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

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Abstract

The photometric behaviour of XY UMa, an eclipsing binary showing photospheric and chromospheric activity, has been described by spot hypothesis. They are based on the all the available *UBV* light curves, which were carried out by Geyer since 1955. A "spherical rectangular" spot model shows very pronounced spot activities during the last 30 years. On the average, the spot covered about 16% of the visible hemisphere. Observational evidence for photospheric and chromospheric activities on the XY UMa and related systems are also discussed.

I. Introduction to the characteristics of RS CVn-type stars

The best known examples of RS CVn-type systems are the RS Canum Venaticorum and the BY Draconis stars. RS CVn's are mostly post-main-sequence subgiants or giants, whereas the BY Dra's are pre-main-sequence dwarfs. These stars show also evidence of spot and activity cycles which are ranging from as short as 5 years to as long as 30 years on the RS CVn's(Vogt 1982). The asymmetry of the light levels out-of-eclipse regions show longitudinal migrations of spots, indicative of period changes to values both larger and/or smaller than the orbital(Rodono 1981). These photometric irregularities exhibit some characteristics common to "semi-detaches" system, but the observed photospheric dimensions of the components are often well inside their respective Roche limits, which means that these binaries, by their geometry should be classified as "detached systems"(Kopal 1955).

There is now strong evidence to suggest that large dark star spots are spatially associated with regions of enhanced chromospheric emission and flare activity. Moreover, it has been shown to be statistically related to rotation and age(Kraft 1967). On the Sun, there is a direct correspondence between areas with strong surface magnetic fields and areas of intense chromospheric Ca II H-and

K-emission(Skumanich *et al.* 1975). Wilson(1978) showed by monitoring of Ca II emission that many of the late type dwarf stars(up to 40%) show fluctuations which appear to be cyclic with periods of 5-10 years or slightly larger.

The emission reversal profiles of Ca II(H and K) and Mg II(h and k) lines are used as a diagnostic of the properties of chromospheric activities in these group of stars. These emission line reversals are present even during the quiescent state of chromospheric activity. These strong chromospheric and coronal activities, which may arise from an enhanced dynamo effect due to the rapid rotation of the relevant binary components are enforced by tidal interaction(Hall 1976, Linsky 1980). These binary components should have deep convection zones, and the combination of extensive convection with rapid rotation would lead one to expect strong magnetic activity produced by dynamo effects.

Flare like events(radiation outburst) in RS CVn systems with time scale of hours and even days or weeks, much longer than the common flare events on M dwarf stars like UV Ceti, are sometimes observed. The energy of these flare like events in chromospheric emission observed in G-K stars is similar to those seen in flare stars and large solar flares(Baliunas *et al.* 1981). The observations of RS CVn binaries in soft X-rays (Walter *et al.* 1980) and in radio wavelengths(Feldmann *et al.* 1978) indicate the presence of vigorous coronae and the occurrence of flares. These, combined with the starspot hypothesis in the light curves, suggest that these high temperature or high energy phenomena may be due to activated magnetic fields in the outer atmospheres of the component stars, as already found in the case of the Sun.

All these types of intrinsic variabilities in these binary stars can be explained basically by the transient presence of subluminous starspots and/or spot groups covering a significant portion(up to 30%) of the visible stellar hemisphere having temperatures 800-2000°K lower than the undisturbed photospheric regions. In the next chapter we try to explain the XY UMa syndrome on the basis of the magnetic spot hypothesis.

II. Spot modelling of the intrinsic light curve variations of XY UMa

1. Background of Spot Models

As early as in the mid 19th century, Zöllner(1865) proposed the spot model("slag theory") for the explanation of the Mira variables. The mathematical aspects of the spot theory have been given by Bruns(1882) for convex bodies without atmosphere, and by Russell(1906) for relevant bodies with atmospheres. Star spots were again proposed by Kron(1952) for the explanation of the light variations in red dwarfs. The procedure for spot modelling has been described by Torres and Ferraz Mello(1973). It consists in introducing a non-uniform distribution of surface brightness in the form of areas which are cooler than their surroundings. The observed light variation is then a result of the changing aspects for the observer in the distribution of the subluminous areas, their variation in shape with phase, and the average photospheric light level when the star rotates.

The simple geometric spot models to date have the following three basic types: single-circular spot, two circular or rectangular spots (i.e., parallel bound of longitude and latitude), and equatorial bands. A single circular spot of certain radius(*e.g.*, Budding 1977) is adopted for its center at stellar longitude λ, and latitude θ. A two spot model is sufficient to provide reasonable fits to the observed light curves having still many free parameters due to the ambiguity(*e.g.*, Dorren and Guinan 1982, Guinan *et al.* 1982). Eaton and Hall(1979) assumed that spots are distributed non-uniformly in size and in longitude in mid-latitude bands symmetric about the equator. Despite of nonuniformity of the geometrical form of the adopted spots, by they circular, elongated, or whatever shape, star spots of quite large extension are necessary on the stellar surface.

2. Analysis Procedure

In this chapter, the photometric behaviour of XY UMa will be described by one/two spot hypothesis. The method follows the procedure outlined by Torres and Ferraz Mello(1973), and Friedemann and Gürtler(1975), in which the total flux from the star is the sum of the contributions from the unspotted photospheric region and from the spots of assumed uniform brightness. In the case of XY UMa a minimum number of one/two spots is at least required. The theoretical light curve, which is assumed to be free from star spots, is therefore used as the reference to determine the distribution of star spots on the surface of the primary component from the observations as outlined in the previous papers(Lee 1988, henceforth Paper I). We assumed the spots to be of rectangular shape, for ease in computation, and located in the equatorial region. Here, one must remember, that most of the spots(as in the case of the Sun) tend to reside at latitudes $5^\circ < |\beta| < 45^\circ$ (Butterfly diagram) with the life times from a few days(small spots) to months (large spots). We also assume that the rotational period of the star is identical to the orbital period (synchronous rotation) and its rotation vector is parallel to the orbital angular momentum vector having an angle i to the line of sight.

The geometrical situation is illustrated in Figure 1 with the following definitions

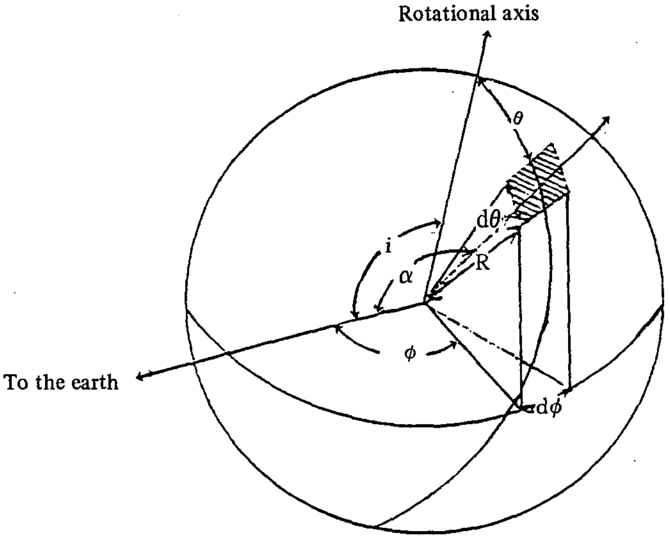


Fig. 1. The geometrical situation of the spot on the photosphere of a rotating star.

ϕ, θ = the longitude and the polar distance of a point on the stellar surface

i = the inclination of the rotational axis towards the direction to the observer $(0 < i < 90^\circ)$

R = the stellar radius

μ = the coefficient of the limb darkening

$B_\lambda(T)$ = the Planck function

T = photospheric temperature

T_s = spot temperature

α = angle between surface element vector and the line of sight vector.

We assume that the undisturbed photosphere radiates like a black body of temperature T, the spot with temperature T_s, and that the limb-darkening function in the spot is the same as for the photosphere given by the linear relation: $I = I_o(1-\mu+\mu\cos\alpha)$ where I_o is the intensity of radiation emerging normally from the surface. The total luminosity of the star without spot is then given by

$$\begin{aligned} L_\lambda &= R^2 B_\lambda(T) \int_{\theta=0}^{\pi} \int_{\phi=-\pi/2}^{\pi/2} (1-\mu+\mu\cos\phi\sin\theta)\cos\phi\sin^2\theta\, d\theta d\phi \\ &= \pi R^2 B_\lambda(T)(1-\mu/3) \end{aligned} \qquad \cdots\cdots\cdots\cdots \tag{1}$$

The contribution of the spot to the star's luminosity is on the other hand given by

$$\triangle L_\lambda = R^2\{B_\lambda(T)-B_\lambda(T_s)\} \iint_{\mathrm{spot}} (1-\mu+\mu\cos\alpha)\cos\alpha\sin\theta\, d\theta d\phi \qquad \cdots\cdots\cdots\cdots \tag{2}$$

The integration has to be done over the spot area. The angle α is

$$\cos\alpha = \sin i \sin\theta \cos\phi + \cos i \cos\theta \qquad \cdots\cdots\cdots\cdots \tag{3}$$

According to the astronomical definition, the magnitude difference between the spotted and the unspotted star is then given by

$$\triangle m_\lambda = -2.5 \log\left(1-\frac{\triangle L_\lambda}{L_\lambda}\right) \qquad \cdots\cdots\cdots\cdots \tag{4}$$

then with the aid of equations (1) and (2)

$$\triangle m_\lambda = -2.5 \log\left\{1-\frac{1-\exp\left\{\frac{h}{\lambda}\frac{c}{k}\left(\frac{1}{T}-\frac{1}{T_s}\right)\right\}}{\pi(1-\mu/3)} \iint_{\mathrm{spot}} (1-\mu+\mu\cos\alpha)\cos\alpha\sin\theta\, d\theta d\phi\right\} \qquad \cdots\cdots\cdots\cdots \tag{5}$$

The values of the limb-darkening coefficient are taken from Schneller's compilation(1959). Any small(about 0.1) difference in limb-darkening coefficient between star and spot will have no perceptible effect on the computed light curves(Bopp and Noah 1980). If we adopt the spectral type G2V for the primary component of XY UMa, the effective temperature of the unspotted photosphere of the primary component, as the observation suggests, will be around 5700 K(*e.g.*, Lamla 1965). For the inclination i we take the value of the derived system constants: $i=83\overset{\circ}{.}5$.

The (*O-C*)-light curve residuals represent the rotational variations due to the nonsymmetric brightness distributions on the photosphere of the primary component. Because of the complication in the minimum phase, due to the light loss through eclipse, we considered only phases outside of eclipses. These (*O-C*)-residual light curves can now be analyzed according to the above outlined method for the following spot parameters: number of spots, photospheric and spot temperature, and their longitude and latitude extensions.

3. Results and Interpretations

The obtained model parameters for all observed light curves in B-, and V-colours are given in Tables 1, 2. In the final light curve approximation, a spot temperature of 3700 K(ΔT=2000 K)

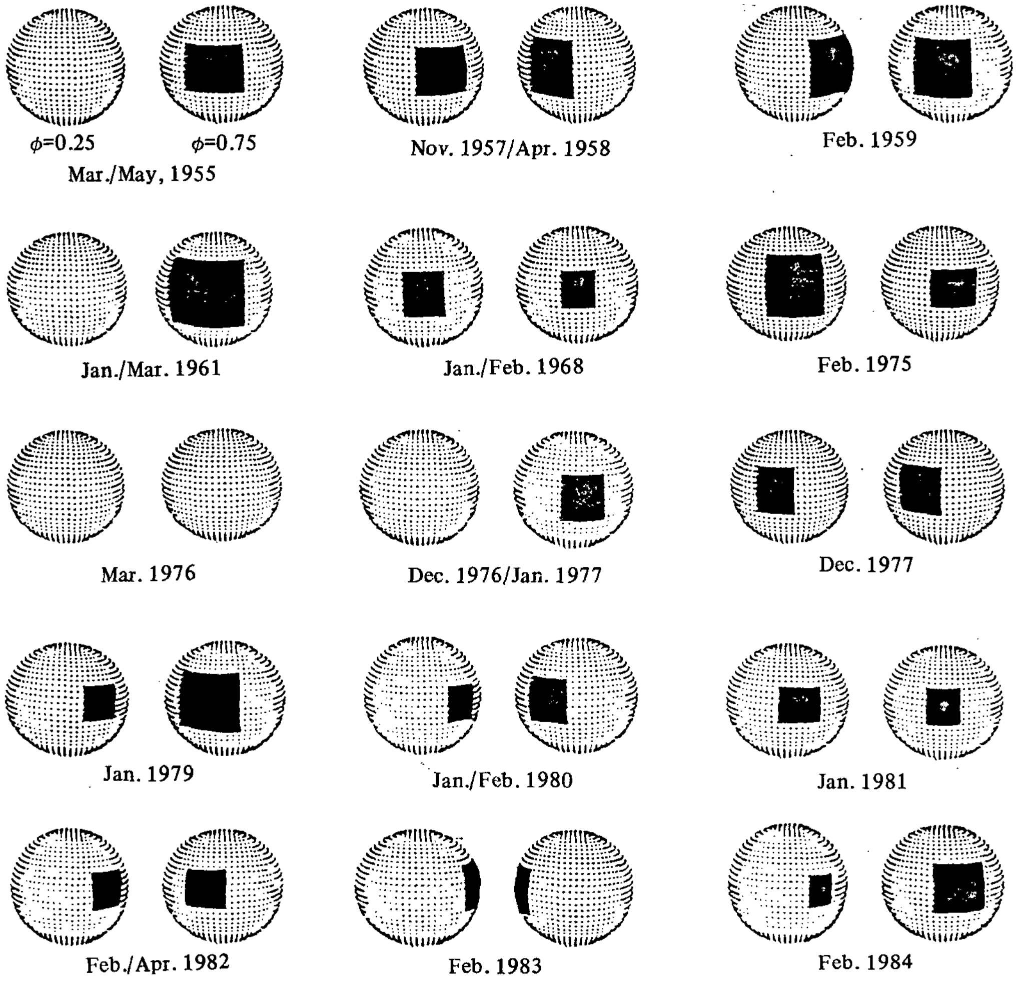
Table 1. Spot model parameters for B-colour (4350 Å) residual light curve from 1955 to 1984 in the spot model fits are: Star Temp.=5700 °K, Spot Temp.=3700 °K, $i = 83^{\circ}\!.5$, $x=0.85$

Season	Spot limits		Amplitude	Percentage of spot-area(unit: stellar-hemisphere)	Mid-phase	Number of assumed large scale spots
	Stellar longitude	Stellar polar distance				
1955	230°-288	61°-119°	0.150	15.6	259°	1
1958	77 -139	59 -121	0.165	17.4	108	2
	196 -264	56 -124	0.195	21.0	230	
1959	109 -179	55 -125	0.205	22.3	144	2
	213 -291	51 -129	0.245	27.5	252	
1961	239 -337	41 -137	0.330	41.2	288	1
1968	60 -112	64 -116	0.120	12.0	86	2
	246 -286	70 -110	0.080	7.7	266	
1975	60 -134	53 -127	0.225	24.9	97	2
	258 -304	67 -113	0.105	10.0	281	
1977	253 -305	64 -116	0.125	12.6	279	1
1978	41 - 95	63 -117	0.130	13.2	68	2
	207 -261	63 -117	0.130	13.2	234	
1979	102 -150	66 -114	0.110	10.1	126	2
	205 -281	52 -128	0.235	26.2	243	
1980	120 -168	66 -114	0.110	10.1	144	2
	200 -254	63 -117	0.130	13.2	227	
1981	78 -124	67 -113	0.095	9.2	101	2
	244 -296	64 -116	0.125	12.6	270	
1982	121 -167	67 -113	0.095	9.2	144	2
	219 -271	64 -116	0.120	12.0	245	
1983	148 -212	58 -122	0.180	19.2	180	1
1984	112 -148	72 -108	0.060	5.8	130	2
	254 -322	56 -124	0.200	21.7	288	

Table 2. Spot model parameters for V-colour(5550 Å) residual light curve from 1955 to 1984 in the spot model fits are: Star Temp.=5700 °K, Spot Temp.=3700 °K, i=83°.5, x=0.70.

Season	Spot limits		Amplitude	Percentage of spot-area(unit: stellar-hemisphere)	Mid-phase	Number of assumed large scale spots
	Stellar longitude	Stellar polar distance				
1955	234°-284°	65°-115°	0.110	11.6	259°	1
1958	75 -141	57 -123	0.175	19.8	108	2
	203 -273	55 -125	0.195	22.4	238	
1959	106 -182	52 -128	0.220	25.7	144	2
	208 -294	48 -132	0.260	31.2	252	
1961	236 -340	38 -142	0.340	45.4	288	1
1968	62 -110	66 -114	0.100	10.4	86	2
	254 -294	70 -110	0.070	7.2	274	
1975	72 -144	54 -126	0.200	23.0	108	2
	249 -299	65 -115	0.110	11.6	274	
1977	235 -297	59 -121	0.155	17.3	266	1
1978	42 -102	60 -120	0.145	16.0	72	2
	201 -259	61 -119	0.140	15.4	230	
1979	101 -159	61 -119	0.140	15.4	130	2
	192 -268	52 -128	0.225	26.3	230	
1980	122 -180	61 -119	0.140	15.4	151	2
	193 -253	60 -120	0.150	16.6	223	
1981	83 -133	65 -115	0.105	11.0	108	2
	243 -289	67 -113	0.090	9.3	266	
1982	123 -179	62 -118	0.130	14.1	151	2
	202 -258	62 -118	0.130	14.1	230	
1983	147 -213	57 123	0.175	19.8	180	1
1984	109 -151	69 -111	0.080	8.3	130	2
	255 321	57 -123	0.180	20.4	288	

appeared to be a reasonable choice, giving acceptable fits to the observed (*O-C*)-residual light curves. This temperature difference ΔT is similar to the temperature difference between the solar photosphere and umbral regions of sunspots. In order to schematically demonstrate this model, the distribution of spot areas(visible hemisphere of the primary component) for the observations in B are shown in Figure 2. In Figure 3, the long-term trends of longitudinal distribution of one/two spots, and the spot areas(%) of the visible hemisphere are shown since 1955.



ϕ=0.25 ϕ=0.75
Mar./May, 1955

Nov. 1957/Apr. 1958

Feb. 1959

Jan./Mar. 1961

Jan./Feb. 1968

Feb. 1975

Mar. 1976

Dec. 1976/Jan. 1977

Dec. 1977

Jan. 1979

Jan./Feb. 1980

Jan. 1981

Feb./Apr. 1982

Feb. 1983

Feb. 1984

Fig. 2. Schematic representation of the distribution of star spots on the photosphere of the primary component of XY UMa in B at phases ϕ=0.25 and 0.75, resp.

The spot modelling of the light curves of XY UMa shows very pronounced spot activities during the last 30 years. As already mentioned, the largest spot occurred in 1961: one large spot at a stellar longitude 288° with an area of about 41% in B, and 45% in V on the stellar hemisphere

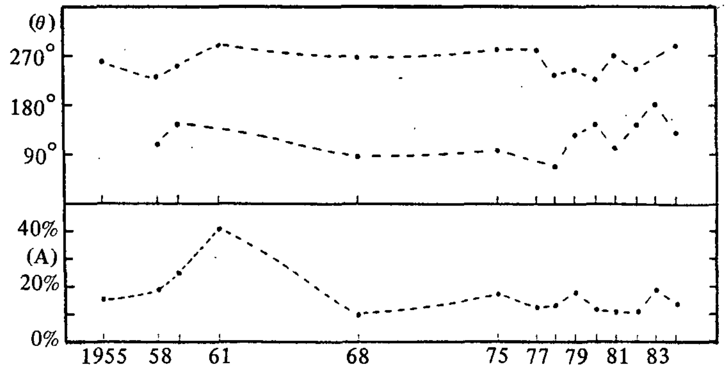


Fig. 3. The longitude distribution (θ) of spots No.1 and No.2 (top part) of B-light curves, and total spot area (A) (lower part) of the primary component XY UMa in the years 1955-1984.

which produced amplitudes of $0^m.33$ in B, and $0^m.34$ in V in the (*O-C*)-residual curves. The spot location on the stellar surface depends primarily on the changing shape and amplitude of the (*O-C*)-residual light curves. If the spot would be located at the pole or in circumpolar region, and with the large orbital inclination of the XY UMa system, large parts of the spotted area would be always visible and not such a strong light curve deformation like in 1961 could be seen. This finding is therefore in favour of our assumption that the spots are assembled along low stellar latitudes, not exceeding ±50°. By analogy to the Sun, spots may form at the beginning of the new spot cycle at the higher latitudes and then drift toward the equator during the course of a spot cycle. It would generally be expected that spots at relatively low latitudes would rotate slightly faster than orbital synchronously, whereas spots at relatively high latitudes would rotate slightly slower than synchronously. Therefore, as was mentioned before, irregular or random distribution of star spots in stellar longitude and latitude with different sizes would produce the nonuniform luminosity distribution on the component in the course of time which should give rise to the period changes and also to unsymmetric light curves.

The distribution of the star spots in the two spot model is characterized by very large separations in stellar longitude. The largest longitudinal separation(180°) in B-colour occurred in 1968, and the smallest(83°) in 1981. On the average, the mean longitudinal spot position in B-colour occur about 115° and 260°, respectively. The long-term variation of the longitudinal distribution and the values of spot area show similar changes in B-colour (Figure 3) which was to be expected on account of the assumptions. From the analysis of some RS CVn type stars, Dorren *et al.*

(1984) showed that the observed unsymmetric light curve variations result mainly from the relative longitudinal motion of star spot groups.

On the average, the spot coverage of XY UMa is about 16.2% in B, and 17.8% in V of the visible hemisphere within the 30 years photoelectric record. Such large sized spots seem reasonable to assume not a single spot, but a group of individuals extending one predominantly in longitude. In many RS CVn type stars a large portion of spots(up to 30%) is suggested, and a deep convective zone may exist on the spotted star (Mullan 1974).

Owing to many free parameters, it is difficult from this simple picture of spot model to say exactly how the spots are distributed on the stellar surface. However, if one or more parameters can be estimated independently, as the inclination of the system from light curve solutions and the longitude distribution from (*O-C*)-residual light curves, reasonably significant solutions can be obtained. Therefore, this spot modelling of XY UMa seems fairly reasonable to explain the behaviour of the observed light curve variations.

III. Summary of discussion and conclusions

This spot model which we made, the size and position of the spots primarily depend on the assumed values for the spot temperature, the derived orbital inclination of the system, and the changing shape and amplitude of the (*O-C*)-residual light curves. The photospheric temperature was taken to be 5700 K, appropriate for a G2V star, and the (*O-C*)-residual light curve amplitudes in the two wavelengths were calculated using the spot model for different values of the photospheric temperature, and varing spot areas. The adopted temperature of 3700 K(cooler than the photosphere by 2000 K) is reasonable to explain the (*O-C*)-residual light curve amplitude, and which is consistent with the solar value of spot temperatures. In some RS CVn binaries and many related flare stars, the temperature difference ΔT has been estimated to be about 500-2000 K (Eaton and Hall 1979, Bopp and Noah 1980).

The mean spot area of about 16% in B, and 18% in V is indicated to yield the derived (*O-C*)-residual light amplitudes. The distribution of star spots preferentially formed at limited stellar longitudes(about 115° and 260°, respectively). According to Vogt(1982) spot and activity cycles in the RS CVn systems(with orbital periods between 2-7 days) range from 5 to 30 years, and such systems show spot cycle lengths increasing linearly in accordance with Geyer(1976, 1980a) that a spot cycle of about 4 years is present in the XY UMa system, superposed onto a more than 30 years system brightness variations.

Due to the spot activity in XY UMa up to 30% of the total brightness in the optical wavelength bands may be blocked off than the observational errors. These so-called missing flux (Hartmann and Rosner 1979) has to be re-radiated in other spectral ranges, predominantly in the euv- and/or radio wavelength bands. In the latter case Geyer(1977) observed a strong radio source near the position of XY UMa. Later on, this radio source turned out to be a quasar. Therefore, he obtained IUE spectrograms to explain the UV radiation from the XY UMa system(1980b). The most important lines are those of the Mg II resonance doublet and of Fe II emission line blends. The comparison with nearly simultaneous optical photometric and spectroscopic observations exhibits the interaction of the photospheric and chromospheric activity, the latter of which is much enhanced whenever the optical light shows depressions. There is now much evidence to suggest that large dark star spots are spatially associated with regions of enhanced chromospheric emission, and there are many other reports of such correlations between chromospheric emission and spot visibility. Baliunas and Dupree(1982), for example, found λAnd that the phase of maximum spot visibility corresponds with enhancement of both Ca II K emission and the ultraviolet transition region lines.

According to Linsky(1983, 1984) and Charles(1983) the RS CVn and similar binaries show their activities in the visible light, radio, IR and soft X-ray wavelength bands. Recent UV and X-ray observations with the UV Explorer(IUE) and other satellites(Einstein) have been found abnormally high emission in UV chromospheric and transition region lines and soft X-ray continuum, also even during the quiescent phase(Hartmann 1980, Dupree 1981). The atmospheric structure of these stars – chromosphere, transition region and corona – is only quantitatively different from the solar one. Typically, a factor of ten additional nonradiative heating and huge regions covering a large fraction of the stellar surface are inferred(Linsky 1980). Variable radio emission has been also recently detected from several RS CVn binaries(Feldmann 1983). The radio fluxes are smoothly varying with scales of hours to a few days.

Further continuous observations in different spectral regions, from radio to euv wavelengths, are required for our better understanding of the nature of stellar activity of XY UMa and also related binary systems.

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