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Photometric Study on the Spot-Double Star XY Ursae Majoris (I)

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Abstract

The long-term observational properties of the photometric behaviours of the short period (p=0.48 day) eclipsing binary system XY UMa are discussed. They are based on the UBV observations, which were carried out by Geyer in the years 1955-1961, 1968, 1975-1984. Light curves of XY UMa revealed very large changes not only between consecutive observing nights, but also from season to season. Between 1955 and 1984, the mean system brightness increased about 30% during this time intervals, meanwhile, the orbital period of this system was constant whithin 1.6% of its period. The colour index curve shows similar variations like the light curve but with a phase offset oscillation around the time instants of the primary minima. Observational evidence for photospheric and chromospheric activities on the XY UMa are also discussed.

I. Introduction

The eclipsing binary nature of the XY UMa was detected by Strohmeier in 1955, and the very short orbital period of 0.478995 day was found by Kippenhahn(Geyer *et al.* 1955). The system was extensively observed photometrically during the past 30 years by Geyer (1976, 1977b, 1980). The spectral types of the components are G2-5V + K5V derived photometrically, the system is a detached one, although the primary component is close to its critical Roche lobe. Simultaneous ground based and UV-observations with the IUE satellite shows strong chromospheric UV-activity of the XY UMa(Geyer and Hoffmann 1980). Lorenzi and Scaltriti(1977) observed also photoelectrically the light curve in 1975/76 and they confirmed the short-term light curve variability of this system. According to Hall(1976, 1981) and Milano (1981) XY UMa belongs to the short period group of RS CVn-type binaries. Zeilik *et al.*(1983) claim to have observed in the *UBV* spectral bands a flare-like phenomena at phase 0.57 in 1982.

This paper mainly deals with the photometric behaviours of the XY UMa and the following paper contains a more detailed analysis of the light variations in terms of a spot model.

II. Observations and Light Curves

The short period of eclipsing binary XY UMa(BD+55° 1317, SAO 27143) was observed photometrically by Geyer during the last 30 years beginning in 1955: Five light curves in *B* and *V* bands were obtained with the 60cm Cassegrain reflector of the Remeis Observatory at Bamberg within 1955 to 1961, and since 1968 up to 1984, 10 further light curves were observed with the double beam photometer with the 106 cm(F/14.5) Cassegrain telescope at the Hoher List Observatory. The original instrumentation and further remarks about this system are all described by Geyer and Hoffmann(1974, 1975).

For XY UMa the star BD +55° 1314 was used as the primary comparison star for all of the observations and its constancy was checked against BD +54° 1278. The observational material which described in this work was obtained in the time interval from 1955 to 1984 (on the total of 51 nights) by Geyer. The atmospheric extinction coefficients are derived nightly for each colour. The orbital phase of the observations were calculated from the light ephemeries given by Geyer(1977a).

$$\text{Pr. Min.} = \text{JD } 2435216.4972 + 0\overset{d}{.}4789952 \text{ E}$$

Due to the amount of data, only three examples of extreme case of light, and colour curves in the year 1975, 1976, and 1984 are presented in Figures 1, 2, and 3, respectively.

III. Long-term photometric variations of XY UMa

The long-term photometric behaviour of the mean system brightness, the brightness of the primary minimum(ϕ=0.00), secondary minimum II(ϕ=0.50), and the difference between maximum I(ϕ=0.25) and maximum II(ϕ=0.75) phases for the ΔB, and ΔV colours are shown in Figures 4 to 7, respectively. Here, ΔB and ΔV are the magnitudes in reference to the comparison star and ΔM is the magnitude difference between maximum II and maximum I.

These intrinsic photometric variations of XY UMa can be described as follows: the mean system brightness($\Delta\overline{m}$), Fig. 4, which is given by

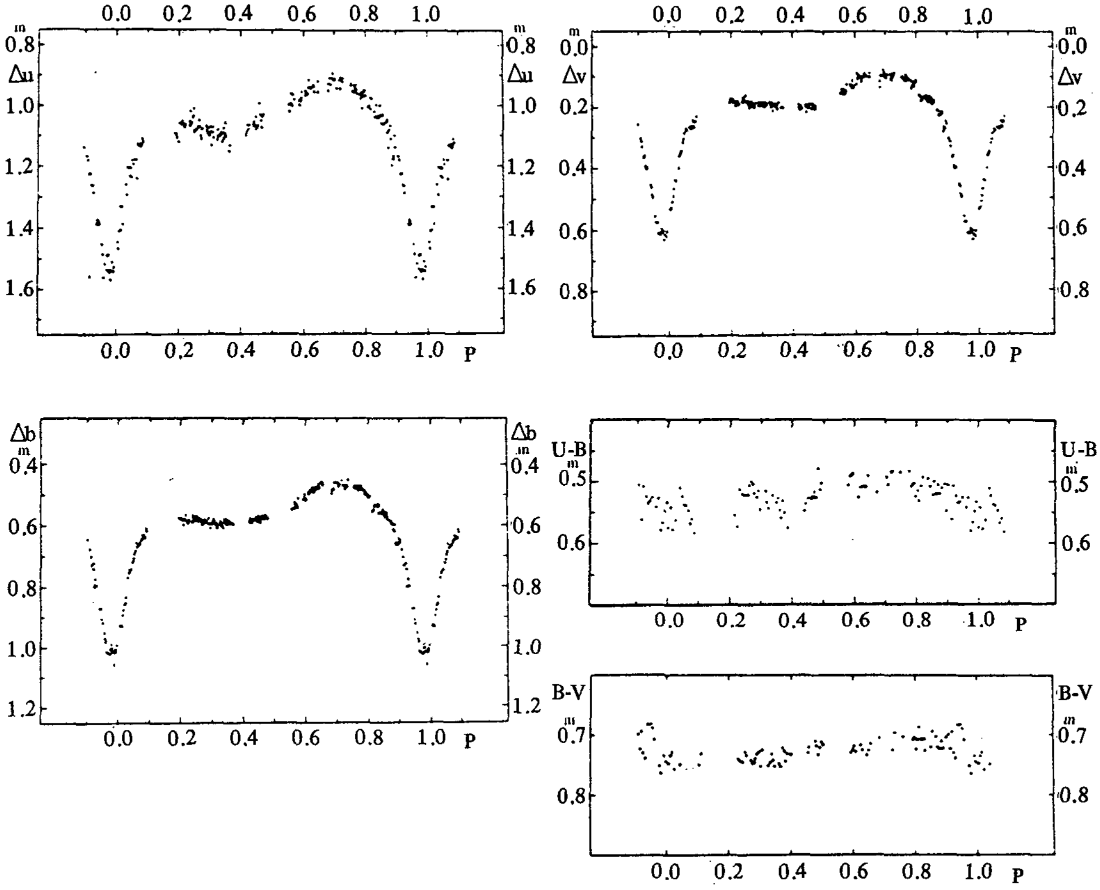

Fig. 1. The light-, and colour curves in 1975.

$$(\Delta\bar{m}) = \frac{1}{p}\int_0^p m(t)dt$$

shows a large long-term variability. The mean system brightness in blue light of $0\overset{m}{.}81$, which was observed in 1961 changed by $0\overset{m}{.}28$ until 1983 were the system(Δm) of $0\overset{m}{.}53$ was observed. This amplitude($0\overset{m}{.}28$) means a system brightness increase of 30% during 22 years and which took place almost monotonically since 1961. The average(Δm) of XY UMa was within 30 years by $0\overset{m}{.}65$, and $0\overset{m}{.}25$ in ΔB, and ΔV colours.

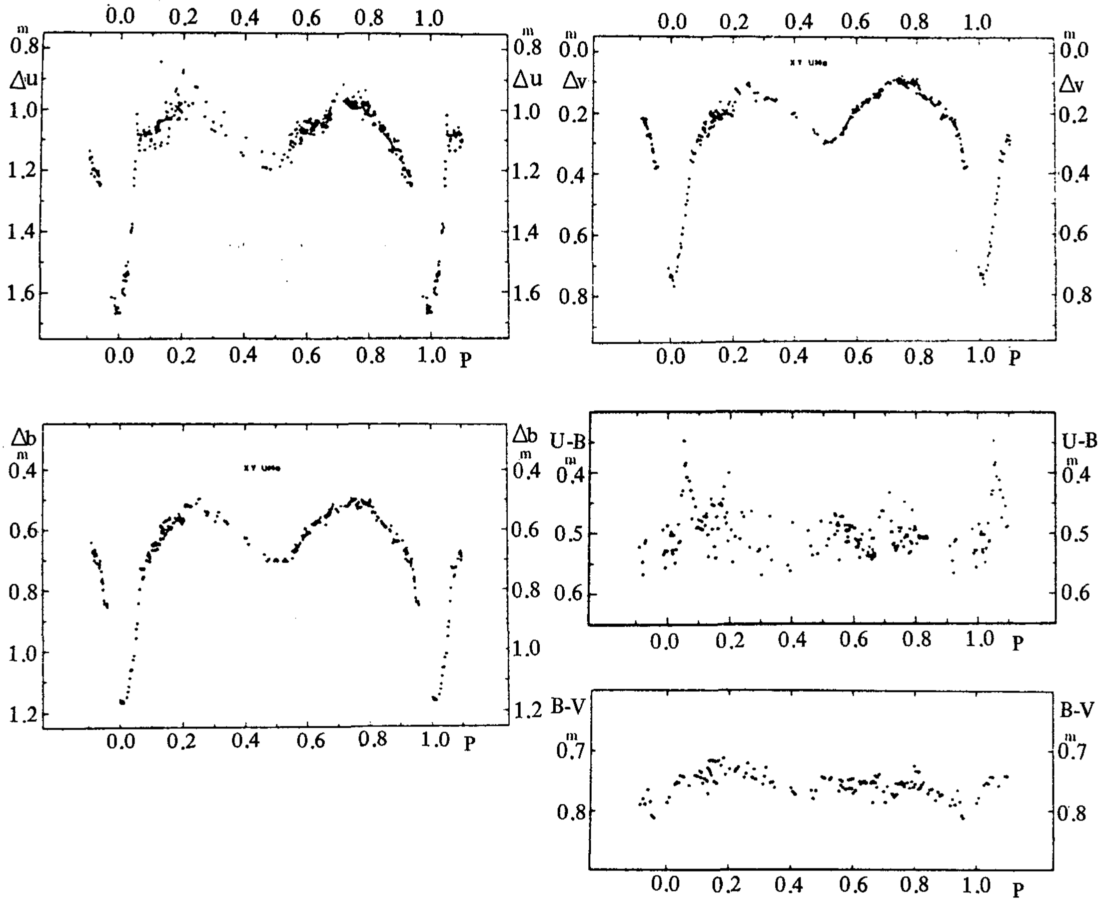

Fig. 2. The light-, and colour curves in 1976.

The depth of the primary(Fig. 5) and secondary minima(Fig. 6) show also pronounced variations. The minimum brightness of the primary phase of $1^{m}.31$ in blue colour was observed in 1961 and a maximum value of $0^{m}.87$ was reached in 1983. At the secondary eclipse the minimum value of $0^{m}.88$ was observed also in 1961, which is nearly as faint as the primary minimum observed in 1983. Its relevant maximum value of $0^{m}.55$ was observed in 1984 in the blue colour. As the secondary minimum turned out to be a total eclipse, the variations at this phase reflect only intrinsic variations of the primary component of the system. Therefore, the primary component of XY UMa in 1984 was almost 36% brighter than in 1961. *This means that the light curve variations of this system is due to the primary component. These variations show the largest amplitude of all*

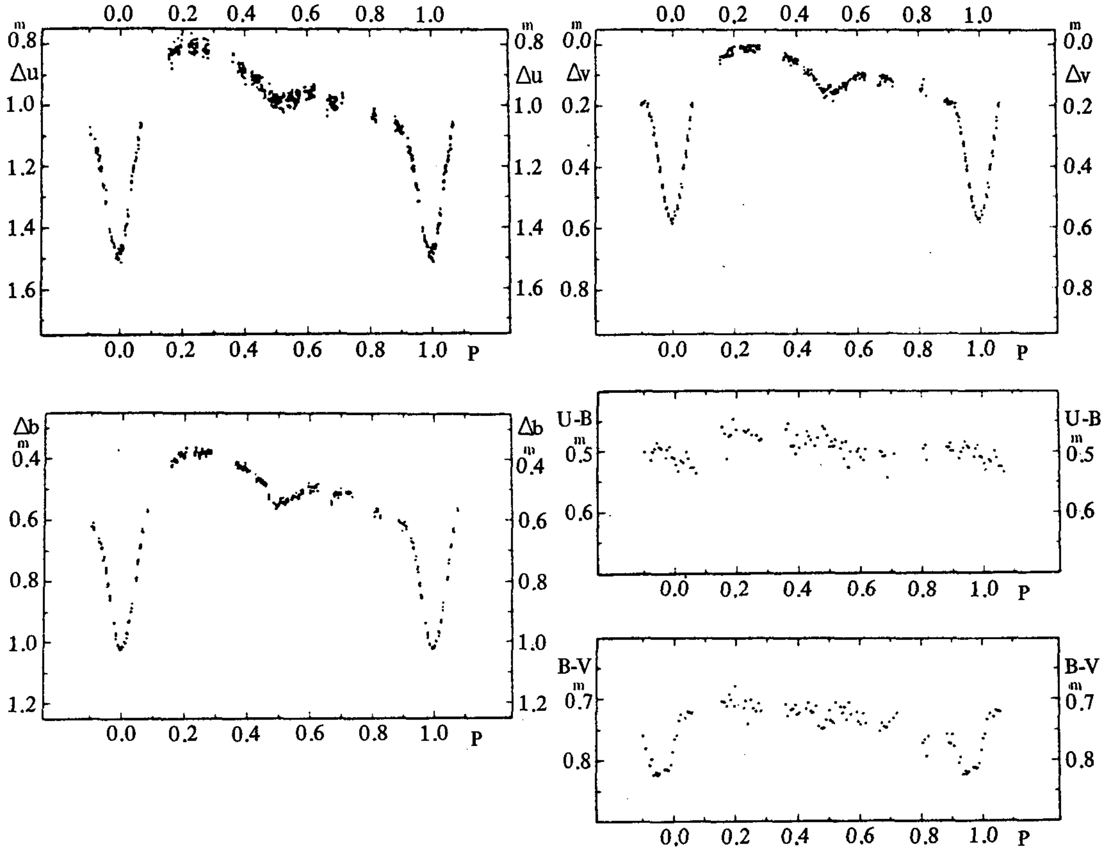

Fig. 3. The light-, and colour curves in 1984.

known eclipsing binaries of this type having an orbital period less than 1 day. The long term system brightness changes of cyclic nature is still an open question. It can only solved by further intensive observations in the coming decades. A similar system, in this respect, may be the RS CVn type star SV Cam(Cellino *et al.* 1985), though its long term variations are smaller than in XY UMa.

As is well known, many eclipsing binaries show brightness differences of the maxima, the so-called Mergentaler (1950) – O'Connell (1951) effect. For XY UMa it is shown in Figure 7, which gives the brightness difference of the light curve of the two maxima defined by:

$$\Delta M = \Delta m(\text{max. II}) - \Delta m\ (\text{Max. I}).$$

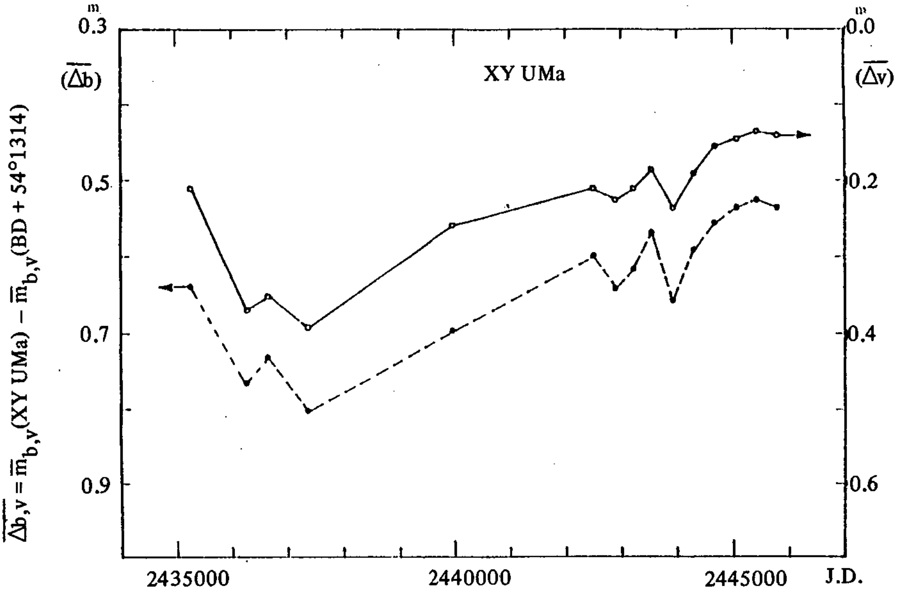

Fig. 4. The long-term variations of the mean system brightness Δb, Δv of XY UMa(in reference to the comparison star (BD +54°1314)). Left ordinate: Δb(symbol •), right ordinate: Δv(symbol o)

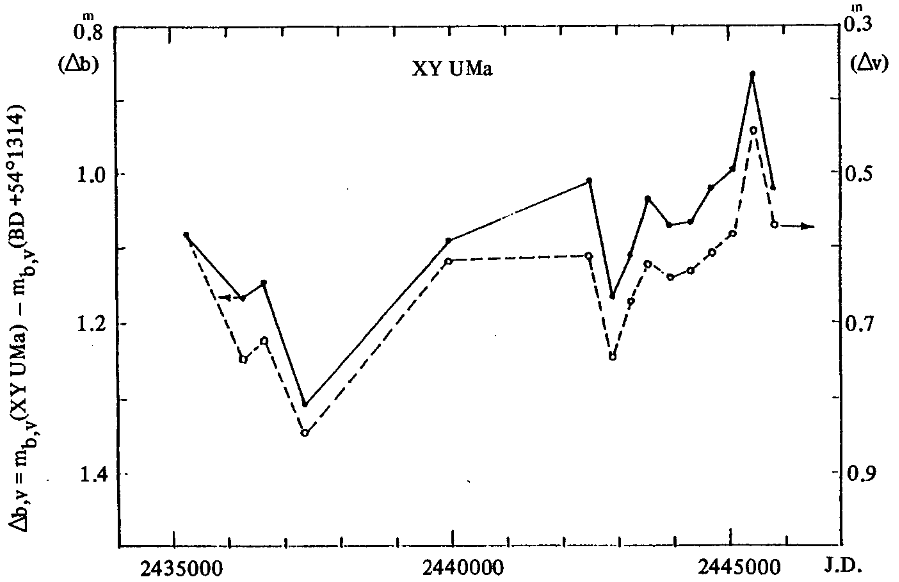

Fig. 5. The long-term variations of the primary minimum $\Delta b_{min.I}$, $\Delta v_{min.I}$ brightness of XY UMa(in reference to the comparison star BD +54°1314). Symbols like Figure 4.

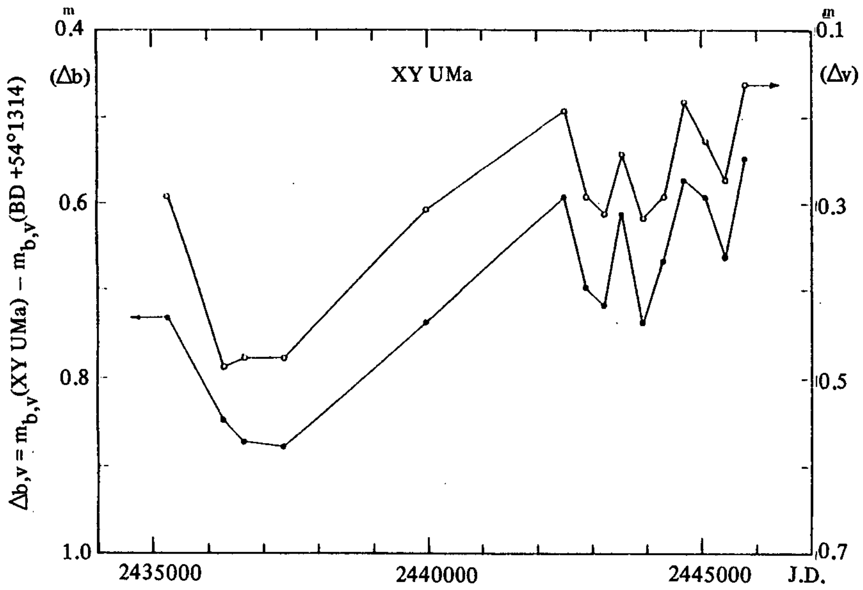

Fig. 6. The long-term variations of the secondary minimum $\Delta b_{\mathrm{min.II}}$, $\Delta v_{\mathrm{min.II}}$ brightness of XY UMa(in reference to the comparison star BD +54°1314). Symbols like Figure 4.

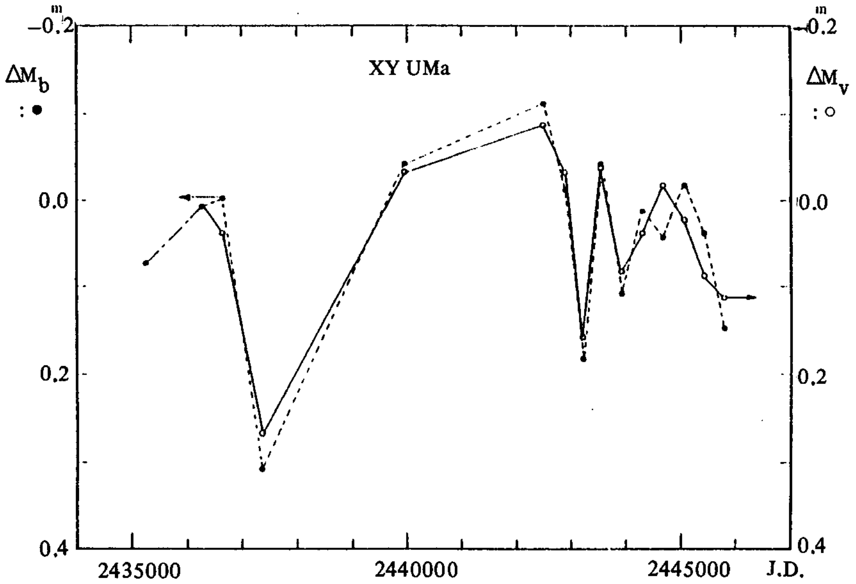

Fig. 7. The long-term variations of the difference between max.II and max.I brightness ($\Delta M_{b,v}=m_{b,v}$ max.II$-m_{b,v}$ max.I) of XY UMa. Symbols like Figure 4.

If ΔM is positive, the maximum after the primary minimum is brighter. Roberts(1906) first explained this by a periastron effect. However, Mergentaler(1950) argued that periastron effect cannot account for the asymmetry of the light curves of eclipsing variables. He instead postulated that the asymmetry is caused by the gaseous envelope surrounding one or both components.

In the case of XY UMa, these Mergentaler – O'Connell effects are very pronounced and time dependent variable. The observed light curve in 1975 exhibits a remarkable brightness depression at the phase interval from ϕ=0.1 to 0.35 compared with the corresponding phase range 0.65 to 0.85. According to the observations in November 1975 by Lorenzi and Scaltriti(1977), about 9 months apart, this depression was still present at that time. These brightness depressions(the so-called "plateau" which were observed in 1975 and 1984 at max.II and max.I phases) of the light curve are nearly as deep as the secondary minimum. In this respect, the light curve observed in 1975 seems to be a mirror image of the 1984 observations.

The adequate interpretation of these very pronounced long term variations of ΔM and/or plateau parts of the XY UMa is that there are sublumionus chromospheric areas of different sizes and at different locations on the receding and advancing hemispheres of the primary component of this system(Geyer 1976b). For example, if during a primary minimum, the spotted area is on the far side of the observer, a light curve of the 1984 type is observed. In this case the observer always sees parts of the spotted area and therefore the system brightness has its lowest value.

The colour index shows redder around the primary minimum than the secondary minimum. The extreme values of $\Delta(B\text{-}V)=0^{m}.10$ occur at the phase 0.76 in 1983, and $0^{m}.11$ at the phase 0.95 in 1984, respectively. Generally, the colour curve of XY UMa shows similar variations like the light curve, and around the primary minimum phase shifts back and forth. This is caused by the so-called Nordmann-Tikov effect (see Chapter V). Generally, such behaviour has been found in many late type stars(Bopp and Espenak 1979).

IV. Period constancy of XY UMa

A total of 22 times minimum of XY UMa are collected for the blue light curves which are determined by Pogson's method. The *O-C*'s are calculated using the light elements already given. Here the photoelectric times of minima are accurate to less than ± 0.001 day. Figure 8 shows the *O-C* diagram which were the first photoelectric time instants were obtained. Geyer(1977a) reported the orbital period of XY UMa to be constant in the time interval 1931 to 1975. As can be seen from Figure 8, the *O-C* diagram shows also no large variations from 1975 on. This diagram

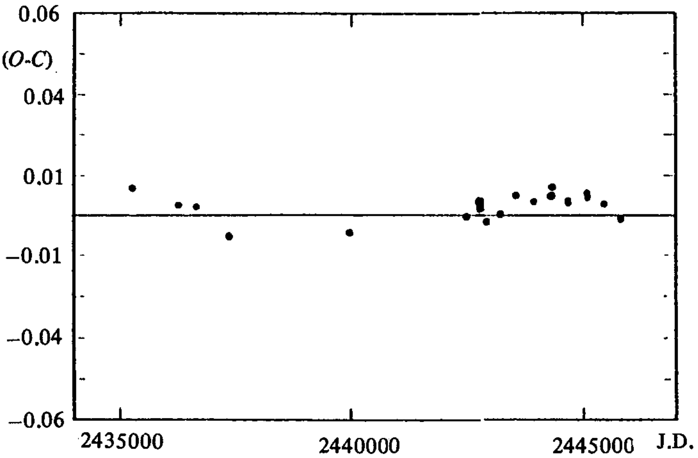

Fig. 8. (*O-C*)-diagram of primary minima of XY UMa from 1985 to 1984

shows that the orbital period of this system was constant within 1.6 percent of its period during at least 30 years.

The interpretation of period oscillations by time-limited mass transfer beyond the Roche equipotential lobes even for semidetached binaries is not very plausible, since such a process is lengthening the period and not shortening it. Whatever the physical cause for the minimum asymmetries may be, they give rise to spurious period variations on account of the following reasons: For an eclipsing binary the time instant of minimum is geometrically given by the smallest projected distance of the centers of the stellar discs of the components seen by the observer. If now the brightness distribution over the stellar disc is completely symmetric with regard to its geometric center, then the time instant of minimum derived from the light curve coincides with the geometric one. On the other hand, if we assume the inhomogeneous surface brightness, the photocenter determined now from an asymmetric minimum profile no longer coincides with the geometrical disc center. Such photometric time of minima give rise to periods for the individual cycles affected with systematic errors, if the position of the photocenter on the stellar disc is variable with time.

V. Minimum phase variations

There was a long debate and discussion about the so-called "Nordmann-Tikov" effect which consists in a difference of the time instants of minima derived from the light curves in different spectral ranges. Tikov(1908) explained this effect by dispersion of light in the interstellar medium, but which is not plausible at all. Several other explanations were summarized by Szafranie(1962).

Figures 9, 10 illustrate 12 photoelectric *U, B, V* times of minima of XY UMa since 1975 which show possible colour dependent shifts in the time instants of minima. All individual *U, B, V* time instants of primary minima were obtained by using Pogson's method as previously outlined. Here, ΔT is the difference between mean time instants of the 3 colours and the individual colour time instant. Figure 9 illustrates the correlation of $\Delta T(U)$ and $\Delta T(U)$, and Figure 10 shows the difference between $\Delta T(U)$, $\Delta T(U)$ versus time in Julian days. In Figure 9, one can immediately notice that there are "anti-correlation" between the $\Delta T(U)$ and $\Delta T(V)$. A linear least square solution for such a dependence yields.

$$\Delta T(U) = +0.00036 - 0.923 \cdot \Delta T(V);$$

having a correlation coefficient of R = –0.77. Figure 10 shows that the largest ΔT values occurred in 1976 though the light curves in *B* and *V* were most symmetric. In this year the minimum in ultraviolet light occurred earlier by 0.0013 day(112 sec), and in yellow later by 0.0019 day(164 sec) than expected. This is an indication that spots on the primary component were present during the minimum phase facing towards the observer.

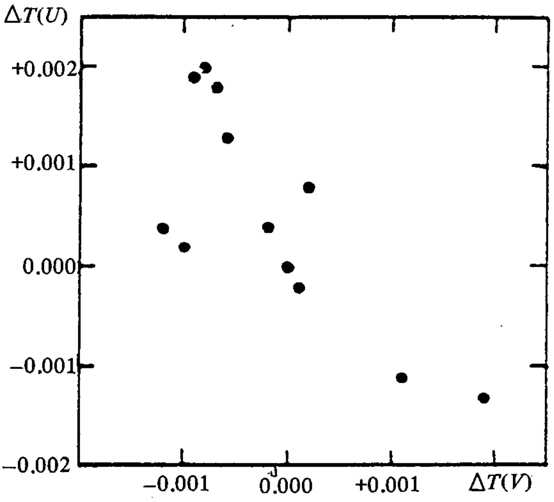

Fig. 9. Relation between $\Delta T(U)$ and $\Delta T(V)$. ΔT is the differences between mean time instant of the 3 colours and the individual colour time instants.

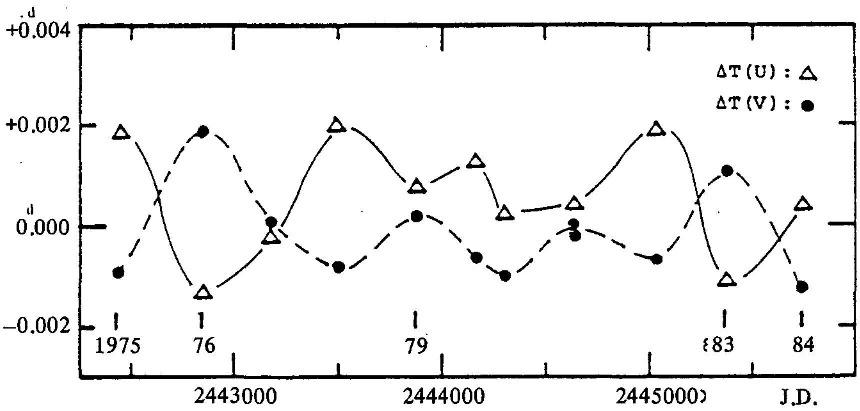

Fig. 10. Differences between $\Delta T(U)$ and $\Delta T(V)$ versus time in Julian days.

On the average, the mean value of the minima in ultraviolet occur later by 0.0005 day(43 sec), however, in yellow earlier by 0.0002 day(17 sec) than expected. The Figure 10 show also an oscillation of the individual time instants of the minima in the three colours around the mean values. This fact completely outrules the explanations of the "Nordmann-Tikov" effect by dispersion of light in interstellar space. As mentioned already by Szafranie(1962), such an explanation would contradict our knowledge about the physical conditions in interstellar space. Geyer (1980) explained this effect in the XY UMa as a consequence of the colour curve asymmetries.

Certainly, some eclipsing binary systems like XY UMa may show this phenomenon significantly larger than the observational errors. As already mentioned such an effect could be interpreted by the non-uniform star spot distribution on the photosphere of the primary component which during its occultation phase. The resulting superposition of the eclipsed photospheric flux and that of the spots should gives rise to different time instants of the minima in different spectral bands.

VI. The orbital and physical parameters of XY UMa

In order to interpret the observed light curve variations, it is necessary to determine the orbital elements and the average physical parameters of the components. The light curve in 1976 will be used to an appropriate analysis of the system constants on the basis of the spherical model because its light curve represents the most symmetric one observed during the last 30 years. The analysis of the rectified light curve in the blue and yellow spectral bands are used to determine the orbital elements of the system and the construction of the theoretical light curves using Russell and Merrill's(1952) and Schneller's(1959) methods.

The rectification coefficients, and orbital elements and physical parameters which were finally derived from the $\Delta \underline{B}$ and $\Delta \underline{V}$ light curves of XY UMa in 1976 are listed in Table 1. The photometric orbital solution shows that the primary minimum is caused by a transit eclipse.

Table 1. Rectification coefficients, orbital elements, and physical parameters of the components of XY UMa for the 1976 $\underline{B}$, $\underline{V}$ light curves.

	$\underline{B}$ light curve	$\underline{V}$ light curve
A_0	0.9279	0.9330
A_1	−0.0240	−0.0284
A_2	−0.0686	−0.0597
Max. brightness	$10\overset{m}{.}33$	$9\overset{m}{.}60$
Prim. min. brightness	$10\overset{m}{.}99$	$10\overset{m}{.}24$
Sec. min. brightness	$10\overset{m}{.}53$	$9\overset{m}{.}80$
Limb dark. coeff. x	0.85 (adopted)	0.70 (adopted)
k	0.539	0.563
α_o^{tr}	1.158	1.111
r_g	0.408	0.343
r_s	0.222	0.193
ϵ	0.373	0.348
i	83.51	85.39
L_g	0.931	0.904
L_s	0.069	0.096

VII. Roche limited surfaces and the chromospheric properties of XY UMa

The Roche equipotential surface of XY UMa which is derived from the system parameters and from table by Plavec and Kratochvil(1964) is shown in Figure 11. Here, the spectral type of the primary component is assumed to be G2V, the secondary is K5V according to Geyer(1980). Therefore we assume the masses $m_1 = 1.03\ m_\odot$ and $m_2 = 0.65\ m_\odot$, respectively, which yields a mass ration $q = 0.63$. This diagram shows that the photosphere of the components of this system are still whitin their Roche limit configuration which means this system is a detached one.

Yet there remains not enough space to form a ring of matter around the primary component with sufficient stability, which could be made responsible for the light curve phenomenology of

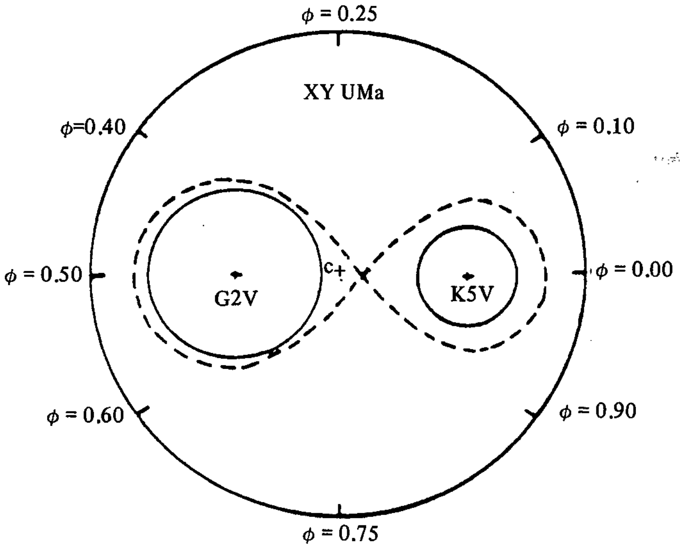

Fig. 11. Roche configuration of the components of XY UMa in the orbital plane according to a mass ratio q=0.63. The centers of the components and the center of gravity (c) are marked. The shown orbital phases refer to the absolute orbits of the components around c.

XY UMa. However, the chromosphere of the spot active primary fills already its relevant Roche lobe, and it is therefore semi-detached for the atmosphere and corona.

From the photometric and spectroscopic phenomenology of XY UMa and their interpretation, we generally conclude that it is caused by *magnetic star spots on the primary component* of the system and not by a common circumstellar envelope. Grating slit spectrograms(136 A/mm in the spectral range 3800 A to 6700 A) show at all phases a G2-5V type star without emission lines. Yet, since the H and K lines are only marginally visible on these spectra, nothing can be stated about the CaIIK line emission which would be of chromospheric origin. Therefore, from these findings it can be concluded that detectable circumstellar matter does not exist in this binary system. This conclusion is supported by polarimetric observations which also show that the system is on the average unpolarized(Geyer and Metz 1977). Furthermore, the star spots infected component must be mainly the primary component, as the brightness contribution of the secondary component to the total system brightness is less than 10%, as was shown in Chapter IV. In this respect, it should be noted that the observed phenomenology of XY UMa does not fit into the adopted scheme for RS CVn-binaries(Hall 1976). Accordingly, it should be called, according to the proposal of Geyer(1981), the "XY Ursae Majoris syndrome".

Although many of the properties of BY Draconis and RS CVn type stars seem not to be understood, it is generally accepted that the light changes in these stars are caused by the existence of subluminous spots on the star's photosphers(Bopp and Evans 1973; Vogt 1981; Dorren *et al.* 1984; Binnendijk 1984; and many others). Therefore in the next chapter we try to explain the XY UMa syndrome on the basis of the magnetic spot hypothesis.

VIII. Summary of discussion and conclusions

The short period(0.48 day) eclipsing binary XY UMa, of which photomeric observations exist now since 30 years, shows the most variable light curve of all known eclipsing binaries with orbital periods less than 1 day. All of the light curves show large variations not only between consecutive observing nights, but also varying from season to season. The mean system brightness changed between 1955 and 1984 by 0.27 mag. in *B* and 0.26 mag. in *V*, which means that there is a relative brightness increase of about 30% since the observed minimum value in 1961. The orbital period of this system, however, was constant during at least 30 years. The colour index shows also large variations. Generally, the minimum values of the colour curves show a phase offset in comparison to the light curve minimum. As the polarimetric and spectroscopic observations by Geyer and Metz(1977), and Geyer and Hoffmann(1980) do not give observational evidence of circumstellar matter within the system, these light and colour curve variations can only be explained by the presence of subluminous spots with time dependent different size and location on the primary component of this system.

The light curve obtained in 1976 represents the most symmetric one during the last 30 years. It seems that in this year the stellar activity was very low or, by chance, the spots were unifromly spread in longitude over the stellar surface. Therefore, this light curve was used to derive the system constants on the basis of the spherical model, and which served by means of the theoretical light curve as the reference for the interpretation of the light curve changes. With these system constants and the theoretical light curve, an attempt is made, to develop a spot model which will be described in the following paper.

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