a mass ratio q = 0.83 ± 0.01 and an inclination angle i = 76^o from light-curve analysis. They ignored the mass function given above and derived the masses of the components of XY UMa as M_1 = 0.90 $M_\odot$ and M_2 = 0.75 $M_\odot$. These values, however, imply f(m) = 0.142 $M_\odot$.

New spectroscopic observations performed by Pojmanski & Udalski (1997) confirmed the previous spectroscopic orbit: K_1 = 123.2 ± 3.0 km s^{-1}, V_0 = -9.8 ± 2.0 km s^{-1}, f(m) = 0.093 ± 0.008 $M_\odot$. The authors for the first time determined also K_2 = 203 ± 16 km s^{-1} and found the physical parameters of the system as follows: $M_1 \sin^3 i$ = 1.07 ± 0.19 $M_\odot$, $M_2 \sin^3 i$ = 0.65 ± 0.07 $M_\odot$, q = 0.61 ± 0.05 and a sin i = 3.09 ± 0.15 $R_\odot$. They suggested the presence of a dusty envelope surrounding the system to explain the disagreement between the G3 spectral classification and F9-G0 spectral type derived from the mass and radius (1.13 $R_\odot$) of the primary. They pointed out that: (i) the infrared index of the G3 primary J-K ≈ 0.62 - 0.65 (Arévalo & Lázaro, 1990) shows over 0.25 mag excess when compared with a main-sequence calibration; (ii) Jassur (1986) found B-

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Table 2. Times of minima of XY UMa.

Epoch	JD_{hel}	Fil.	Epoch	JD_{hel}	Fil.
-17788	26696.1488	NE	32566	50815.4507	U
-16714	27210.5906	NE	32612	50837.4842	V
-13982	28519.2053	NE	32612	50837.4832	B
32564	50814.4935	R	32612	50837.4842	U
32564	50814.4934	V	32616.5	50839.6450	V
32564	50814.4932	B	32616.5	50839.6450	B
32566	50815.4510	R	32718.5	50888.5001	V
32566	50815.4510	V	32718.5	50888.5019	R
32566	50815.4507	B			

V ≈ 0.95 in 1979 observations while the colour index of G3 main-sequence star should be B-V = 0.65.

2. New observations and O-C diagram

Our photoelectric observations of XY UMa were obtained at the Skalnaté Pleso (SP) and Stará Lesná (SL) Observatories of the Astronomical Institute of the Slovak Academy of Sciences from December 31, 1997 to March 30, 1998. Observations at SP were carried out through V and R filters while U,B and V filters were employed at SL. In both cases a single-channel pulse-counting photoelectric photometer installed at the Cassegrain focus of the 0.6m reflector was used. The integration time of one measurement depended on observational conditions and was generally between 6 and 10 seconds. SAO 27139 and SAO 28151 served as a comparison and check star, respectively. Data reduction, atmospheric extinction correction and transformation to the international UBVR system were carried out using standard methods. The light-curves of XY UMa are shown in Fig. 1. During our observations the UBVR light-curves were quite stable, except for a small increase of brightness in B and V on the declining branch to primary minimum, which occurred on March 30, 1998. The depth of the secondary minimum strongly depends on the wavelength.

Our observations led to the determination of 3 primary and 2 secondary minima times. They have been calculated separately for each passband using Kwee & van Woerden's (1956) method. The minima are listed in Table 2 together with 3 normal epochs (NE) which we have calculated from 12 old minima times, based on patrol plates of the Bamberg Observatory (Geyer, 1977).

The photoelectric times of minima and their weights were taken from Pojmanski & Geyer (1990). We have added the minima times from BBSAG, Qisheng et al. (1989), Hanžl (1991), Hilditch & Bell (1994), Jeffries et al. (1995), Ogloza (1997) and Erdem & Güdür (1998) and the minima from Table 2. They were weighted by w = 16. Photographic minima including NE were weighted by w = 8. As can be seen in Fig. 3 of the paper of Erdem & Güdür (1998), the scatter of visual estimates is at least three times higher than that of photoelectric ones. Hence they were neglected in our analysis. Since the secondary minima are very shallow, the precise determination of the time of the minimum is strongly affected by the light-curve asymmetry (Pojmanski & Geyer, 1990). Therefore, only primary minima were used for the study of period changes.

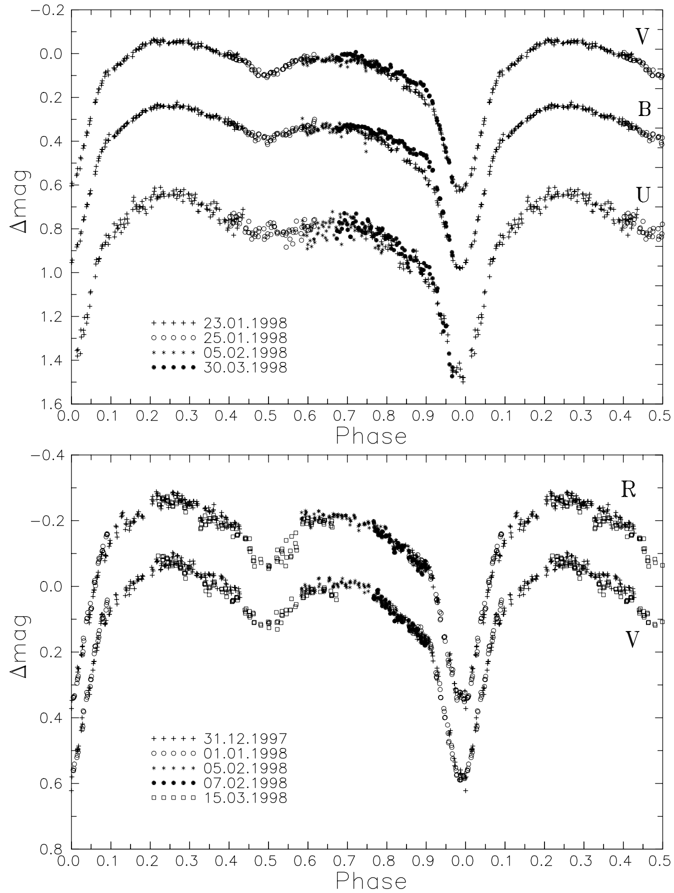

Fig. 1. U,B,V observations at the Stará Lesná Observatory (top) and V,R observations at the Skalnaté Pleso Observatory (bottom) expressed in Δmag (XY UMa - SAO 27139).

As can be seen from the O-C diagram (Fig. 2), constructed using the quadratic ephemeris, the orbital period of XY UMa is changing both in a periodic quasi-sinusoidal and erratic way. The periodic part of the variation can be explained either by the presence of the third body in the system or by the Applegate mechanism.

2.1. The presence of a third body in the system

We have assumed that the times of the primary minima follow a quadratic ephemeris and are deviated by the light-time effect, so the times of the minima can be computed as follows:

$$\text{Min I} = JD_0 + P \times E + Q \times E^2 + + \frac{a_{12} \cdot \sin i}{c}\left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right], \quad (1)$$

where $a_{12}\sin i$ is the projected semi-major axis, e is the eccentricity, ω is the longitude of the periastron, ν is the true anomaly of the binary orbit around the center of the mass of the triple system. $JD_0 + P \cdot E + Q \cdot E^2$ is the quadratic ephemeris of the minima in an eclipsing binary and c is the velocity of the light. Erdem & Güdür (1998) employed an erroneous formula in their computation of the light-time effect (their Eq. (3)).

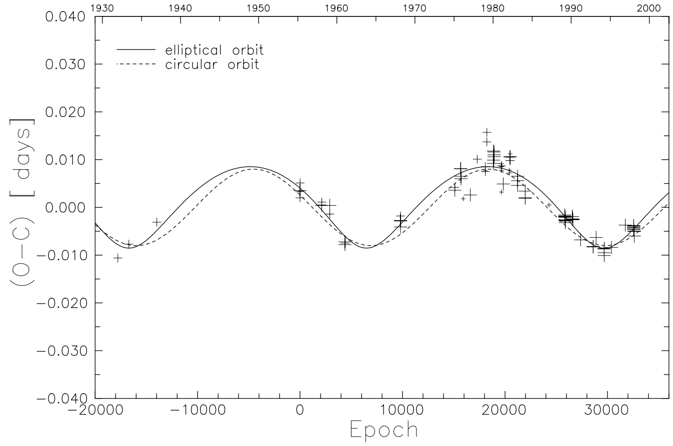

Fig. 2. O-C diagram for weighted primary minima, quadratic ephemeris and the light-time effect best fits for a circular orbit (dashed line) and elliptical orbit (solid line).

Table 3. The light-time effect solutions and corresponding ephemerides of the binary system for a circular and elliptical orbit. T_{super} and T_{infer} are the times of the superior and inferior conjunction of the third body, respectively.

Element		Circular	Elliptical
$P_{third\ body}$	[days]	10990	11130
		±160	±130
e		0	0.294
		–	±0.069
ω	[°]	–	-101
		–	±19
T_0	[JD]	2 441 270	2 438 050
		±230	±530
a_{12}sin i	[AU]	1.384	1.479
		±0.066	±0.082
$f(m_3)$	[$M_\odot$]	0.00293	0.00349
		±0.00042	±0.00059
T_{super}	[JD]	2 449 510	2 449 360
		±260	±610
T_{infer}	[JD]	2 444 010	2 444 210
		±230	±1140
JD_0	[JD]	2 435 216.5020	2 435 216.5010
		±0.0005	±0.0006
P_{binary}	[days]	0.47899428	0.47899426
		±0.00000005	±0.00000005
Q	[days]	$2.48\ 10^{-11}$	$2.58\ 10^{-11}$
		$\pm1.9\ 10^{-12}$	$\pm2.0\ 10^{-12}$
$\sum$(O-C)^2	[days^2]	0.0004959	0.0004653

To obtain the optimal fit and corresponding elements of the light-time orbit including errors, we have used the differential corrections method. The resulting ephemeris of the binary as well as the elements of the circular and elliptical orbit of the eclipsing pair around the center of mass of the triple system are given in Table 3. The corresponding fits are depicted in Fig. 2. As the sum of the residuals is smaller for an elliptical orbit than for a circular one, the elliptical orbit seems to be more probable.

Erdem and & Güdür determined an incorrect value of the error in the quadratic term Q = $1.85\ 10^{-11} \pm 3.4\ 10^{-14}$. The correct value of the quadratic term is Q = $(1.91 \pm 0.28)\ 10^{-11}$. The difference between this value and the value for the elliptical orbit given in Table 3 is caused by different sets of data used for the calculation of the quadratic term. We have used 14 new photoelectric minima (two of them published by Hilditch & Bell (1994) were also at the disposal of Erdem & Güdür, but they did not use them for their calculations) and 3 normal points instead of 12 individual times of photographic minima. The covariance matrix for fitted parameters does not show any significant correlation between the value of Q and parameters of the third body (except r(Q,a_{12} sin i) = 0.67).

The brightness decrease in 1978-79 (see Fig. 3) with the minimum at JD 2 443 947 - 962 observed by Jassur (1986) nearly coincides with the time of the inferior conjunction of the third body, which occurred at JD 2 444 010 ± 230 and JD 2 444 210 ± 1140 for a circular and elliptical orbit, respectively. This decrease and increase of the B-V index (reddening) observed by Jassur can be naturally interpreted as an eclipse of the close binary by a third body. The mass of the third body can be calculated from the mass function given in Table 3 and the total mass of the close pair $(M_1 + M_2)\sin^3 i = 1.72 \pm 0.20\ M_\odot$ (Pojmanski & Udalski, 1997). Since the inclination angle of the binary orbit is between 82° (Hilditch & Bell, 1994) and 88.2° (Budding & Zeilik, 1987) and the binary and triple star orbits are most probably coplanar, the mass of the third body is 0.23 ± 0.03 $M_\odot$. Its Roche-lobe radius exceeds 500 $R_\odot$. If all three bodies were formed from one protostellar cloud, the third component has to be still contracting towards ZAMS, so it is a protostar. An extended dusty envelope of this pre-main-sequence object can cause attenuation of the light and increase of the B-V index (reddening) during the eclipse of XY UMa binary.

The observed infrared excess of XY UMa out of eclipse (Arévalo & Lázaro, 1990; Arévalo et al., 1994) can be explained by thermal emission from the circumstellar dust (Rydgren & Cohen, 1985). It is well known that all pre-main-sequence objects possess such infrared excess. The presence of a dusty envelope surrounding the system was suggested also by Pojmanski & Udalski (1997). We bring to mind that the luminosity of a protostellar object evolving vertically downward in the HR diagram exceeds that of a main-sequence star of the same mass.

Using the quadratic ephemeris and parameters of the circular orbit given in Table 3 one can easily find ephemeris for the future minima of XY UMa as:

$$\mathrm{Min\ I} = 2\,435\,216.502 + 0.47899428 \times E + \\ + 2.48\ 10^{-11} \times E^2 + 0.008 \cdot \sin\left[\tfrac{E-12644}{63.756}\right], \quad (2)$$

where the sine argument is calculated in degrees.

2.2. The Applegate mechanism

Erdem & Güdür (1998) explained the period changes by a combination of the Applegate mechanism (with the magnetic cycle of the primary component of 31.1 years) and a mass loss

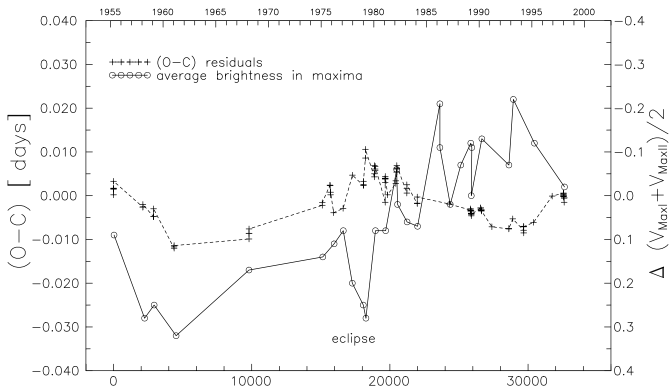

Fig. 3. The O-C residuals and brightness of XY UMa expressed in ΔV (XY UMa - SAO 27139).

from the system. According to Applegate (1992) the magnetic cycles cause quasi-periodic orbital period changes in binaries containing a convective star. The changes in quadruple moment require changes in luminosity of order 0.1 mag with the same cycle length. Therefore, the light-curve and the O-C curve should have the same cycle length and the extrema should coincide with each other. Correlation between the O-C curve and brightness variations serves as a crucial proof of validity of the Applegate (1992) mechanism. Erdem & Güdür (1998) ignored the long-term brightness variations of XY UMa discussed by Jeffries et al. (1995). Fig. 3 displays the brightness of XY UMa (mean values of the brightness in the primary and secondary maximum) in the V passband and the O-C curve. The brightness estimates were taken from Hilditch & Collier Cameron (1995), Jeffries et al. (1995) and Geyer (1980) (see Table 1). Our new observations were included. Fig. 3 does not show any correlation between the brightness of the system and the O-C curve, so the explanation of the periodic variations by the Applegate mechanism is questionable. Our observations indicate that the brightness of the system has started to decline, implying that its period is at least 45 years.

3. Discussion and conclusion

XY UMa is a chromospherically active star, the most active member of the short period RS CVn binaries. It displays long-term changes of the orbital period and mean brightness of the system. We did not find the correlation between these two quantities, so the explanation of O-C changes by the Applegate mechanism proposed by Erdem & Güdür (1998) is not probable. We cannot completely reject the Applegate mechanism, since most of the system variations could be due to the spots (dark or bright), which continuously modulate the local surface brightness of this active star by as much as 0.2 mag. Observations of a few complete O-C cycles are necessary to give the definitive answer.

New observations support the view that XY UMa binary is accompanied by a third body with an orbital period of 30.5 years. The crucial observations, which support the light-time effect in XY UMa, were taken by Geyer (1980) and Jassur (1986) in 1978-79. We interpret the observed dip in brightness and increase of the B-V index as an eclipse of XY UMa binary by the dusty envelope of the protostellar object. For the confirmation of the light-time orbit and pre-main-sequence nature of the third body we have to wait till the next eclipse in 2009. Present observations are not sufficient to study the dust distribution in the system and its influence on the light of the XY UMa binary. Long-term infrared photometry of the system as well as multifrequency study of XY UMa during the next eclipse are required to solve this problem.

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