

Long-term starspot evolution, activity cycle and orbital period variation of AR Lacertae

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Abstract. A sequence of AR Lac seasonal light curves covering the period 1967–1992 is analysed in the framework of the starspot hypothesis to derive the spot distribution and evolution on the component stars. The adopted approach makes use of the Maximum Entropy and Tikhonov principles to compute maps of the stellar photospheres exploiting also the eclipse scanning technique. Reliable results on the distribution of the spotted areas can be derived through a critical comparison of the maps obtained by the above quoted regularizing criteria. Satisfactory fits are computed assuming that spots are located on the photospheres of both components and that their unspotted luminosity ratio in the V band is: $\frac{L_1}{L_2} = 0.59 \pm 0.03$.

The derived yearly spot distributions are analysed to infer general activity characteristics. The spot patterns appear to consist of two components, one uniformly and the other non-uniformly distributed in longitude, the latter suggesting the presence of preferential longitudes. Starspots at latitudes higher than $\sim 50^\circ$ are not needed to reproduce the photometric modulation. On the less luminous primary we find evidence for quite compact spotted areas ($\sim 30^\circ - 40^\circ$ in diameter) which are occulted during primary eclipses. On the more luminous and larger secondary, spots cluster preferentially around longitudes $\sim 60^\circ$, $\sim 180^\circ$ (i.e., around the substellar point) and $\sim 300^\circ$ without showing evidence for a regular migration. The variation of the spotted area does not give a significant evidence for an activity cycle on the primary, whereas a possible modulation on a time scale of about 17 yr may be present on the secondary.

The spatial association among photospheric spots and chromospheric and coronal plages (as detected in the UV and X-ray spectral domains) is significant for the large active region around the substellar point on the secondary and is suggested also for the smaller starspots on the secondary and primary components.

A possible relationship between the orbital period modulation with a period of ~ 35 yr and an activity cycle on the secondary component is tentatively suggested and, if confirmed by future observations, can provide further support to recently

proposed models for the connection between magnetic activity and orbital period variations.

Key words: stars: activity – binaries: close – stars: individual (AR Lacertae) – starspots

1. Introduction

AR Lacertae (HD 210334, BD +45° 3813) is an eclipsing binary (G2 IV + K0 IV) belonging to the RS Canum Venaticorum class of variable stars first introduced by Hall (1976). Such a class comprises binary systems showing the characteristic signatures of an intense solar-like activity with energy scales and flux variations up to two or three orders of magnitude larger than on the Sun (Linsky 1988, Guinan & Gimenez 1993, Strassmeier et al. 1993 and references therein).

In addition to intense and time variable H α , Ca II H&K and Mg II h&k emissions, AR Lac shows an out-of-eclipse light modulation in the optical band, as well as radio, EUV and X-ray emissions with variations on several time scales (e. g., Rodonò et al. 1986, Walter et al. 1987, Strassmeier et al. 1993, Ottmann et al. 1993, Lefèvre et al. 1994, Mutel et al. 1993, Ottmann & Schmitt 1994, Christian et al. 1996).

Due to its brightness in all spectral domains, from X-rays to infrared and radio (Lefèvre et al. 1994, Mitrou et al. 1996), the presence of eclipses and the short orbital period of ~ 1.9832 days, AR Lac is an ideal candidate for spatial and time resolved studies of the atmospheric structure of RS CVn binaries and has been purposely observed for more than a decade (e. g., Walter et al. 1983, Rodonò et al. 1987, Walter et al. 1987, Neff et al. 1989, White et al. 1990, Ottmann et al. 1993, Singh et al. 1996, Kaastra et al. 1996, Siarkowski et al. 1996).

All those studies were developed within the framework of the *solar-stellar connection*, i. e., by adopting the observed structure of the outer solar atmosphere as a paradigm to interpret stellar observations. Such an approach has proved very fruitful

in the analysis of stellar data, but a more detailed comparison requires to go beyond a purely phenomenological approach, i. e., toward a comprehensive model on generation of magnetic fields and their role in the dynamics and non-radiative heating of the outer atmosphere. A fundamental contribution can be given by a detailed picture of the activity in the best studied RS CVn systems for which sequences of data extending over one or two decades are available. In particular, wide-band optical light curves usually form the most extended and continuous data base suitable for the study of the photospheric temperature inhomogeneities, to which the out-of-eclipse flux modulation is attributed. Such surface inhomogeneities are called starspots and are considered as stellar analogues of sunspots or sunspot groups, but with a much larger area (Mullan 1974, Eaton & Hall 1979, Byrne 1992, Solanki 1996). By a suitable analysis of sequences of wide-band optical light curves, it is possible to derive the variation of the area covered by starspots and the existence and period of a stellar activity cycle. Moreover, the presence of active longitudes and their migration may provide information on stellar dynamos and differential rotation regimes (e. g., Catalano 1983, Rodonò et al. 1995, Rodonò & Lanza 1996). The positions of the largest photospheric magnetic flux concentrations, corresponding to starspots, can also be compared with the longitudes of the plages and flares detected in the chromosphere, transition region and corona, allowing us to check the solar paradigm also from the point of view of the spatial and temporal association of activity in different atmospheric layers (Rodonò et al. 1987, Catalano et al. 1996).

In the light of these considerations, the present study of the optical light curves of AR Lac is aimed at a better understanding of its hydromagnetic dynamo and the relationship among magnetic structures in different atmospheric domains. The method adopted is a refinement of that already proposed for the study of the prototype RS Canum Venaticorum (Rodonò et al. 1995) and is particularly suited for a comparison with the results obtained in other spectral domains (e. g., Neff et al. 1989, White et al. 1990, Pagano et al. 1996, Siarkowski et al. 1996).

The information on the geometry of the surface inhomogeneities provided by wide-band flux modulation is usually limited to an evaluation of their projected area vs. longitude. The situation is significantly better in the case of an eclipsing binary system because during the eclipses the disk of the eclipsing component scans the disk of the component being eclipsed, thus increasing the spatial resolution allowed by standard flux data (e. g., Spruit 1994).

In order to take full advantage from the eclipse scanning technique it is important to adopt a model which does not constrain a priori the shape of the spotted areas and their brightness distribution. Light curve fits based on too restrictive hypotheses may be affected by systematic errors, in particular during eclipses, or require a variation of the effective temperature of the unspotted photosphere or a spotted polar cap to account for the different mean magnitudes in different seasons (Rodonò et al. 1986, Kang & Wilson 1989).

In the present paper we adopt a model with very general assumptions. Each star is divided into several hundreds pixels

the brightness of which is allowed to vary continuously within a prescribed range. Such a model allows many different solutions within a specified χ^2 level. In order to select one of the possible solutions, we have to introduce some kind of a priori assumption. We shall adopt the maximum entropy and the Tikhonov regularization criteria. These criteria are the most popular in the field of active star mapping and are useful when no detailed information on the distribution of the active regions is available, as in our case (Vogt et al. 1987, Piskunov et al. 1990, Cameron 1992). We shall obtain fits with both criteria in order to recognize the artifacts in the maps introduced by their specific a priori assumptions.

The results obtained by the present approach include a better determination of the unspotted luminosity ratio of the components of AR Lac and a characterization of their activity. We confirm the existence of active longitudes and the lack of a long-term migration of the spot pattern, as well as an activity cycle on the secondary component, suggested in a preliminary study (Lanza et al. 1995). On the basis of these new results, the relationship between magnetic activity and orbital period variations is also addressed.

2. Observations

Our data set consists of 20 yearly light curves of AR Lac obtained from 1967 to 1992. Previous light curves were disregarded because the AR Lac magnitudes were derived from visual or photographic estimates or the comparison star was HD 209813 (BD +46° 3572), lately recognized as the variable HK Lac by Blanco & Catalano (1968, 1970). In the present analysis we consider only the V band light curves because they are the most complete and homogeneous.

In addition to the standard correction for atmospheric extinction, all our magnitudes are referred to HD 208728 (BD +45° 3741), the comparison star adopted by Rodonò et al. (1986). In Table 1 we present for each yearly light curve the mid epoch of the observations, the number of normal points (M), the aperture of the used telescope (D_T), the photometric system (I instrumental, S standard UBV), the ephemeris adopted to compute the phase of the light curve and the literature reference.

Due to the orbital period being very close to two days, it is difficult to obtain a good phase coverage of the light curve from a single observing site. Therefore points which appear to be near in phase could have been obtained after an interval of several weeks or a few months, during which the system might have undergone significant variations.

Indeed AR Lac is a very active RS CVn system and out-of-eclipse light variations up to 0.05 mag have been detected in the course of a single night. This intrinsic variability seems to have a somewhat larger amplitude during primary minima, when only the K0 IV component is visible. Srivastava (1986) studied in detail such variations in the V and B bands, attributing them to flares with timescales of 10-100 minutes. Due to the unfavourable orbital period and intrinsic light variations, a significant part of our light curves shows both phase gaps and large dispersion of the observations with an intrinsic standard

Table 1. V-band light curves of AR Lac.

<i>Light curve</i>	<i>Mid Epoch</i> (JD – 2400000)	<i>M</i>	<i>D_T</i> (cm)	<i>P</i>	<i>Min. Epoch</i> HJD-2400000	<i>Reference</i>
1967	39785.4233	66	30	I	$39749.3331 + 1.98322300 \times E$	present paper
1968	40089.4767	196	30	I	$39749.3297 + 1.98322300 \times E$	present paper
1970	40667.8430	92			$37569.7977 + 1.98320900 \times E$	Babaev (1974)
1973	41865.7818	679	46	I	$39376.4955 + 1.98319870 \times E$	Chambliss (1976)
1975	42725.3431	233	38	S	$39376.4928 + 1.98319100 \times E$	Srivastava (1981)
1977	43396.8351	663	40	I	$39376.4856 + 1.98319870 \times E$	Nha & Kang (1982)
1978	43744.2574	637	48	I	$43672.0867 + 1.98318235 \times E$	Kurutac et al. (1981)
1979	44100.5160	334	48	I	$43672.0867 + 1.98318235 \times E$	Kurutac et al. (1981)
1980	44473.4440	434	48	I	$43672.0867 + 1.98318235 \times E$	Ertan et al. (1982)
1981	44883.6022	336	48	I	$43672.0867 + 1.98318235 \times E$	Ertan et al. (1982)
1982	45290.8585	305	48	I	$43672.0818 + 1.98318235 \times E$	Evren et al. (1983)
1983	45636.8306	99	25-91	S	$47295.6369 + 1.98317400 \times E$	present paper
1984	45948.7671	53	91	S	$47295.6369 + 1.98317400 \times E$	present paper
1987	47057.2783	107	30-91	S	$47295.6369 + 1.98317400 \times E$	present paper
1988	47465.8115	67	25	S	$47295.6369 + 1.98317400 \times E$	present paper
1989	47776.2998	142	25-91	S	$47295.6369 + 1.98317400 \times E$	present paper
1990	48183.2939	176	25-91	S	$47295.6369 + 1.98317400 \times E$	present paper
1991	48520.2529	142	25-91	S	$47295.6369 + 1.98317400 \times E$	present paper
1992a	48827.0000	43	25-80	S	$47295.6369 + 1.98317400 \times E$	present paper
1992b	48934.5000	68	25-80	S	$47295.6369 + 1.98317400 \times E$	present paper

deviation of $\sim 0.02 - 0.03$ mag. In order to avoid a loss of information by averaging such variations, whenever possible the available observations were not averaged into normal points for the subsequent analysis. Moreover, all points in the AR Lac light curves were given the same unity weight, whereas in the previous analysis of the RS CVn light curves we used normal points with different weights (see Rodonò et al. 1995).

The brightest magnitude of AR Lac from our light curve sequence turned out to be $m_V = 6.030 \pm 0.005$ at orbital phase 0.7395 in the 1987 light curve. This value is assumed as the magnitude of the unspotted system at phase 0.7395, thus establishing the magnitude scale calibration for the subsequent light curve modelling.

The V-band data from Catania Observatory used in the present paper will be described in detail in a forthcoming paper dealing with long-term UBV photometry of AR Lac.

3. Spot modelling technique

The reconstruction of a surface map of an active star using photometric data alone is an ill-posed problem. The wide band flux modulation provides information only on the distribution of the projected spotted area vs. phase, i. e., stellar longitude, whereas a unique mapping requires information both on longitude and latitude. In the particular case of an eclipsing binary system, eclipses increase the information on the hemisphere of the active star being occulted, but the reconstruction problem still remains ill-posed even in the most favourable cases.

As a matter of fact, one can obtain a unique solution in most

cases by selecting the surface map which minimizes the χ^2 , but such an approach is highly unsatisfactory because most of the structures appearing in the map will result from the modelling of the noise present in the data and are not related to any real pattern on the star. Moreover, the solution which minimizes the χ^2 is usually highly unstable, i. e., small variations in the input data induce very large changes in the solution. It is possible to reduce the influence of the noise on the map and increase that of the signal by establishing a priori a χ^2 limit for the fit, greater than the minimum. The main drawback of this approach is that the solution is not unique, i. e., many (virtually infinite) maps fit the light curve within the given χ^2 limit.

It is possible to select a unique and stable solution if some a priori assumption on the properties of the picture elements (pixels) of the map is introduced (e. g., Nityananda & Narayan 1982, Tikhonov & Goncharov 1987).

There are two main a priori assumptions which have been widely used in the field of active star mapping: the maximum entropy criterion (hereinafter ME, e. g., Gull & Skilling 1984, Vogt et al. 1987) and the Tikhonov criterion (hereinafter T, e. g., Piskunov et al. 1990).

The implementation of these regularization methods has been made starting from the computational tools applied for the analysis of the light curves of RS CVn (Rodonò et al. 1995). For calculation purposes, the photosphere of each of the two stars is divided into N surface squared elements (hereinafter pixels) of side s . Therefore pixels from 1 to N map the first component whereas pixels from $N + 1$ to $2N$ map the second component.

The contribution of the pixel i to the observed wide-band flux F_j at orbital phase j can be written as: $\Delta F_{ji} = R_{ji}I_i$, where R_{ji} is an element of the *response function matrix* $\mathbf{R}$ relating the observed wide-band flux to the photospheric brightness of the components (e. g., Vogt et al. 1987) and I_i is the specific intensity of the i -th surface element at the given isophotal wavelength (Golay 1974). Therefore, the observed flux at phase j is:

$$F_j = \sum_{i=1}^{2N} R_{ji}I_i \quad (1)$$

The elements of the response function matrix are computed using the computer code for the synthesis of binary system light curves described by Lanza et al. (1994). It assumes that stellar photospheres are triaxial ellipsoids of semi-axes a_k , b_k and c_k ($k = 1, 2$), respectively, and treats ellipsoidicity, gravity darkening and the geometry of the reflection effect according to Kopal (1959). The physics of the reflection effect is treated assuming black-body re-irradiation with given bolometric albedo.

Once the matrix $\mathbf{R}$ has been evaluated, a suitable algorithm must be applied to solve for the brightness vector $\mathbf{I}$ given the ill-conditioned nature of the problem defined by Eq. (1) alone. We construct a regularized solution by finding the appropriate extreme value of the entropy or Tikhonov functionals, subject to the condition of a given χ^2 limit (e. g., Press et al. 1992, Cameron 1992). As a mapping parameter, we choose the spot covering factor f_i , that is the fraction of the i -th pixel covered by spots. It is more adequate as a mapping parameter than the temperature because it guarantees the additivity of the image entropy (Cameron 1992).

The surface intensity of the i -th pixel is a function of its spot covering factor f_i according to:

$$I_i = f_i I_s + (1 - f_i) I_u \quad (2)$$

where I_s is the brightness of the spotted photosphere of the i -th pixel and I_u the corresponding unspotted brightness. They are computed using the empirical photospheric flux distributions given by Poe & Eaton (1985), including also the effects of the limb and gravity darkenings.

The χ^2 corresponding to a given surface distribution of the spot covering factor is defined as:

$$\chi^2 = \frac{1}{M} \sum_{j=1}^M \frac{(F_j - D_j)^2}{\sigma_j^2} \quad (3)$$

where M is the total number of observations in the light curve, F_j the flux at the phase j -th computed by Eq. (1) adopting the surface intensity resulting from Eq. (2), and D_j is the observed flux at the phase j -th with standard deviation σ_j .

The functional form we have assumed for the entropy S_k of the surface map of star k ($k = 1, 2$) is:

$$S_k = - \sum_i w_i \left[f_i \log \frac{f_i}{m} + (1 - f_i) \log \frac{(1 - f_i)}{(1 - m)} \right] \quad (4)$$

where the sum is extended over the pixels belonging to the k -th star, w_i is the relative area of the i -th pixel of the star (total area of the star = 1), m the default spot covering factor which determines the limiting values for f_i : $m < f_i < (1 - m)$. In all our computations we have adopted: $m = 10^{-6}$.

The Tikhonov functional T measures the smoothness of the map of a star and is defined in the case of a continuous covering factor $f(\theta, l)$ as:

$$T = \int \int \left[\left(\frac{\partial f}{\partial \theta} \right)^2 + \frac{1}{\sin^2 \theta} \left(\frac{\partial f}{\partial l} \right)^2 \right] \sin \theta d\theta dl \quad (5)$$

where θ and l are the colatitude and longitude and the integration is extended over the photosphere of the star (Piskunov et al. 1990). In our model the numerical expression of the Tikhonov functional for the k -th component is:

$$T_k = \sum_i \sum_{n(i)} g_{in} (f_i - f_n)^2 \quad (6)$$

where the external sum is over the star's pixels, while the inner one is over the neighbour pixels of the i -th pixel. A generic pixel has up to four neighbours, two with the same latitude and two with the same longitude. The factor g_{in} is given by: $g_{in} = \frac{1}{2}(w_i + w_n)$ when the pixels i -th and n -th are at the same longitude, and $g_{in} = \frac{1}{2\sin^2 \theta_i}(w_i + w_n)$ when the pixels are at the same colatitude θ_i .

The regularized solution is obtained by a constrained minimization of the functionals (cf., e. g., Vincent et al. 1993):

$$Q_{ME} = \chi^2 - \lambda_{ME}(S_1 + S_2) \quad (7)$$

for the ME criterion, and:

$$Q_T = \chi^2 + \lambda_T(T_1 + T_2) \quad (8)$$

for the T criterion, where $\lambda = \lambda_{ME} > 0$ or $\lambda = \lambda_T > 0$ is the Lagrange multiplier. The adopted algorithm is a version of the conjugate gradient method developed by Byrd et al. (1994) and implemented by Zhu et al. (1994).

When $\lambda = 0$ the solution minimizes the χ^2 , but it is severely affected by noise and instability. By increasing the value of λ , the χ^2 increases and the solution becomes unique and stable. The features of the map are determined as a combination of the information coming from the data and the a priori assumptions, while the value of λ quantifies the relative weights of such two sources of information (see, e. g., Titterton 1985, Narayan & Nityananda 1986). We select the most appropriate value of λ by a careful inspection of the fit, because the usual criterion of fixing a limiting χ^2 is not completely satisfactory in the case of a wide-band light curve, whose noise level is not exactly known a priori. Specifically, we consider the distribution of the residuals between the computed and the observed fluxes, which, due to the a priori assumptions, is not that expected from the pure χ^2 statistics, the difference becoming the larger, the greater the value of λ (Bryan & Skilling 1980). From the analysis of the residual distributions obtained for different λ 's, we determine

Table 2. Geometrical and physical parameters adopted in modelling the AR Lac light curves

Orbital Elements of AR Lac		
Element		Ref. ^(a)
Semi-major axis	1.00	
Eccentricity	0.00	1
Inclination (deg)	87.0	1
Time of conjunction	mid primary eclipse	
Period (day)	~ 1.983	1

Stellar and Model Parameters			
Stellar Parameter	G2 IV	K0 IV	Ref. ^(a)
Ellipsoid semi-axis a	0.1680	0.3160	1, 7
Ellipsoid semi-axis b	0.1666	0.2998	1, 7
Ellipsoid semi-axis c	0.1658	0.2930	1, 7
Mass ($M_{\odot} = 1$)	1.23	1.27	1
V band fractional luminosity	0.371	0.629	7
Linear limb darkening	0.65	0.80	2
Gravity darkening	0.25	0.25	3
Bolometric albedo	1.00	0.30	3, 5
Albedo in the V pass band	1.01	0.28	7
Bolometric correction (mag)	-0.04	-0.30	4
Effective temperature (K)	5560	4820	1, 5
Starspot temperature (K)	4100	3450	6

^(a) The references are as follows: [1]: Popper (1990); [2]: Al-Naimiy (1978); [3]: Eaton et al. (1993); [4]: Allen (1973); [5]: Gray (1992); [6]: Poe & Eaton (1985) and Eaton (1992); [7]: present paper. When two references are quoted, the adopted value is a weighted mean of the data given in the two sources.

the appropriate Lagrange multiplier as the greatest value giving a distribution which does not appreciably differ from the normal one (i. e., by more than $\sim 1\sigma$), particularly during the course of eclipses when the information content of the data is higher.

An estimate of the errors on the computed f_i 's is made difficult by the use of a regularization scheme. In fact it is based on an a priori constraint and hence systematic errors prevail in the present approach. They can be estimated only through a comparison of solutions obtained with different regularization criteria.

For a given regularization criterion and the corresponding solution, it is only possible to estimate the variations of the f_i 's produced by a variation of the observed flux D_j at constant λ , obtaining an estimate of the stability of the given solution. In

Table 3. The Lagrangian multipliers and the χ^2 of the light curve fits with ME and T regularizing criteria, respectively.

Light curve	λ_{ME}	χ^2_{ME}	λ_T	χ^2_T
1967	0.5	0.686	9.0	0.679
1968	1.0	0.228	90.0	0.276
1970	1.0	1.533	360.0	1.557
1973	0.5	0.461	360.0	0.473
1975	1.0	1.258	40.0	1.254
1977	0.5	0.776	90.0	0.825
1978	1.0	0.264	9.0	0.180
1979	0.5	0.549	90.0	0.580
1980	0.5	0.286	9.0	0.274
1981	0.5	0.192	9.0	0.172
1982	0.5	0.455	40.0	0.477
1983	0.5	0.127	9.0	0.114
1984	0.5	0.075	40.0	0.088
1987	0.5	0.501	40.0	0.577
1988	0.5	0.186	9.0	0.180
1989	1.0	0.816	90.0	0.792
1990	1.0	0.256	40.0	0.228
1991	1.0	0.415	40.0	0.319
1992a	1.0	0.123	90.0	0.050
1992b	1.0	0.196	40.0	0.121

particular, we shall estimate the variations of the f_i 's for the ME solutions, for which an analytical expression can be derived assuming that the variations of the observed fluxes D_j are uncorrelated and that λ is constant (see Sect. 5.1).

4. Model parameters

All of the solutions have been computed using a map pixel side $s = 18^\circ$ for both components. Since infrared photometry to constrain spot temperature is not available, in the empirical surface flux relation given by Poe & Eaton (1985) we have assumed $V - R = 0.52$ for the unspotted photosphere of the G2IV primary and $V - R = 1.0$ for its spotted photosphere and 0.70 and 1.5 for the corresponding values of the K0IV secondary. Such values are appropriate for the approximate effective temperatures listed in Table 2 together with the other model parameters. They were derived from the quoted references, except for the fractional luminosities.

In order to fit all the light curves with fixed values of the stellar fractional luminosities, we redetermined the luminosity ratio $\frac{L_1}{L_2}$ in the V band, assuming it as an additional free parameter in the fitting procedure. All the fits were regularized using the ME criterion with a fixed $\lambda_{ME} = 0.5$. By minimizing the sum of the χ^2 's of the light curve sequence, we derived the best value for the luminosity ratio in the V passband:

$$\frac{L_{G2IV}}{L_{K0IV}} = 0.59 \pm 0.03 \quad (9)$$

The quoted uncertainty is an estimate of the standard deviation of the ratio, computed by assuming a mean uncertainty of 0.03 mag for the normal points. The above luminosity ratio leads to the fractional luminosities reported in Table 2.

The fractional radius adopted for the secondary component is slightly larger than the value given by Popper (1990), but still within the uncertainty of Popper's determination. The adopted value slightly improves the fit of the minima of our ellipsoidal model.

5. Results

5.1. Light curve fitting and spot maps

The light curve fits we obtained with the model parameters listed in Table 2 and the ME criterion are shown in Figs. 1 and 2, whereas those obtained with the same parameters and the T criterion are shown in Figs. 3 and 4, respectively. The corresponding values of the Lagrange multipliers and the χ^2 's are listed in Table 3. The χ^2 's were computed assuming $\sigma_j = 2 \times 10^{-2} F_0$ for all the measurements, where F_0 is the unspotted flux of the system at quadrature. The mean standard errors of the observations turn out to be between 0.005 and 0.03 mag. The fits are always satisfactory and small systematic deviations, especially during primary minima, can be accounted for by intrinsic light fluctuations of the system (see Sect. 2).

The derived covering factor distributions on the components are displayed using IDL and plotted on Mercator maps. Specifically, the original maps, having squared pixels with a side of 18° , were smoothed for presentation purposes to maps with a pixel side 5 times smaller using a bilinear interpolation (function REBIN of IDL) and then displayed as images (Figs. 5, 6, 7 and 8). On the maps of the primary the longitude is measured from the substellar point in the direction opposite to the orbital motion, whereas on the secondary it is measured from the antipodes of the substellar point, again in the direction opposite to the orbital motion. Thus on all the maps the phase at which a given spot element crosses the central meridian of the stellar disk is equal to its longitude.

The ME maps of both components never show spots at latitudes higher than $45^\circ - 50^\circ$, so that polar spots are not needed to fit the wide-band light curves even during eclipses when the resolution is increased due to the occultation of one component by the other. Several small structures are present on the occulted hemispheres, but they are the result of image artifacts due to the ME regularization, the so-called *superresolution effect* (Narayan & Nityananda 1986). The actual resolution deduced from the analysis of several simulated light curves with a pseudo-Gaussian noise of $\sigma = 0.02$ mag and $M = 40$ normal points is $\sim 20^\circ - 30^\circ$ on the strips occulted during eclipses and $\sim 40^\circ - 60^\circ$ outside of them. Light curves with the same σ and a larger M have a somewhat higher resolution, but in any case structures smaller than $30^\circ - 40^\circ$ should be regarded with caution because they might be artifacts even within the eclipsed strips.

An alternative description of the spot pattern is provided by

the maps regularized with the T criterion. Those maps are the smoothest maps which fit the light curves. They show that several details in the ME maps are not actually needed by the data.

The T maps of the primary usually agree quite well with the corresponding ME maps in spite of the fact that the photometric modulation is dominated by the larger spots on the more luminous secondary. Only those spotted structures on the G2IV star which are needed to reproduce the descending and ascending branches of the primary eclipses can be regarded with confidence. Structures at longitudes corresponding to phases out of primary eclipse should be considered with some caution.

The most prominent features on the photosphere of the primary are the dark and compact spotted areas which are occulted during primary eclipse (cf., e. g., the 1979, 1980, 1987 and 1988 maps). They have diameters between 30° and 40° also on the T maps, i. e., comparable to the geometrical resolution of the eclipse mapping, and suggest that even smaller, solar-sized spots may be present on the G2 star.

The features on the ME and the T maps of the K0IV secondary are remarkably similar, even if several small details appearing on the ME maps are not found on the T maps and are therefore not needed by the data. In particular, the secondary eclipse modulation can be reproduced, in most cases, by only one large and smooth spot centered on the equator around longitudes $180^\circ - 210^\circ$. Its shape and extension changes in time, but it never extends beyond latitude 50° . Other active regions seem to be present around longitudes 60° and 300° , respectively. They appear in most of the ME maps and in several T maps.

The main drawback of the T regularization is the presence of an high latitude spot pattern which is not actually needed to fit the data, as shown by the ME fits. Since the orbital inclination is near 90° , photometric data give very poor constraints on the high latitude structures which are dominated by the regularization. This produces a uniformly grey area at high latitude, smoothing the variation of the covering factor over the star surface and increasing the total spotted area (the situation is somewhat better in the case of Doppler imaging maps based on spectroscopic data, cf. Hatzes et al. 1996).

The distributions of the spotted area vs. 18° longitude bins are shown in Figs. 9 and 10 for the G2IV primary and in Figs. 11 and 12 for the K0IV secondary, respectively. The plotted distributions are those derived from the actual spot covering factor distributions, without any smoothing with the IDL REBIN function. The ME distributions give the lowest area per longitude bin actually required by the data, for the assumed system parameters and unspotted magnitude. In the case of the ME distributions, an estimate of the stability of the area per bin at constant λ has been computed (see Sect. 3). Assuming $\sigma_j = 2 \times 10^{-2} F_0$, the relative variations are always smaller than $\sim 10\% - 15\%$ and are within the dimension of the symbols used in the plots.

The maps obtained with the T regularization usually show a significantly larger spotted area per longitude bin than those obtained with the ME criterion, due to the presence of the high latitude "grey caps". Of course, the disk-projected spot area, which is responsible for the photometric modulation, is the same

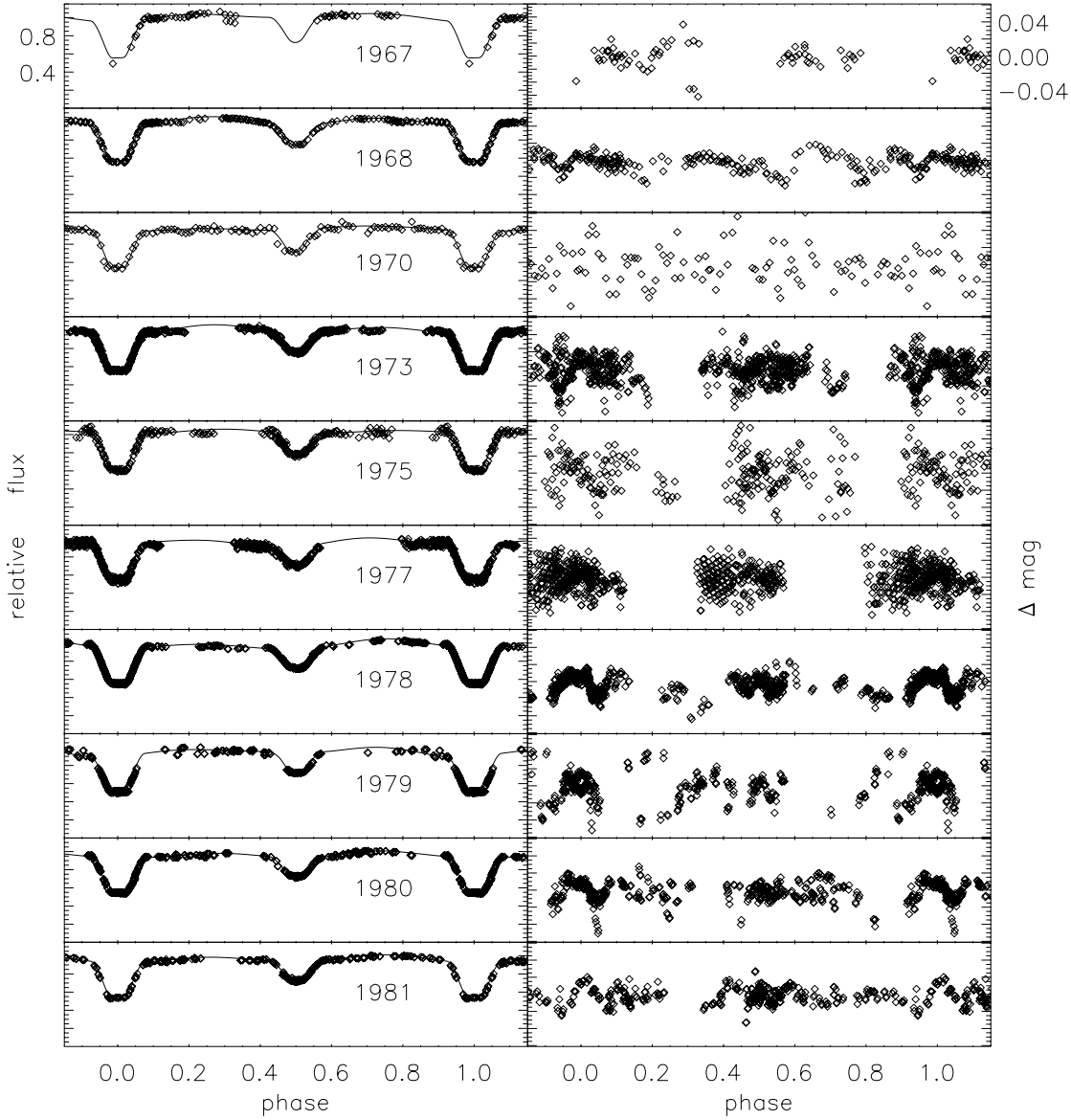


Fig. 1. The V-band light curve fits with the Maximum Entropy regularization from 1967 to 1981 (left panels) and the corresponding residuals (right panels). Zero phase corresponds to mid primary eclipse.

within the data uncertainty.

Each distribution of spotted area vs. longitude can be represented as the sum of a uniform term a_U , which is defined as the minimum spotted area common to all longitudes, and a term $a_D(l)$ which varies vs. longitude l . The latter term often shows more than one relative maximum and minimum, thus suggesting the presence of several preferred longitudes.

5.2. Overall evolution of the spot pattern

The total area covered by spots $A = A_U + A_D$, and the total areas of the uniform and longitude-dependent components $A_U = \int_0^{2\pi} a_U dl$ and $A_D = \int_0^{2\pi} a_D dl$, are plotted vs. time in

Figs. 13a, 13b and 13c for the G2 IV primary and in Figs. 14a, 14b and 14c for the K0 IV secondary, respectively. The relative uncertainties of the values of A related to the stability of the solutions is between $\sim 10\%$ – 25% for the primary component and $\sim 5\%$ – 10% for the more luminous secondary. An additional source of uncertainty is the non-standard photometric system of some light curves, but the advantage of analysing data in different systems is that the errors tend to become stochastic.

The total spotted area A for the primary ranges from $< 1\%$ to $\sim 8\%$ for the ME models and from $\sim 1\%$ up to $\sim 15\%$ for the T models. As on the Sun, the total spotted area can be used as an index of the overall magnetic activity. A Fourier analysis based on the Scargle method (Scargle 1982, Horne & Baliunas 1986) gives a period for the areal modulation of 5.4 yr with a

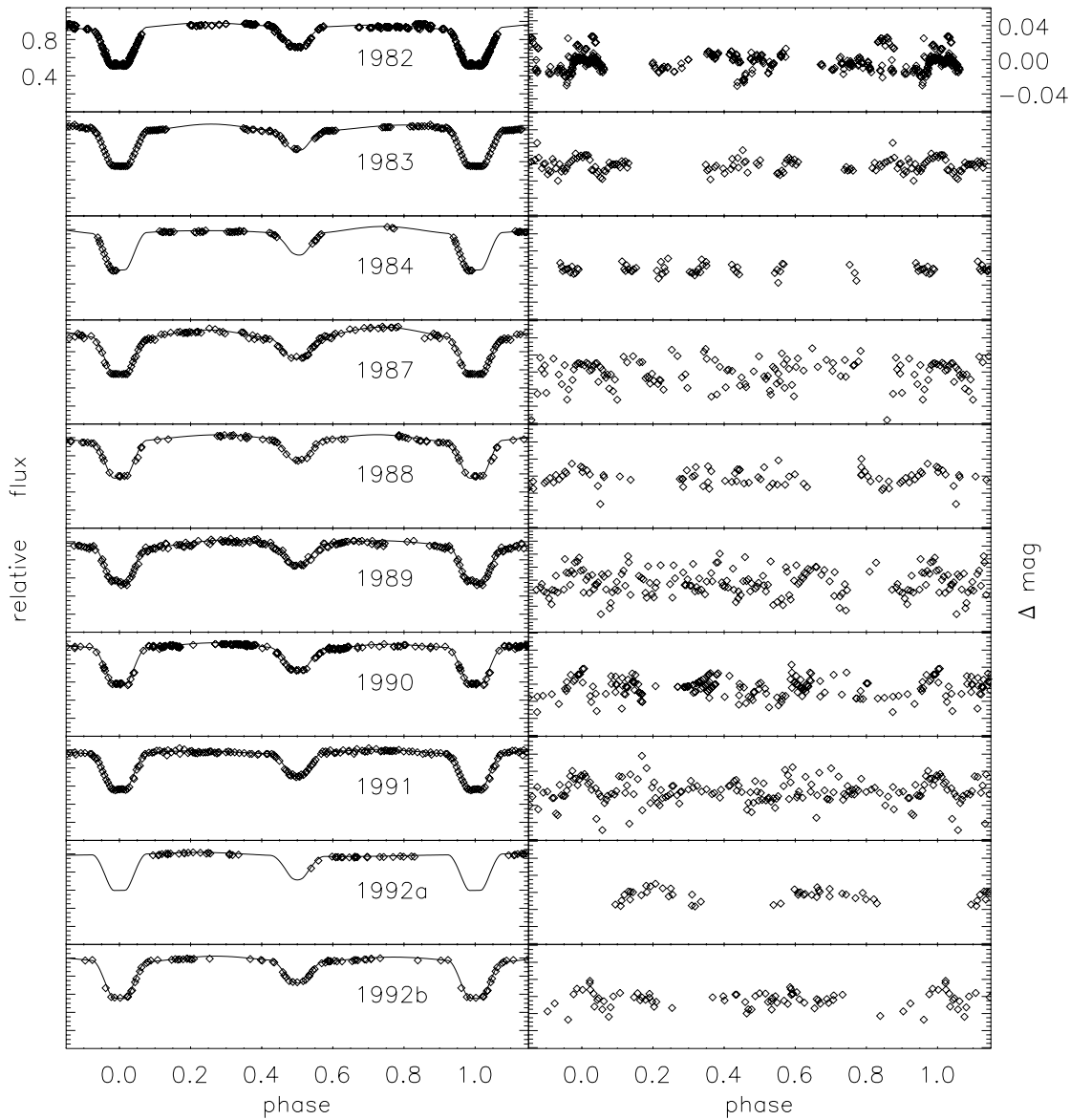


Fig. 2. The V-band light curve fits with the Maximum Entropy regularization from 1982 to 1992 (left panels) and the corresponding residuals (right panels). Zero phase corresponds to mid primary eclipse.

confidence level of only 5% for the ME solutions and of 9.3 yr with a confidence level of 87% for the T solutions. The periodic modulation of the total area derived from the T maps is strikingly apparent from the plot, but such a result should be considered with caution because photometric data have a low information content on the overall spot distribution of the primary. For the same reason it seems premature to derive any detailed conclusion on the evolution of the active regions present on the primary. We limit our consideration to the starspots located around longitude zero which are occulted during primary eclipses. Referring to the ME maps, in the 1979 light curve the stronger concentration was centered around longitude 310° and had an extension of about 40° ; in 1980 it has moved its center to longitude 40° . In the successive ME and T models spot con-

centrations are present up to 1989, with the exception of 1984, usually centered around longitude 0° , sometimes with a somewhat larger extension up to $\sim 100^\circ - 120^\circ$ in longitude.

The overall migration of the spot pattern can be studied also by a cross-correlation of successive distributions of the sequences in Figs. 9 to 12, respectively. In Fig. 15 we report the distribution of the cross correlation shifts for the covering factor distributions on the primary. There is no evidence for a uniform migration in time and the results are probably dominated by random fluctuations.

The total area A of the spots on the secondary component ranges from $\sim 3\%$ up to $\sim 15\%$ and the values derived from ME and T models agree quite well. A periodogram analysis shows a modulation with a period of 16.8 yr for both models

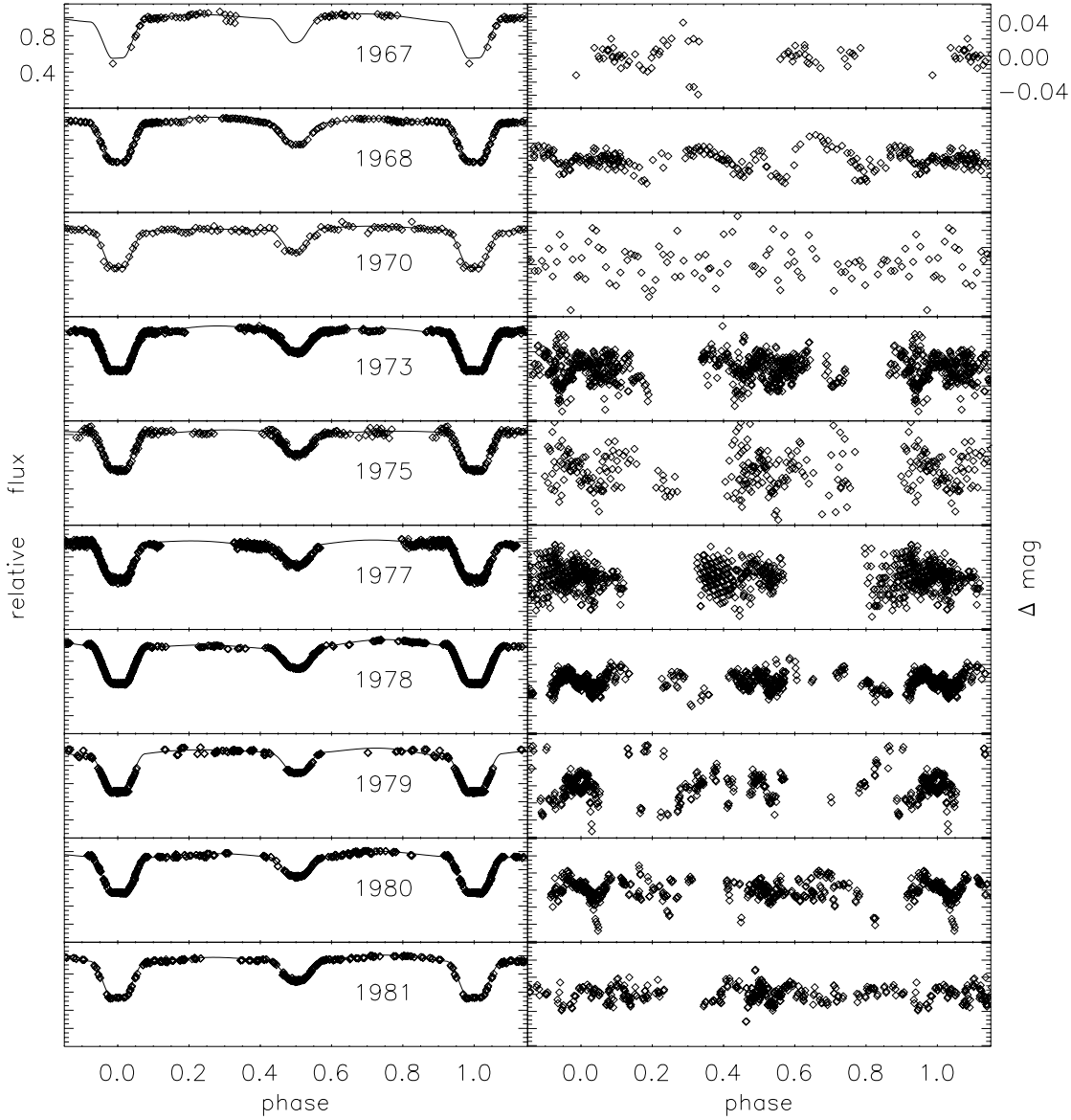


Fig. 3. The V-band light curve fits with the Tikhonov regularization from 1967 to 1981 (left panels) and the corresponding residuals (right panels). Zero phase corresponds to mid primary eclipse.

with confidence levels of 53% and 83% for the ME and the T models, respectively. However, the presence of only one maximum of activity in the analysed time span does not allow us to draw any definitive conclusion on the existence and period of an activity cycle on the secondary component. Even less significant are possible periodicities in the variation of the uniformly and non-uniformly distributed components of its spot pattern.

The active longitudes identified on the secondary do not show any clear evidence for a long-term migration as for RS CVn (cf. Rodonò et al. 1995). In particular the active region centered around $180^\circ - 210^\circ$ appears to be remarkably stable whereas the less prominent active regions around 60° and 300° sometimes show small excursions in longitude with amplitudes between 20° and 50° , i.e., comparable with the map resolution

and which may therefore be a consequence of the noise in the data.

The absence of migration is confirmed also by the distribution of the cross-correlation shifts (see Fig. 16) which show peaks around zero shift and 180° shift, the latter being clearly due to the long-lived starspot centered around $180^\circ - 210^\circ$.

5.3. Orbital period variations

The epochs of primary minima listed by Pagano (1990) allow us to study the variation of the orbital period since about 1900. In Fig. 17, the $O - C$ residuals for the epochs of primary minima are plotted vs. time. The ephemeris used to obtain the computed

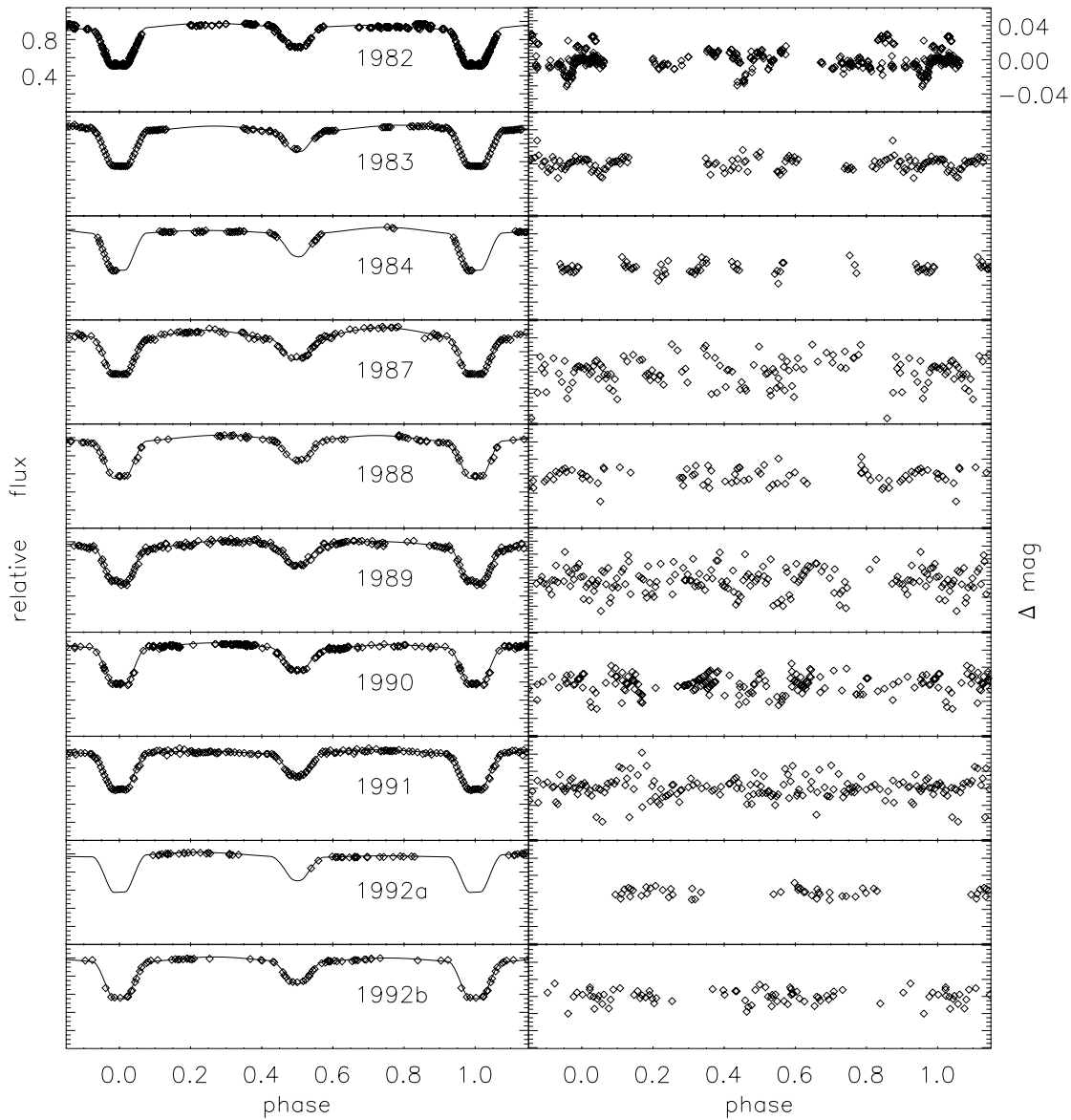


Fig. 4. The V-band light curve fits with the Tikhonov regularization from 1982 to 1992 (left panels) and the corresponding residuals (right panels). Zero phase corresponds to mid primary eclipse.

epochs is that determined from the same data set by Pagano (1990):

$$HJD = 2426624.3817 + 1.9832142 \times E \quad (10)$$

where E is the number of elapsed orbital periods since the initial epoch. Fig. 17 shows that the $O - C$'s modulation might be periodic with a period of the order of 100 years. However, the present time series is too short to determine a reliable value of the period of such a possibly long-term oscillation, also because the shape of the $O - C$ diagram depends on the assumed mean orbital period. When the long-term trend is filtered out, a Fourier analysis with the Scargle method reveals also a period of 43.0 ± 0.5 years with a significance level $> 99\%$.

In a recent paper Jetsu et al. (1997) have investigated the

same data set of primary minimum epochs using non-parametric methods which can test the hypothesis of a periodic modulation under broader assumptions than Fourier-based methods. Their results would suggest the presence of a short-term quasi-periodic oscillation of the orbital period with a period of ~ 35 yr, i.e., nearly twice the ~ 17 yr period for the modulation of the starspot area on the secondary component. However, given the uncertainties on the modelling of the orbital period changes, any conclusion about its possible connection with the spot cycle on the secondary appears to be premature.

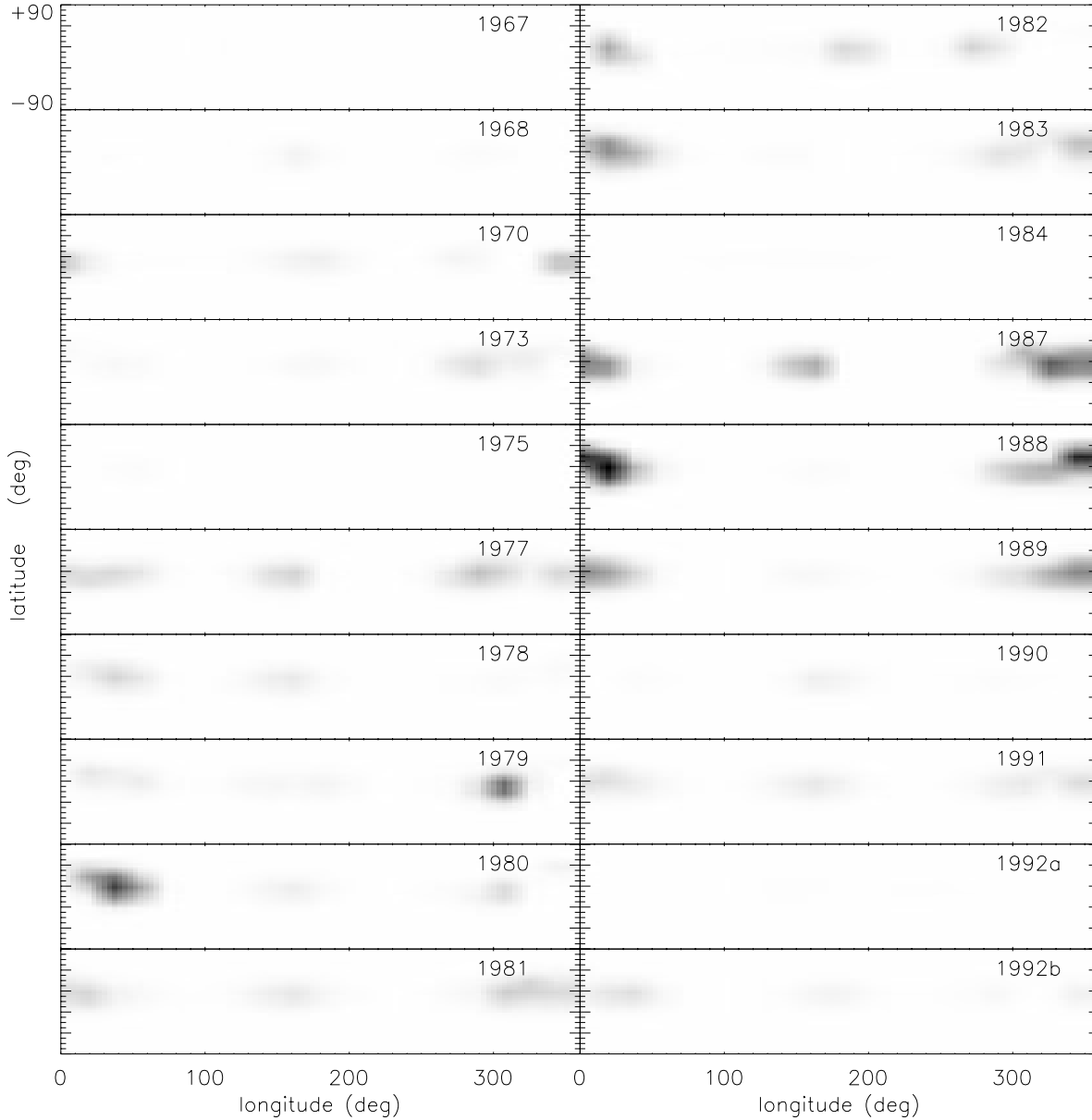


Fig. 5. The distribution of the covering factor on the G2 IV primary corresponding to the Maximum Entropy regularized fits for the V-band light curves from 1967 to 1992.

6. Discussion

The first result of our analysis concerns the luminosity ratio of the two components in the V band $\frac{L_{G2IV}}{L_{K0IV}} = 0.59 \pm 0.03$. Our value is in agreement with the values given in the literature, which fall in the range: 0.60–0.65 (Lee et al. 1986, Kang & Wilson 1989, Popper 1990). Indeed, previous determinations of the luminosity ratio did not take into account the presence of spots on the binary components thus underestimating their unspotted luminosities. Only Kang & Wilson (1989) considered spots in their analysis, but they adopted a discrete model with two circular spots located on the secondary. Therefore they could not take into account the role of the uniformly distributed spot component and were forced to consider a changing luminosity

ratio, hence underestimating the luminosity of the secondary. By considering spots on both components, we found a value of $\frac{L_1}{L_2}$ at the lower limit of those determined by previous investigators, probably because the effects of spots are stronger on the luminosity of the secondary, thus leading to a higher value of the luminosity ratio when they are not adequately accounted for. In any case, our result can also be improved, since it might be sensitive to the adopted unspotted magnitude of the system. A more detailed discussion on the problems encountered in the determination of the photometric parameters of RS CVn systems can be found in Poe & Eaton (1985) and Popper (1988).

In the analysis of RS CVn binaries' light curves, spots have been usually assumed to affect only the secondary components.

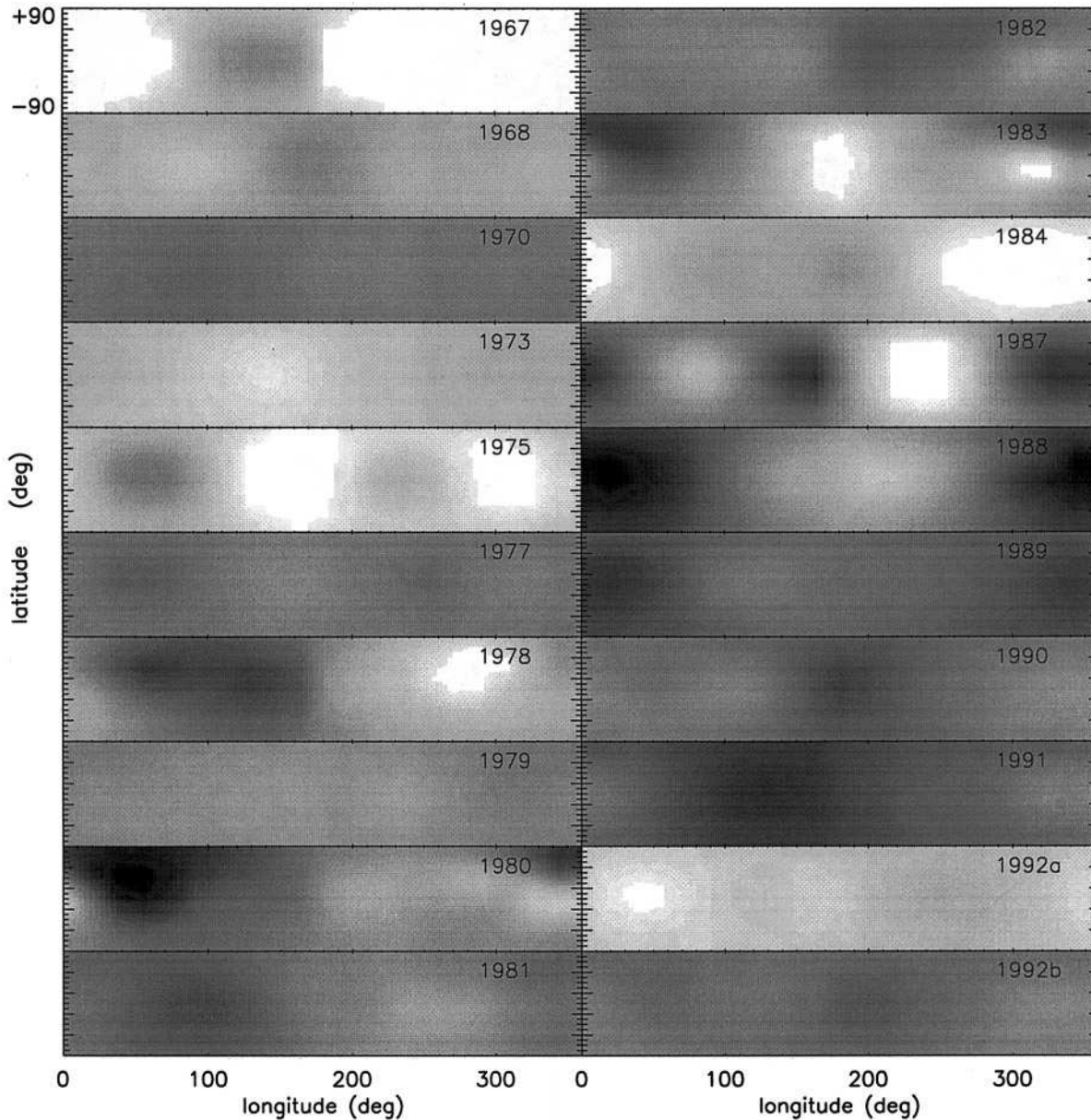


Fig. 6. The distribution of the covering factor on the G2 IV primary corresponding to the Tikhonov regularized fits for the V-band light curves from 1967 to 1980.

In the case of AR Lac, the presence of spots on the primary is supported by the observations of changes in the slope of the descending and ascending branches during primary eclipse and by the presence of compact plages up to coronal levels (Siarkowski et al. 1996). The slope changes during eclipses can be interpreted as the photometric effect of the ingress or egress of spots located on the G2 star (Rodonò 1986, Rodonò et al. 1986). As noted above, the information concerning spots on the primary, as provided by wide-band photometry, is less accurate than for spots on the more luminous and larger secondary. An unambiguous and complete mapping of the photospheric inhomogeneities of the primary may be obtained only through spectroscopic techniques such as Doppler Imaging (e. g., Vincent et al. 1993).

The application of regularization methods, such as ME and T, proved very useful in our modelling of wide-band light curves. They were introduced in the field of spectroscopic Doppler Imaging and their potentialities and drawbacks were widely discussed in that context (e. g., Piskunov et al. 1990, Cameron 1992, Unruh & Cameron 1995). Maps obtained from the same spectroscopic data set with the two criteria are generally very similar if the signal-to-noise ratio of the data is $\frac{S}{N} \geq 150 - 200$. However, in the case of wide-band light curve analysis, the ME maps look different from the T maps, as can be seen by comparing Figs. 5 and 6 with Figs. 7 and 8, respectively. Such a difference is due to the intrinsic low information content of photometric data, so that the regularizing criteria have a very

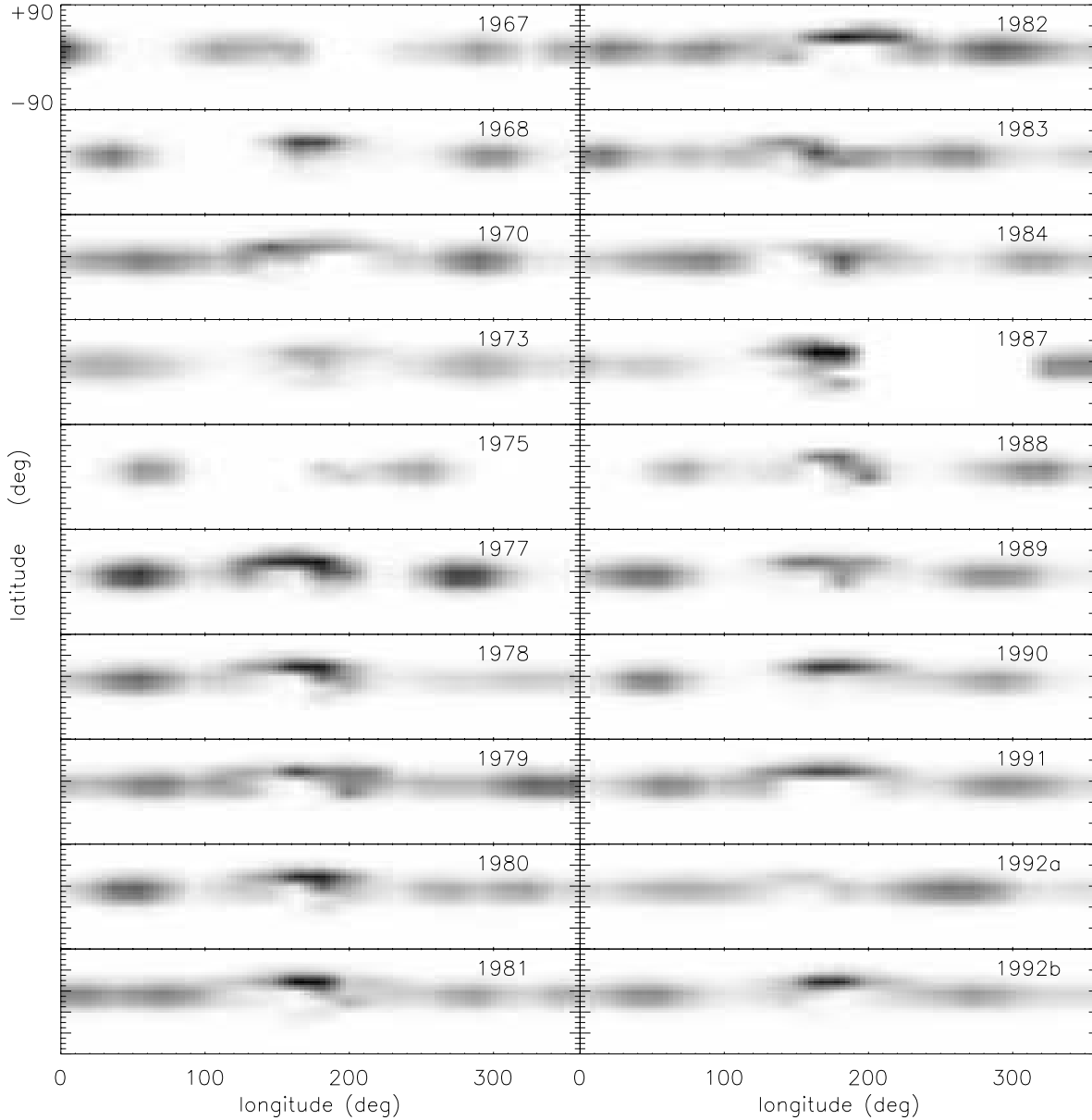


Fig. 7. The distribution of the covering factor on the K0 IV secondary corresponding to the Maximum Entropy regularized fits for the V-band light curves from 1967 to 1992.

significant influence on the maps even for a theoretical signal-to-noise ratio of infinity. As noted in Sect. 5.1, the ME maps often show fine details which are absent in the T maps. They are produced because, in the absence of sufficient information, each pixel is driven towards the default value m , but different pixels are not compared among each other since only the sum of their “specific entropies” is maximized. Therefore, small scale patterns may be produced with isolated and very dark pixels in place of a more extended area of less darker pixels, because the former configuration may give a lower total entropy (see also Nityananda & Narayan 1982, Narayan & Nityananda 1986). In this context, only an analysis of a series of simulated light curves, computed from a known spot configuration, can give us

reliable information on the actual resolution provided by light curve modelling (see Sect. 5.1).

The T criterion does not suffer from superresolution effects, but it tends to produce a large and smooth pattern on those regions for which the information is insufficient, such as polar caps or longitude ranges corresponding to phase gaps in the observations.

From these arguments, it is not possible to specify an ideal regularizing criterion for wide-band light curve analysis. In our opinion the best approach is to regard regularized maps as an intermediate stage of the analysis and use them only to derive quantities which do not depend on the regularizing criterion it-

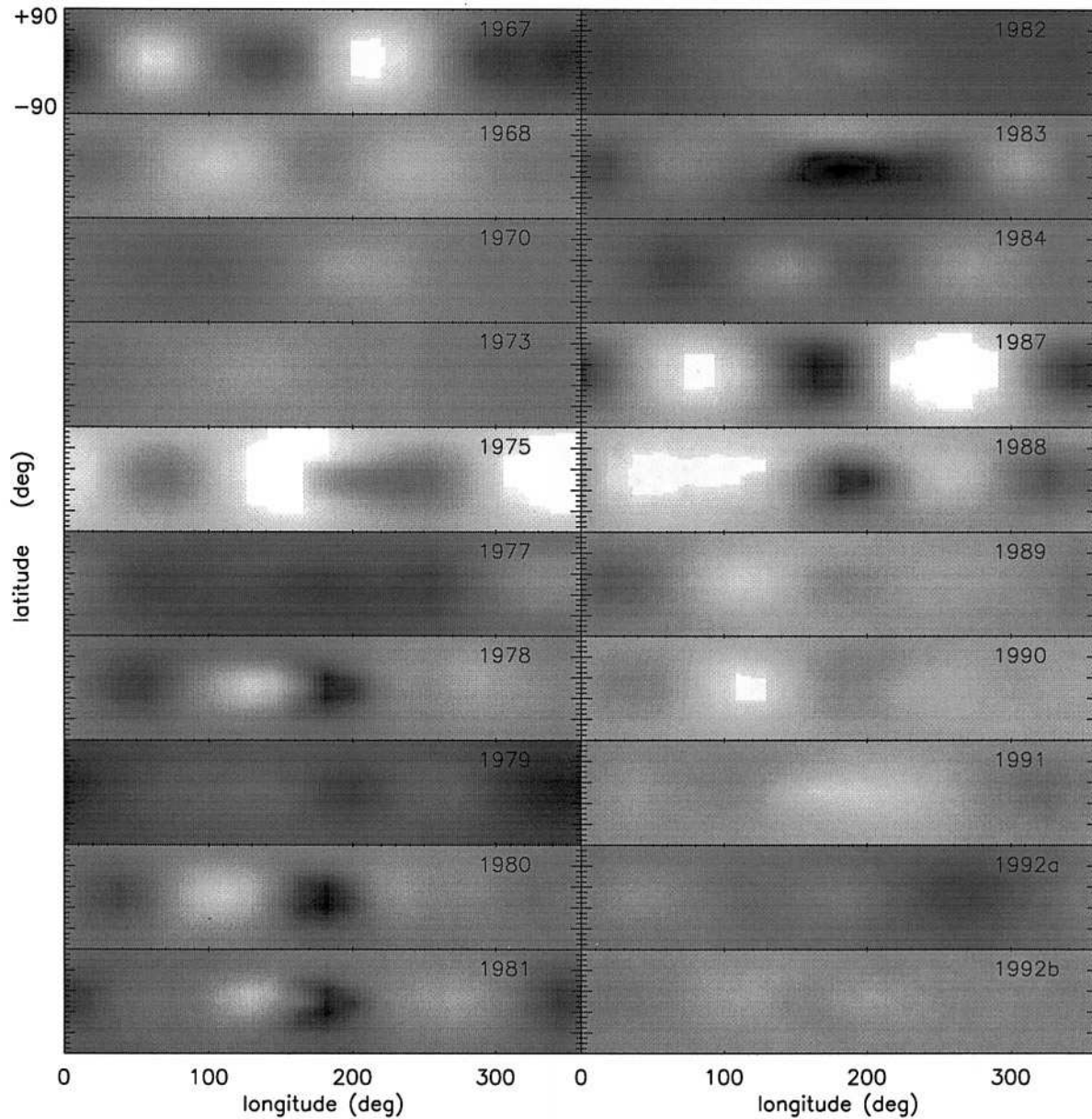


Fig. 8. The distribution of the covering factor on the K0 IV secondary corresponding to the Tikhonov regularized fits for the V-band light curves from 1967 to 1980.

self, e. g., the spot longitudes, their changes in time and the variations of the total spotted area. Absolute values of the total spotted areas are not reliable since they depend on the unspotted magnitude and the regularizing criterion adopted, but their time changes show a very small dependence on both of them (see, in particular, Fig. 14 referring to the secondary component, for which the information content of the data is sufficiently high).

The time variation of the total spotted area of the secondary component provides some hint for an activity cycle of ~ 17 yr, but a time base of at least 40 – 50 yr is needed to derive any firm conclusion.

The yearly areal changes can be used to estimate the magnetic turbulent diffusivity $\eta_T \simeq \frac{\Delta A}{\Delta t}$, where ΔA is the spot area

decrease due to turbulent decay of the magnetic field in the time Δt (Priest 1984). In the hypothesis that the spot area decrease on the K0IV star between 1970 and 1975 was due only to a turbulent decay, we obtain:

$$\eta_T \simeq 4 \times 10^{10} \text{ m}^2 \text{ s}^{-1} \quad (11)$$

Such a value is significantly larger than those deduced from typical single sunspot decay $\eta \simeq 2 \times 10^7 \text{ m}^2 \text{ s}^{-1}$ (Meyer et al. 1974) or large sunspot groups $\eta \simeq 10^9 \text{ m}^2 \text{ s}^{-1}$, but is smaller than that estimated for the active component of RS CVn: $\eta \simeq 2 \times 10^{11} \text{ m}^2 \text{ s}^{-1}$ (Rodonò et al. 1995). Such large values are not unreliable since on a K0 subgiant we expect that the length scale of the turbulent convection might be much larger than on the Sun

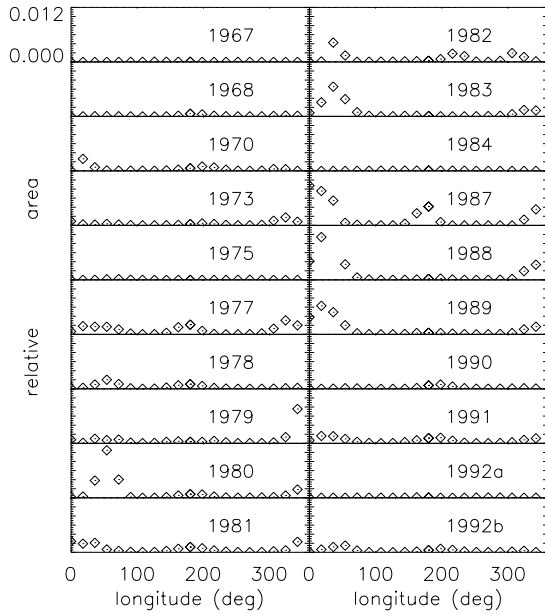


Fig. 9. The distribution of the relative spot area vs. longitude obtained from the ME models for the G2IV primary. The area unit is the photospheric area of the component (see text).

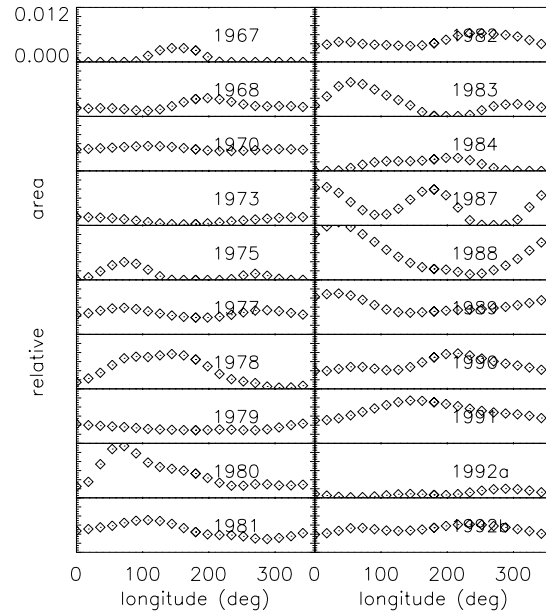


Fig. 10. The distribution of the relative spot area vs. longitude obtained from the T models for the G2IV primary. The area unit is the photospheric area of the component (see text).

(Schwarzschild 1975).

The analysis of the longitude distributions of the spotted area on both components does not provide evidence for a regular migration, as found in other RS CVn systems (Catalano 1983, Rodonò et al. 1995). Conversely, we have some evidence for the existence of stationary active longitudes on both stars. On the primary we detected a concentration of spot activity around the substellar point, even if the presence of other active longitudes cannot be ruled out. On the secondary there is a large active longitude around the substellar point, which appears in all of the ME maps and in about 50% of the T maps. The ME maps give also evidence for a sector structure with smaller and less persistent active longitudes around 60° and 300° , separated by $\sim 120^\circ$ from each other. We believe that such active longitudes are real and are not due to, e.g., errors in the treatments of proximity effects because the spot pattern is not stationary, as we should expect in such a case. However, the unfavourable orbital period and the short-term intrinsic light fluctuations can mask the short-term evolution of the spot pattern and increase the difficulty in detecting a photometric wave produced by spots, which is apparent in, e. g., the prototype RS CVn.

The results by Kang & Wilson (1989), though derived in the assumption of spots located only on the secondary, may provide further support for the existence of active longitudes on AR Lac (cf. the clustering of starspots around longitudes 0° , 180° , 270° in their Fig. 11). However, the location of their centers of activity cannot be directly compared with those derived in the present analysis because we have allowed for spots on both components.

It is interesting to compare the present results on the existence of a sector structure on the K0IV secondary with the recent

analysis of a long-term photometric sequence of HK Lac showing the presence of two persistent active longitudes at $\sim 120^\circ$ from each other on the K0III secondary of this long period RS CVn system (Oláh et al. 1997). Previous observational evidence for active longitudes on short period RS CVn systems has been provided by, e. g., Budding & Zeilik (1987), Zeilik (1991), Zeilik et al. (1994) but the suggested geometry is different (two active longitudes around 90° and 270° , with one longitude usually more active than the other at any given time).

Mean field dynamo models predict the possible existence of active longitudes related to non-axisymmetric modes when the amplitude of the stellar differential rotation does not exceed about half of the solar value. Only non-axisymmetric field geometries with an azimuthal wavenumber $m = 1$ have been found to be stable, but such a result may possibly be due to the many simplifying assumptions of present mean field models (Rädler et al. 1990, Moss et al. 1991, Rüdiger & Elstner 1994, Moss et al. 1995). Moreover, it is possible that the binary nature of the RS CVn's has an influence on the activity of the single components (Schrijver & Zwaan 1991). Specifically, the presence of stationary preferential longitudes may be related to perturbations on the magnetic fields stored at the base of the convective envelope, due to tidal forces, which eventually trigger the emergence of magnetic flux tubes.

Polar spots are not required by our solutions, but this leaves unanswered the question of their existence, claimed by several authors (see, however, Hatzes et al. 1996 for a critical discussion of the related spectroscopic evidence). The presence of large low latitude spots, as deduced by our eclipse mapping, suggests the existence of MGauss toroidal fields in the over-

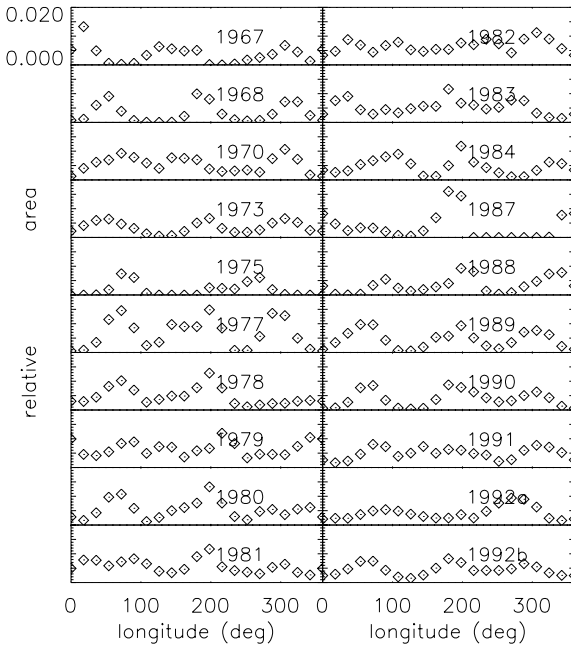


Fig. 11. The distribution of the relative spot area vs. longitude obtained from the ME models for the K0IV secondary. The area unit is the photospheric area of the component (see text).

shoot regions below the convective envelopes of the AR Lac components (Schüssler & Solanki 1992, Schüssler et al. 1996). Toroidal flux tubes with field strengths exceeding $(2 - 4) \times 10^6$ G should have unstable azimuthal modes with azimuthal order $m = 1$ or $m = 2$, whose subsequent non-linear evolution can be quite complex (Caligari et al. 1995, Schüssler et al. 1996).

In the framework of the solar-stellar connection it is interesting to compare our results on the photospheric spot distribution with the information available on other atmospheric domains. The chromospheres and transition regions of the components of AR Lac can be mapped by means of the Spectral Imaging technique, which has been applied to Mg II k line profiles obtained by IUE (Walter et al. 1987, Neff et al. 1989). The asymmetric line profiles in the period 1983-1991, provided evidence for compact plages on the secondary component, whereas the chromosphere of the primary was more or less uniform with a possible small difference in emissivity between its leading and trailing hemispheres (with the latter being about 20% darker than the former). The location of the chromospheric plages on the secondary provides some support for the sector structure suggested by our photospheric ME maps (cf. our maps with Fig. 2 of Pagano et al. 1994). Plages seem to be usually located near the borders of the largest photospheric spot concentrations. A solar-like atmospheric stratification is strongly suggested by the presence of a bright plage associated with the extended spot concentration around the substellar point on the K0IV star. Such a plage seems to be a long-lived structure, possibly slowly migrating from longitude $\sim 160^\circ$ to $\sim 220^\circ$ during the period 1985-1991 (Pagano 1993).

The analysis of X-rays light curves has given hints on the

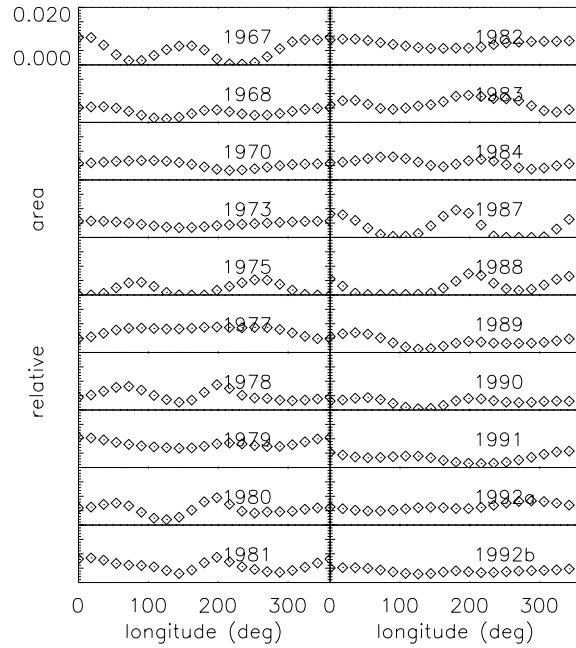


Fig. 12. The distribution of the relative spot area vs. longitude obtained from the T models for the K0IV secondary. The area unit is the photospheric area of the component (see text).

geometry of the coronae of AR Lac components suggesting the existence of discrete active regions on both stars (Walter et al. 1983, Ottmann et al. 1993, White et al. 1990, Siarkowski et al. 1996). The non-uniqueness problems in modelling the coronal emission are even more severe than for the chromospheric lines, due to the extended three dimensional structure of the corona and the lack of sufficient spectral resolution to distinguish unambiguously among components with different temperatures. Therefore any conclusion on the association between coronal emission and photospheric spots can only have an heuristic value.

The 1980 June X-ray observations analysed by Walter et al. (1983) have been modelled assuming a higher brightness of the leading hemisphere of the G2 component, an extended coronal component on the leading hemisphere of the K0 component and an inner component on its trailing hemisphere. Our maps show a spot concentration around longitude 40° on the leading hemisphere of the G2 star and a stronger spot coverage on the trailing hemisphere of the K0 star.

The maps derived by White et al. (1990) refer to X-ray observations obtained in July 1984. Unfortunately the 1984 optical light curve is among the poorest covered so that a fully meaningful comparison is not possible. However, their model IIa shows some general correspondence with our spot maps. A stronger agreement is found between their ME maps corresponding to the same model and our ME maps. In particular, compact active regions are found on the sides of the two stars facing each other, around the substellar points.

A large coronal structure extending from the inner hemisphere of the secondary towards the primary and a smaller structure on

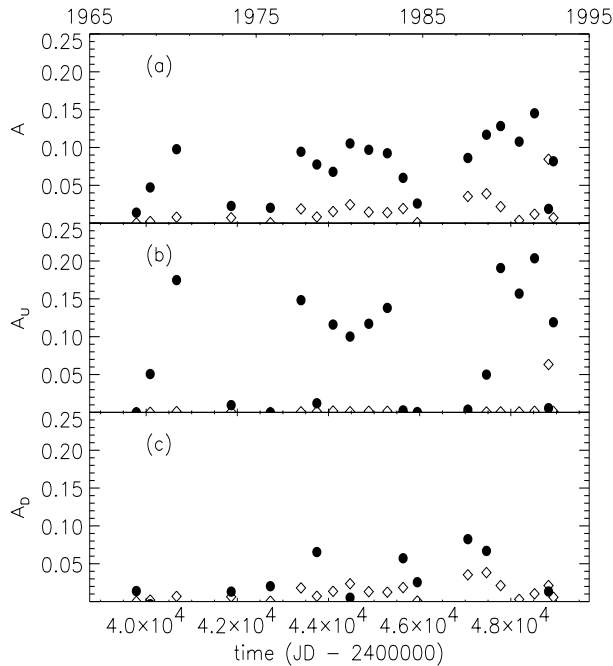


Fig. 13a–c. The total spotted area A (a), the area of the uniform, evenly distributed spot component A_U (b), and that of the discrete, longitudinally dependent spot component A_D (c), vs. time for the G2IV primary. The open symbols refer to the areas derived from the ME models, the filled symbols to the areas derived from the T models, respectively. The areas are normalized to the photospheric area of the G2IV component.

the outer emisphere of the primary is suggested by Siarkowski's (1992) analysis of the same light curve. Also such a model is in general agreement with the longitudinal spot distribution found by the present analysis, even if the regions of strongest X-ray emission near the stellar photophores do not completely overlap with the spot concentrations.

The ROSAT observations of June 1990 have been modelled by Ottmann et al. (1993), whose model I is in general agreement with our ME spot maps. However, the spot concentration around longitude 180° on the primary has no correspondent in the coronal model, as well as the starspots around longitudes 40° and $\sim 160^\circ - 210^\circ$ on the secondary. It should also be noted that no phase independent component has been assumed by Ottmann et al. (1993) in their model, whereas our maps show a uniform spot background on the K0 component.

Siarkowski et al. (1996) have presented a three dimensional model of the X-ray light curve observed by ASCA in June 1993. It is interesting to note the extended coronal emission interconnecting the two stars and the preferential location of coronal plagues on the emispheres of the components facing each other. Even if a detailed comparison is not possible because our light curve sequence ends in 1992, their results support the presence of an intense and long-lived activity center near the substellar point on the secondary component, where the feet of the interconnecting loops may possibly be rooted. Some evidence for Mg II k emission from cooler material near the barycentre of the system has been also provided by Pagano et al. (1994).

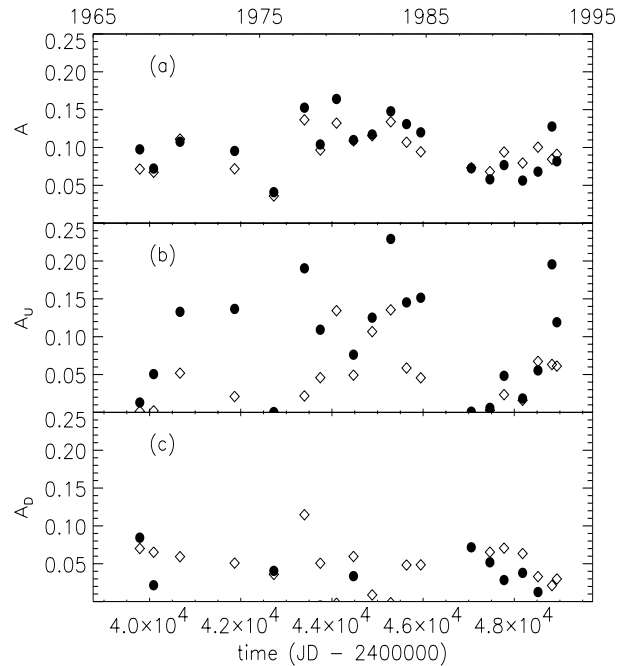


Fig. 14a–c. The total spotted area A (a), the area of the uniform, evenly distributed spot component A_U (b), and that of the discrete, longitudinally dependent spot component A_D (c), vs. time for the K0IV secondary. The open symbols refer to the areas derived from the ME models, the filled symbols to the areas derived from the T models, respectively. The areas are normalized to the photospheric area of the K0IV component.

In the light of the above results, we may conclude that a general association in longitude among spots, chromospheric and coronal plagues is suggested by the available data for the components of AR Lac (cf. Catalano et al. 1996 for a discussion of similar evidence in other RS CVn stars). More compelling evidence has been found for the large spotted region on the side of the secondary facing the primary, between longitudes 150° and 220° , which appears to be associated with bright and compact chromospheric plagues and an extended coronal structure, possibly interconnecting the two stars.

Another fundamental problem is that of the orbital period variations, which have been related also to magnetic activity (Hall 1990, Applegate 1992, Lanza et al. 1998). It is not possible to perform a detailed test of Applegate's (1992) model as done for the prototype RS CVn (Rodonò et al. 1995) because in the case of AR Lac we have no firm results both on the activity cycle and the rotation rate of the two components. However, the suggested orbital period modulation with a period of ~ 35 yr may be related to an activity cycle of ~ 17 yr length according to the mechanism proposed by Lanza et al. (1998) to explain the observed behaviour of RS CVn (cf. also Rodonò et al. 1995). The presence of an activity cycle of 17 yr is indeed suggested by the present analysis, but a definite conclusion has to wait for at least one or two more decades of additional data.

We note that the secondary star is more likely to be responsible for the orbital period modulation because its radius is 1.8 that

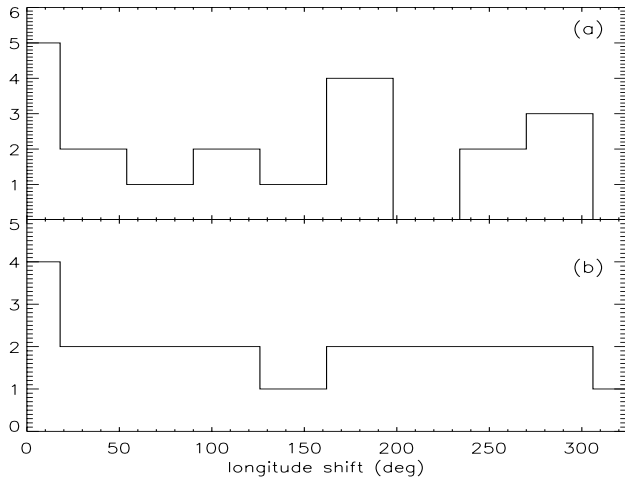


Fig. 15a and b. The distribution of the longitude shifts giving the maximum cross-correlation between successive yearly spot distributions for the ME models (a), and the T models (b) of the G2IV primary, respectively.

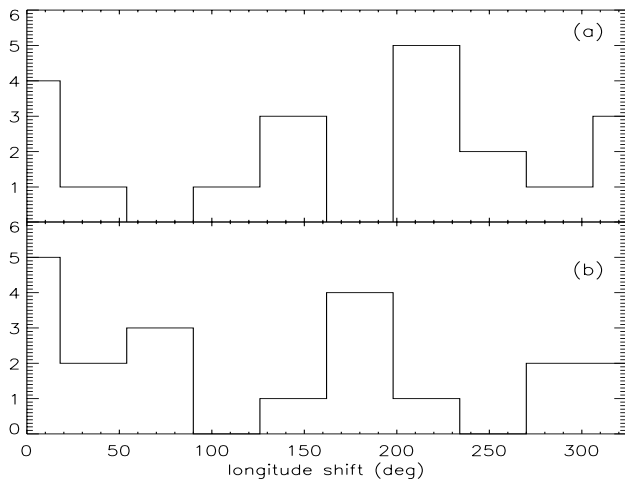


Fig. 16a and b. The distribution of the longitude shifts giving the maximum cross-correlation between successive yearly spot distributions for the ME models (a), and the T models (b) of the K0IV secondary, respectively.

of the primary and the variation of its gravitational quadrupole moment is therefore ~ 20 times larger than expected for the primary, assuming the same relative variation of the kinetic and magnetic energies along the activity cycle (cf. Applegate 1992, Lanza et al. 1998).

7. Conclusion

The adopted approach to the study of the activity of AR Lac has proved fruitful. More reliable values of the unspotted luminosities of the two components have been obtained in the framework of a self-consistent method which takes into account the presence of brightness inhomogeneities on both stars. The analysis of the AR Lac light curve sequence has allowed us to study in

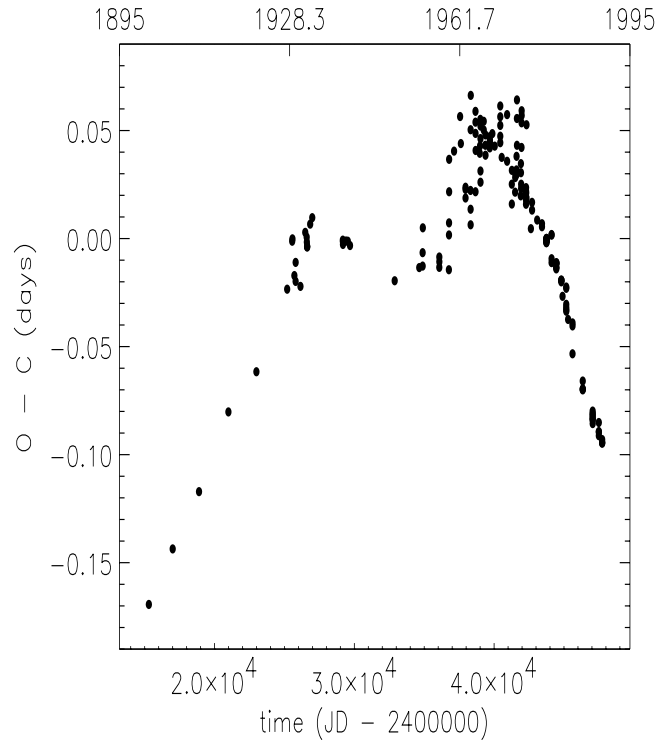


Fig. 17. Orbital period variations of AR Lac vs. time. The $O - C$ residuals were computed adopting the ephemeris reported in the text.

detail the capabilities offered by the ME and T criteria for map regularization. It is necessary to use both criteria in order to find out the image artifacts and the systematic errors associated with the specific hypotheses of each method.

The main results concerning the magnetic activity of AR Lac are the evidence for compact starspots on the primary and a sector structure of the active longitudes on the secondary star, with a general longitudinal association among magnetically controlled emission at different atmospheric heights. In particular, the large active region around the substellar point on the secondary shows itself not only at photospheric levels but also in the chromosphere and corona, with an extended structure which might well be an interconnecting loop between the two stars.

The existence of low latitude starspots on both components can be another important constraint for dynamo models. The possible association between orbital period modulation and the activity cycle of the secondary suggests the same kind of behaviour described by Rodonò et al. (1995) for RS CVn, but at least one or two decades of further observations are required to confirm such a prediction.

In particular, a longer time baseline is needed to establish if the activity levels of the two stars undergo overall cyclical modulations or fluctuate stochastically.

Wide-band observations by a network of ground based telescopes well distributed in longitude will overcome the difficulty of acquiring complete light curves from a single site. Moreover, spectroscopic observations will be extremely useful for a

more detailed mapping of the two components (Vincent et al. 1993). Further observations in the UV, IR and X-ray spectral domains are also needed for a better understanding of the three-dimensional structure of the atmosphere and the role played by the magnetic fields in its dynamics and energetics.

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