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PROBABLE LONG-TERM STARSPOT ACTIVITY OF THE W UMa SYSTEM U PEGASI

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1. INTRODUCTION

The variability of U Peg ($BD + 15°4915$) was discovered by Chandler (1895). The system belongs to the W sub-class of the W UMa-type eclipsing binaries. From its photoelectric observations it was found that its light curves are variable. Struve *et al.* (1950) estimated the radial velocities of the two involved components from four spectra of this system, but the latest and more accurate radial velocity observations were made by Lu (1985).

Some of the light curves of the system have been analysed previously by different methods; e.g. using the classical Russell model (as Binnendijk, 1960), Kopal's frequency domain techniques (as Lafta *et al.*, 1986) or W-D code (as Russo *et al.*, 1982, Zhai *et al.*, 1984, Zhai *et al.*, 1988). In the present paper, photoelectric observations (Binnendijk, 1960, Rigterink, 1972 and Zhai *et al.*, 1984) of U Peg were analysed in order to study the activity of the system.

2. THE LIGHT-CURVE ANALYSIS AND THE RESULTS

To analyse these asymmetric light curves, probably deformed by the presence of spotted areas on the components, we used Djurašević's (1992a) programme generalised to the case of an overcontact configuration (Djurašević, *et al.*, 1998). The degree of overcontact is defined in the classical way (Lucy & Wilson, 1979) as:

$$f_{over}[\%] = 100 \cdot (\Omega_{1,2} - \Omega_i)/(\Omega_o - \Omega_i),$$

where $\Omega_{1,2}$, Ω_i, and Ω_o are the potentials of the common photosphere and of the inner and outer contact surfaces, respectively. The programme is based on the Roche model and the principles arising from the paper by Wilson & Devinney (1971). The light-curve analysis was performed by applying the inverse-problem method (Djurašević, 1992b) based on Marquardt's (1963) algorithm.

In the inverse problem the mass-ratio of the components was fixed at Zhai *et al.*'s (1988) simultaneous (photometric and radial velocity) solution $q = m_c/m_h \sim 3.019$. Based on the spectral type (G2 V; Zhai *et al.*, 1988) the temperature of the less-massive (hotter) component, T_h, was set at 5800 K. The indexes $_{\mathbf{h,c}}$ refer to the hotter (less-massive) an cooler (more-massive) component respectively. The values of the limb-darkening coefficients were derived from the stellar effective temperature and surface gravity, according to the given spectral type, by using the polynomial proposed by Díaz-Cordovés *et al.* (1995). During the optimisation process, according to the temperature changes we have an automatic recomputation of the limb-darkening. Following Lucy (1967), Rucinski (1969), and Raffert and Twigg (1980), the gravity-darkening coefficients of the stars ($\beta_{h,c}$) and their albedos ($A_{h,c}$) were set at the values of 0.08 and 0.5 respectively, appropriated for stars with convective envelopes.

The present analysis yiels $F_h > 1$ for the filling coefficient in the critical Roche lobe, i.e., the overcontact configuration. Tidal effects were expected to contribute to synchronisation of the rotational and orbital periods. Therefore, in the inverse problem we adopted $f_{h,c} = \omega_{h,c}/\omega_K = 1.0$ for nonsynchronous rotation coefficients, where $f_{h,c}$ is the ratio of the components angular rotation rate ($\omega_{h,c}$) to the Keplerian (ω_K) orbital revolution rate.

Among the light curves that were analysed Zhai *et al.*'s (1984) photolectric light curves were the most symmetrical and less distorted ones. In the subsequent analysis, these light curves (very probably clean from spot effects) were used as referent ones.

In previous versions of our programme for the light-curve analysis, there were two different possibilities in the application of the stellar atmosphere model with respect to the treatment of the radiation law: the simple black-body theory, or the stellar atmosphere models by Carbon & Gingerich (1969). Our current version of this programme uses the new promising Basel Stellar Library (BaSeL). We explored the "corrected" BaSeL model flux distributions, consistent with extant empirical calibrations (Lejeune *et al.*, 1997, 1998), with a restricted range of effective temperature $2000K \leq T_{eff} \leq 35000K$, metallicity, $-1 \leq [Fe/H] \leq 1$ and surface gravity, $3 \leq log\ g \leq 5$. The surface gravities can be derived very accurately from the masses and radii of the CB stars by solving the inverse problem of the light-curve analysis, but the temperature determination is related to the assumed metallicity and strongly depends on photometric calibration.

In the inverse-problem solving, the fluxes were calculated in each iteration for current values of temperatures and $log\ g$ by interpolating in both of these quantities in atmosphere tables, as an input, for a given metallicity of the CB components. The metallicity of the involved CB components can be different. Because of that, we can use individual, different tables as an input, for each star, and, in that way, to choose the best calculations for its particular atmospheric parameters. Compared to Vaz *et al.* (1995) our two-dimensional flux interpolation in T_{eff} and $log\ g$ is based on the application of the *bicubic spline* interpolation (Press *et al.*, 1992). This proved itself as a good choice.

By choosing and fixing of the particular input switch, the programme for the light-curve analysis can be simply redirected to the Planck or CG approximation, or to the more realistic BaSeL model atmospheres. A disagreement obtained between individual B and V solutions decreases if we introduce the "corrected" BaSeL model flux distributions. Also, a change in the assumed metallicity causes a noticeable change in the predicted stellar effective temperature. In the case of U Peg, for the metallicity of the components we assumed $[Fe/H]_{h,c} = 0.2$. The results given here were obtained by using this stellar atmosphere approximation.

System's basic parameters, obtained in this way by analysing Zhai *et al.*'s (1984) referent light curves, were used as starting points in the inverse-problem solution for other, more or less deformed and asymmetrical, light curves. In all observations the same comparison star ($BD + 14^o5078$) was used. Because of that, other light curves were scaled to the light level of the referent Zhai's light curves (for the unspotted configuration of the system) at orbital phase 0.25, and their analysis begun by optimisation of the spot's parameters.

Since the results of the light-curve analysis strongly depend on the choice of the adopted working hypothesis, the analysis was carried out within the framework of several hypotheses (bright and dark spotted areas on the primary or on the secondary). We rejected those hypotheses which produced significantly different values of the parameters for the system and active spotted areas, estimated by analysing the individual light curves in the B and V passbands. Finally, we chose the Roche model with dark spotted areas on the more-massive (cooler) component as the optimum solution. Within this hypothesis the analysis of the light curves yield mutually well consistent parameters of the system and active regions in the B and V passbands. Consequently, the presence of dark spotted areas on the secondary can be taken as possible.

The parameters derived from the present light-curves analysis are listed in Table 1. The errors in parameters' estimations arised from the nonlinear least-squares method, in which the inverse-problem method is based on.

Fig. 1. (Left) presents the best fit of observations (LCO) by the optimum synthetic light curves (LCC),following from the inverse-problem solutions for individual light curves. The light curves are scaled to the brightness of the referent (Zhai *et al.* 1984) light curves (LCR) at the orbital phase of 0.25. The final residuals (O-C) between the observed (LCO) and optimum synthetic (LCC) light curves are given, too. The right-hand column on this panel shows the view of U Pegasi's Roche models, obtained with the parameters estimated by analysing the corresponding light curves. By using such plots, one sees how would a CB system look like at a noted orbital phase, chosen so that the spots are visible.

3. DISCUSSION AND CONCLUSIONS

Our light-curves analysis shows that during the deeper (primary) minimum the cooler (more-massive and larger) component eclipsed the hotter (less-massive and smaller) one. The solutions presented above show that U Peg is in the overcontact configuration ($f_{over}[\%] \sim 11\%$), with small temperature differences between the components

Table 1. The results of the analysis of the U Peg light curves obtained by solving the inverse problem for the Roche model with spotted areas on the morer-massive (cooler) component.

Quantity	1958 (B-filter)	1958 (V-filter)	1970 (B-filter)	1970 (V-filter)	1978 (B-filter)	1978 (V-filter)
$\Sigma(O-C)^2$	0.04568	0.03525	0.1991	0.1774	0.004926	0.005273
$A_{S1} = T_{S1}/T_c$	0.69±0.03	0.66 ±0.03	0.830±0.006	0.784±0.008	0.80±0.02	0.81 ±0.01
θ_{S1}	18.6±0.2	19.8 ±0.2	16.6±0.2	18.1±0.2	8.1±0.2	9.7 ±0.2
λ_{S1}	210.8±2.0	217.0 ±1.8	331.1±1.6	336.2±2.0	202.0±3.0	215.3 ±5.0
φ_{S1}	58.1±0.8	61.0 ±0.6	57.5±0.8	68.4±0.7	10.9±2.0	8.6 ±3.6
$A_{S2} = T_{S2}/T_c$	0.800±0.007	0.769 ±0.007	0.773±0.012	0.772±0.009	0.65±0.1	0.71 ±0.03
θ_{S2}	25.6±0.2	27.6 ±0.2	13.7±0.1	13.5±0.1	10.5±0.2	11.8 ±0.3
λ_{S2}	349.5±2.6	360.7 ±2.9	194.8±1.1	195.8±1.2	33.2±2.9	39.2 ±3.6
φ_{S2}	75.1±0.5	78.3 ±0.4	33.7±1.5	29.9±1.5	52.7±1.8	62.2 ±1.8
T_c	5649± 7	5626 ± 8	5599 ± 5	5576 ± 6	5613± 5	5573 ± 7
F_h	1.016±0.000	1.018 ±0.000	1.018±0.000	1.018±0.000	1.018±0.000	1.018±0.000
i	76.3±0.1	76.0 ±0.1	76.0±0.06	76.0±0.06	76.0±0.06	76.00±0.06
u_h	0.74	0.66	0.74	0.66	0.74	0.66
u_c	0.75	0.67	0.75	0.67	0.75	0.67
$\Omega_{h,c}$	6.5785	6.5696	6.5696	6.5696	6.5696	6.5696
Ω_{in}	6.6409	6.6409	6.6409	6.6409	6.6409	6.6409
Ω_{out}	6.0217	6.0217	6.0217	6.0217	6.0217	6.0217
$f_{over}[\%]$	10.09	11.52	11.52	11.52	11.52	11.52
R_h	0.273	0.273	0.273	0.273	0.273	0.273
R_c	0.452	0.453	0.453	0.453	0.453	0.453
$L_h/(L_h+L_c)$	0.321	0.318	0.327	0.318	0.320	0.316

FIXED PARAMETERS:

$T_h = 5800K$ - temperature of the less masive (hotter) star,

$f_h = f_c = 1.00$ - nonsynchronous rotation coefficients of the components,

$q = m_c/m_h = 3.019$ - mass ratio of the components,

$\beta_{h,c} = 0.08$ - gravity-darkening coefficients of the components,

$A_{h,c} = 0.5$ - albedo coefficients of the components.

$[Fe/H]_{h,c} = 0.2$ - accepted metallicity of the components

Note: $\Sigma(O-C)^2$ - final sum of squares of residuals between observed (LCO) and synthetic (LCC) light curves, $A_{S1,2}$ - spot's temperature coefficients, $\theta_{S1,2}$, $\lambda_{S1,2}$, $\varphi_{S1,2}$ - spot's angular dimensions, longitudes and latitudes (in arc degrees), F_h - filling coefficient for the critical Roche lobe of the hotter star, T_c - temperature of the cooler star, i - orbit inclination (in arc degrees), $u_{h,c}$ - limb-darkening coefficients of the components, $\Omega_{h,c}$ - dimensionless surface potentials of the common photosphere, Ω_{in}, Ω_{out} - the potentials of the inner and outer contact surfaces respectively, $f_{over}[\%] = 100 \cdot (\Omega_{1,2} - \Omega_{in})/(\Omega_{out} - \Omega_{in})$ - degree of overcontact, $R_{h,c}$ - polar radii of the components in units of the distance between the components' centres and $L_h/(L_h + L_c)$ - luminosity of the hotter star (including spots on the cooler one).

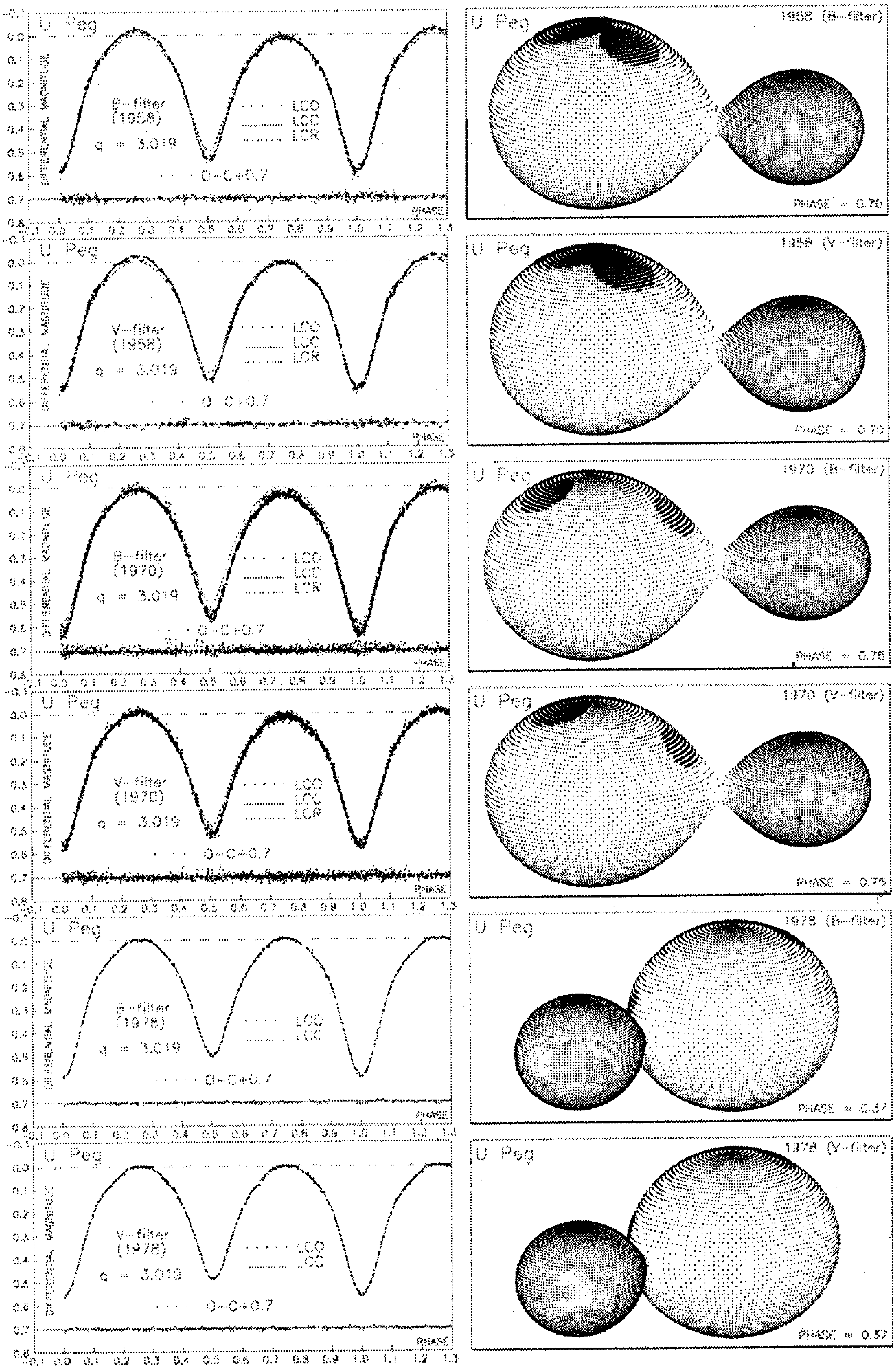

Fig. 1. **Left** - Observed (LCO), referent (LCR) and final synthetic (LCC) light curves of U Peg with O-C residuals obtained by analysing B and V observations within the framework of the Roche model with spotted areas on the more massive cooler star; **Right** - The view of the Roche model for the U Peg at noted orbital phases obtained with parameters estimated by analysing the corresponding light curves.

($\Delta T \sim 150 - 230K$). Since the mass ratio is estimated to $q = m_c/m_h \sim 3.019$, this suggests the energy transfer between components. It is evident from Table 1. and from Fig. 1. that the Roche model with two spotted areas on the cooler component gives a very good fit of the observed light curves. At this point one can see that there are no certain differences between the solutions obtained by analysing individual light curves in different passbands (B and V). So, the model suggested here can be accepted in the simulation of real observations.

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