Astron. Astrophys. 356, 267–273 (2000)

ASTRONOMY AND ASTROPHYSICS

Orbital period variation in close binaries from radial velocity data and magnetic activity cycles

I. AR Lacertae: The test case

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Received 29 November 1999 / Accepted 4 February 2000

Abstract. We check the possibility of detecting orbital period changes in non-eclipsing close binaries by means of spectroscopic orbit determinations. In order to test our method, we selected the eclipsing binary AR Lacertae for which the spectroscopically determined epochs of superior conjuctions can be compared with those provided by the light minima photometry. It is found that intermediate-resolution spectroscopy and IUE archive spectra can be used to build radial-velocity curves which allow us to estimate the epoch of superior conjunction T_0 with an uncertainty of 0.01 days. We present the data-reduction procedure and the method of analysis, based on fitting a sinusoid to the radial-velocity curve, discussing the accuracy of T_0-value determinations and the possible sources of errors, notably those related to surface inhomogeneities, such as spots and faculae. The possibility of testing the hypothesis of a light-time effect for the orbital period modulation is also addressed by means of radial-velocity measurements.

Key words: stars: binaries: close – stars: activity – stars: binaries: eclipsing – stars: binaries: spectroscopic – stars: individual: AR Lac

1. Introduction

Several close binaries belonging to the Algol, RS Canum Venaticorum (RS CVn), W Ursae Maioris (W UMa) and Cataclysmic Variable (CV) groups show cyclical changes of the orbital period with amplitudes of the order of $\Delta P/P \sim 10^{-5}$ in Algols and RS CVn and $\Delta P/P \sim 10^{-7} - 10^{-6}$ in W UMa and CVs. The time scales range from a few years in some CVs, up to several decades (typically around 40-50 yr) in RS CVn and Algol systems (Hall 1989, 1990). On empirical grounds, it has been suggested by Hall (1989) that the modulation of the orbital period is connected with magnetic activity. He pointed out that in a sample of 101 Algols only the systems with secondaries of spectral type later than F5 show orbital period changes of alternate sign. The presence of a sizeable convective envelope and the fast rotation (due to tidal synchronization) are indeed regarded as sufficient conditions for the development of a powerful hydromagnetic dynamo action (Parker 1979, Weiss 1994).

Preliminary models to account for the connection between magnetic activity and orbital period modulation have recently been proposed by Applegate & Patterson (1987), Warner (1988), Applegate (1992), Lanza et al. (1998a) and Lanza & Rodonò (1999). The components of a close binary are distorted from spherical symmetry by tidal and centrifugal forces, so the gravitational potential, responsible for the orbital motion, depends also on the gravitational quadrupole moment terms of the stars. The quadrupole moment of the active component Q may change cyclically, because the distribution of the angular momentum and the Lorentz force inside the star may vary along the activity cycle, and, therefore, induce slight changes of the stellar oblateness. The change of Q directly couples with the orbital motion and produces a modulation of the orbital period (cf. Applegate 1992 for details). The orbital period changes are cyclical because the stellar magnetic fields, causing the variation of Q, are modulated by the stellar activity cycle. Therefore, the modulation of the orbital period may offer the possibility to measure the length of the activity cycles of active stars in close binaries, independently of the detection of any proxy for the magnetic field, such as a flux modulation due to starspots or the flux in the chromospheric and transition-region lines.

In order to test the proposed models, the relationship between the cycle in the starspot area and the orbital period modulation has been studied in a few RS CVn systems. The results obtained are quite intriguing, because there seem to be two different scenarios: a) for RS CVn it is found that the period of the starspot cycle is half that of the orbital period modulation (Rodonò et al. 1995), and there are preliminary indication of a similar behaviour for AR Lac (Lanza et al. 1998b), RT Lac (Keskin et al. 1994, İbanoğlu et al. 1998) and possibly AB And (Demircan et al. 1994); on the contrary, b) for V471 Tau, and possibly CG Cyg, the period of the long-term luminosity variations equals that of the orbital period modulation (İbanoğlu et al. 1994, Hall 1991). The two scenarios may correspond to different modes of operation of the stellar dynamo, as discussed in detail by Lanza et al. (1998a), and, therefore, it is of the greatest

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interest to obtain more information on the relationship between orbital period modulation and activity cycles in other systems.

The most accurate information on the orbital period changes in close binaries has been derived from eclipse timings, by determining the residuals O–C with respect to a constant-period ephemeris (cf., e.g., Batten 1973). For the best observed RS CVn and Algol systems about one century of data are available, but the old visual or photographic epochs are usually affected by sizeable errors, up to one order of magnitude larger than photoelectrically determined epochs.

The orbital period changes determined through eclipse photometry may be accurate up to $\Delta P/P \sim 10^{-8} - 10^{-7}$, but such a precision is limited to eclipsing systems with a period of a few days and without activity-related effects which may distort the light curve (cf. Sect. 4). On the other hand, in the catalogue of chromospherically active close binaries by Strassmeier et al. (1993), about 55% of the listed systems are non-eclipsing. Therefore, it is interesting to investigate whether spectroscopic radial-velocity data may also be used to detect orbital period changes in active close binaries.

Recently, Donati (1999) presented some evidence for orbital period change in HR 1099, from six years' spectroscopy. His study was mainly devoted to Zeeman Doppler imaging of the active component of the system. The good phase coverage of the spectroscopic data allowed him to show a variation of the time of conjunction, while the radial velocity of the barycentre γ remained constant during the same period. This suggests a true orbital period change, because an apparent change due to a light-time effect due to a hypothetical third companion can be ruled out by the constancy of γ.

In the present paper we study the capability of radial-velocity data, obtained by intermediate resolution spectroscopy, to provide us with adequate information on orbital period changes in active close binaries. To this purpose, we analyse all the available radial velocity and photometric data for the RS CVn system AR Lacertae (HD 210334, G2IV+K0IV), so that a direct comparison of spectroscopic and photometric O–C's could be performed. The data set we used consists of literature spectroscopic orbit determinations, IUE archive data and more recent observations obtained within a long-term program of chromospheric activity monitoring in close binaries.

We discuss the differences in the O–C obtained from photometric eclipse timing and spectroscopic time of conjunction and point out the advantages and drawbacks of these two different methods. We show that the O–C's determined from archive spectroscopic data can indeed provide us with useful information on the orbital period changes in active binaries.

2. Observations and data reduction

Since 1994 we have secured many intermediate-resolution spectra of AR Lac in the red-wavelength region, acquired with the échelle spectrograph at the 91-cm telescope of Catania Astrophysical Observatory. The aim of those observations has been that of monitoring the variation of the Hα emission versus the orbital phase as well as variations of the overall chromospheric activity on longer time scales (Frasca et al. 1999). Moreover, the wealth of acquired spectra, well distributed versus orbital phase, has allowed us to determine a more accurate orbital solution. Radial-velocity determinations, made by cross-correlation of the AR Lac spectra with spectra of a radial-velocity standard star, have been presented by Marino et al. (1998) together with the solution to the radial-velocity curve. A more detailed discussion can be found in Frasca et al. (1999).

In view of our interest in orbital period variations on time-scales of decades or more, we then looked for other radial-velocity curves in the literature.

The oldest observations are those of Harper (1933) who measured radial velocities of both components of AR Lac on 22 spectrograms obtained in 1931 with the single-prism instrument attached to the 72-inch reflector of the Dominion Astrophysical Observatory. The reported errors are of 4.6 and 5.8 km s^{-1} for the primary and secondary components, respectively, though the data points seem to show a larger scatter with respect to the sinusoidal best fit. Harper gave the first orbital solution for AR Lac, with a small eccentricity ($e = 0.041 \pm 0.002$). Subsequent studies, like those of Sanford (1951), Popper (1980, 1990) and Marino et al. (1998) led to a circular orbit. Unfortunately, Harper did not list the measured velocities, but gave only the orbital elements derived from his measurements. We have then used his epoch of periastron 2 426 625.732 that has been transformed into the epoch of the center of the nearest primary eclipse (i.e., the superior conjunction, with the hotter primary component behind the cooler secondary component), yielding HJD0 = 2 426 626.366.

The next set of data found in the literature consists of four radial-velocity measurements made by Young (1939) in 1935 and 1936 with the one-prism spectrograph attached to the 74-inch telescope of the David Dunlap Observatory. The linear dispersion was 16 Å/mm at Hγ. The radial velocities of both components were measured by means of 9–19 spectral lines. Young did not report the accuracy of his measurements although it should be probably comparable with that of the radial-velocity determinations of other spectroscopic binaries observed with the same instrumentation, which were typically in the range 5–10 km s^{-1}.

Another useful data set is found in the work by Sanford (1951), who re-determined the orbital solution on the basis of 22 spectrograms in the blue-violet region. Those data were acquired from 1945 to 1948 with a coudé spectrograph of the 100-inch telescope with 10 Å/mm linear dispersion. No information about errors on radial-velocity measurements was reported by Sanford.

We looked for other sets of radial-velocity measurements that could fill the broad gap between that last epoch and our 1994-1997 data, but we did not find any useful reference in the literature. That is probably due to the difficulty of achieving a good phase coverage, the orbital period of AR Lac being almost exactly 2 days. Therefore, we looked for AR Lac observations in the *IUE* Final Archive and we found a large number of high-resolution spectra, mainly obtained during several monitoring campaigns dedicated to the study of AR Lac chromospheric activity (see, e.g., Pagano et al. 1996). Moreover, the satellite observations are much better distributed in phase also for short observing runs, a great advantage with respect to ground-based observations which are hampered by the day-night duty cycle.

The ultraviolet spectra available in the *IUE* Final Archive have been extracted by means of the new image-processing system NEWSIPS which largely reduces the fixed-pattern noise in comparison to the older system IUESIPS. It has been estimated that, for high-resolution spectra, the signal-to-noise ratio has been improved up to 100% or more (Nichols & Linsky 1996). Moreover, a better wavelength calibration has been obtained (see, e.g., Nichols & Linsky 1996, Barylak & Ponz 1998). Since we were interested in the radial velocities of the photospheric lines, we did not consider chromospheric emission lines like Mg II h & k, which seem to be affected by distortions caused by plages or other chromospherically extended structures (see, e.g., Pagano 1993). The long-wavelength high-resolution spectra (the largest part of all the IUE high-resolution observations of AR Lac) are the most useful for an analysis of the photospheric lines, because at wavelengths longer than about 2700 Å the continuum flux of the hotter G2 IV component begins to dominate. The best method to perform radial-velocity measurements in this spectral region, in which the signal is fairly low and many strong absorption lines crowd together, is by cross-correlating the observed spectra with those of radial-velocity standard stars (see, e.g., Stickland & Lloyd 1999).

We selected LWR and LWP spectra acquired in different observing seasons. The first group of data consists of the spectra taken with the long-wavelength redundant camera in 1979, 1980, 1981 and 1983. We were obliged to put together spectra obtained in 5 consecutive years in order to obtain a complete phase coverage for these first IUE observations. As a radial-velocity standard, ϵ Cyg was chosen (K0 III, $v_R = -10.6$ km s^{-1}, already used for the optical spectra), and its spectrum LWR11399, observed in 1981 August with the same instrumental configuration, was used in our analysis. As a matter of fact, it has recently been reported that ϵ Cyg displayed a long-term radial-velocity variation with an amplitude of a few hundreds of m s^{-1} in the time interval covered by the IUE observations (cf. Griffin 1994).

Two other data sets were constructed with spectra acquired with the long-wavelength prime camera in 1985 and 1989 respectively. Since we did not find a LWP spectrum of ϵ Cyg, we used 54 Aql (F8 V, $v_R = +0.1$ km s^{-1}) as a radial-velocity standard for those spectra, taking its LWP15583 spectrum acquired with the prime camera in 1989 May. It is important to adopt a radial-velocity standard observed with the same instrumental configuration because a cross-correlation of the LWP15583 with the LWR11399 spectra showed systematic differences in the wavelength scale calibrations amounting up to $\sim$20-30 km s^{-1}.

We cross-correlated each order of the AR Lac spectra with the corresponding one of the radial velocity standard, starting from the 83rd order ($\lambda_c = 2750$ Å) and ending at the 72nd order ($\lambda_c = 3170$ Å) because thereafter the portion of each order covered by the detector became very small. Chromospheric lines like the Mg II h & k and the spikes sometimes present were excluded from the cross-correlation. The low-signal edges of the orders were also excluded. After many tests, we realized that a 5-point boxcar smoothing (which corresponds to a resolving power $\frac{\lambda}{\Delta\lambda} = 10\,000$) improved the cross-correlation considerably. Although the cross-correlation function of spectra far from the eclipses had a double-peaked appearance, the peak relative to the G2 IV star (which dominates at these wavelengths) was always much higher. Consequently, the radial velocity of the hotter component was much better determined, and the results from the different orders were consistent with each other.

In Table 1 the IUE spectra are listed together with the heliocentric Julian day (HJD), the radial velocity of the G2 IV component of AR Lac and its error. The radial velocities are averages of the values resulting from the different orders, discarding measures outside the $3\,\sigma$ confidence level. The errors in the radial velocities were evaluated by computing the standard deviation of the measurements and were typically a few km s^{-1}. For the cool component we found much larger errors, so we decided to disregard its radial-velocity curves completely in our analysis.

3. Analysis and results

Our latest orbital solution (Frasca et al. 1999) was computed by folding the radial-velocity data in phase with the recent photometric ephemeris by Marino et al. (1998):

$$HJD_{\rm minI} = 2450692.5174 + 1.983188 \times E. \quad (1)$$

The sinusoidal fits (circular orbits assumed) agree very well with our observations and lead to the orbital elements listed in the first row of Table 2.

In order to check the overall goodness of the radial velocities of the G2 IV component derived from IUE spectra, we performed sinusoidal fits to the radial-velocity curves relative to the three IUE radial-velocity data sets, that have been separately folded in phase with the photometric ephemeris closest in time (Ertan et al. 1982, Lanza et al. 1998b, respectively). We used the CURFIT routine (Bevington 1969) based on a gradient-expansion algorithm which gives also standard deviations for the parameters. The values of the barycentric velocity γ and semi-amplitude K_{G2} determined in such a way are in good agreement with those provided by Frasca et al. (1999), as apparent in Table 2.

After checking for the consistency of the various radial velocity-curves, we determined the differences between the epochs of superior conjunction and a fixed ephemeris. All the radial-velocity data were folded in phase with the following ephemeris (Pagano 1990):

$$HJD_{\rm minI} = 2426624.3817 + 1.9832142 \times E. \quad (2)$$

Each radial-velocity curve was then fitted with a sinusoid in which γ, K_{K0} and K_{G2} were fixed to the values determined by the 1994-97 optical solutions. In order to account for the phase shift produced by the orbital period variation, the phase of the superior conjunction (ϕ_0) had to be changed from one data set to

Table 1. Radial velocities of the G2 IV component of AR Lacertae from IUE final archive spectra.

Spectrum	H.J.D.	V_{G2} (km s^{-1})	ΔV_{G2}
LWR05023	2444067.53655	−97.2	7.5
LWR06661	2444252.93263	42.0	3.6
LWR08017	2444404.00326	−88.9	9.7
LWR08029	2444404.40540	−150.5	5.9
LWR09003	2444524.22806	72.1	5.5
LWR09010	2444525.39506	−146.8	3.3
LWR11662	2444880.12225	−126.6	5.1
LWR11666	2444880.48553	−139.9	4.3
LWR11672	2444881.15765	59.5	7.6
LWR11676	2444881.56755	41.7	5.2
LWR16916	2445611.42282	36.8	3.2
LWR16917	2445611.52184	8.3	6.1
LWR16918	2445611.61357	−21.4	14.2
LWR16922	2445612.04109	−151.5	3.4
LWR16925	2445612.56476	−49.0	4.6
LWR16926	2445612.67702	−17.5	3.4
LWR16927	2445612.77900	14.5	3.7
LWR16928	2445612.87780	51.4	2.6
LWP06746	2446326.76309	28.5	3.1
LWP06747	2446326.83970	54.4	5.0
LWP06748	2446326.90493	64.6	3.0
LWP06749	2446326.95214	71.8	10.6
LWP06750	2446327.12876	79.4	2.9
LWP06751	2446327.20250	67.9	4.0
LWP06752	2446327.27699	55.5	3.4
LWP06753	2446327.36153	26.7	3.0
LWP06754	2446327.44639	10.0	1.9
LWP06755	2446327.56224	−25.1	7.1
LWP06756	2446327.64021	−76.4	23.4
LWP06757	2446327.71505	−95.3	3.1
LWP06758	2446327.79058	−115.2	2.4
LWP06759	2446327.86689	−134.6	2.6
LWP06760	2446328.02874	−153.8	2.9
LWP06761	2446328.11497	−153.0	2.2
LWP06762	2446328.18727	−144.7	2.4
LWP06763	2446328.26579	−127.0	3.0
LWP06764	2446328.33710	−106.4	2.2
LWP06765	2446328.40636	−79.0	5.8

Table 1. (Continued).

Spectrum	H.J.D.	V_{G2} (km s^{-1})	ΔV_{G2}
LWP16243	2447769.21199	20.2	2.6
LWP16245	2447769.38414	−82.7	2.7
LWP16246	2447769.46442	−92.8	3.5
LWP16247	2447769.54284	−109.1	1.8
LWP16248	2447769.61839	−129.7	2.6
LWP16249	2447769.69566	−143.9	2.7
LWP16250	2447769.78675	−151.7	3.1
LWP16251	2447769.86499	−147.8	2.7
LWP16252	2447769.94008	−139.9	5.6
LWP16253	2447770.00463	−132.4	8.0
LWP16254	2447770.06308	−112.3	3.8
LWP16255	2447770.13127	−89.7	3.0
LWP16256	2447770.23073	−62.0	4.4
LWP16257	2447770.30788	−34.5	1.8
LWP16258	2447770.38341	−7.6	5.2
LWP16259	2447770.45984	16.5	2.4
LWP16260	2447770.53474	44.9	3.5
LWP16261	2447770.60809	60.5	2.7
LWP16262	2447770.68309	75.8	2.5
LWP16263	2447770.75251	82.9	1.2
LWP16266	2447771.53085	−112.2	2.7
LWP16267	2447771.60020	−128.9	3.6

the other. For the data sets containing radial velocities of both components, this analysis was applied to both radial-velocity curves, and an average phase shift was derived. For the IUE data, only the G2 IV component was taken into account.

In Fig. 1 we present the radial velocity curves computed according to the ephemeris (2) (continuous lines), and the observed radial velocity curves (dashed lines). Their comparisons clearly show the amounts of phase shift ϕ_0.

These phase shifts ϕ_0 were then converted into O–C time differences.

In Table 3 we list the mean epoch of the spectroscopic observations together with the time interval during which the observations were performed, the corresponding O–C, and the data reference. The spectroscopic O–C's are plotted in Fig. 2 (circles) versus time, together with the photometric O–C's (filled squares), derived from the epochs of primary eclipses. The photometric O–C's were taken from Lanza et al. (1998b) and extended to very recent times with the new data of Marino et al. (1998).

In spite of the small number of spectroscopic O–C's, the resulting period variation very closely follows that of the more numerous photometric O–C's. Unfortunately spectroscopic data are not available during the monotonically increasing part of the O–C curve, before 1930, or in the time interval 1950–1970, during which the system underwent a small increase of period and reached a maximum positive O–C (+0.06 day). Conversely, there is a very good superposition in the descending branch of the curve, from the late seventies up to present time.

4. Discussion

We have determined the epochs of superior conjunctions of the binary components T_0 by fitting a sinusoid to the radial-velocity curves of the components of AR Lac. The accuracy of the radial-velocity determinations will affect the derived epochs of conjunctions. Assuming that the orbital period and the amplitude of the radial-velocity curve K are precisely known and that the errors of the radial velocity-data are uncorrelated, we may estimate the standard deviation of the epoch of conjunction as:

$$\sigma_{T_0} \simeq \frac{\sigma_v}{4\pi K} P \qquad (3)$$

where σ_v is the standard deviation of the radial-velocity measurements. In the present case, both for the radial velocities determined by IUE spectra and our échelle observations, we have: $\sigma_v = 4.5$ km s^{-1}, $K \simeq 120.0$ km s^{-1} (for the G2 primary),

Table 2. Orbital elements of AR Lacertae

Data	K_{K0} (km s^{-1})	K_{G2} (km s^{-1})	γ (km s^{-1})	Reference
1994-97	106.73 ± 0.29	119.43 ± 0.49	-34.54 ± 0.50	Frasca et al. 1999
1979-83	—	117.41 ± 1.43	-34.72 ± 1.03	IUE archive
1985	—	117.42 ± 0.94	-36.05 ± 0.71	IUE archive
1989	—	117.70 ± 0.78	-33.89 ± 0.55	IUE archive

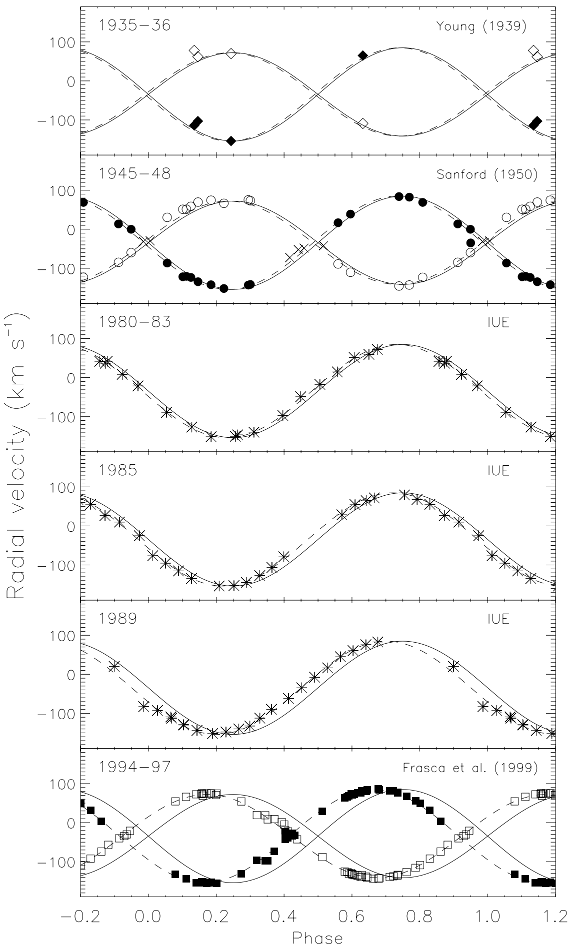

Fig. 1. Radial-velocity curves and best-fit solution of AR Lac. The continuous lines are the radial-velocity curves computed according to ephemeris (2), the dashed lines are the actual radial-velocity curves, fitted to the observational data by varying the phase of superior conjunction ϕ_0.

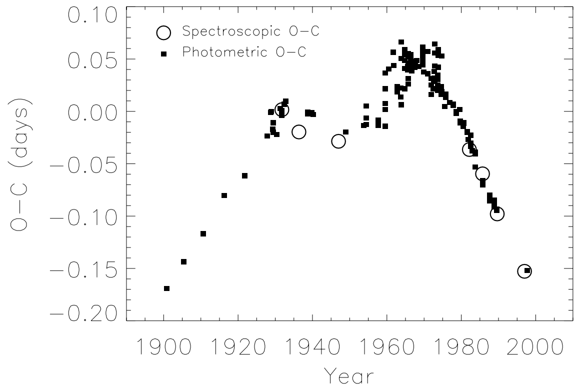

Fig. 2. Orbital period variations of AR Lac vs. time. The O–C residuals were computed from the ephemeris reported in the text (see Eq. 2). The photometric O–C's are displayed as filled squares, while the spectroscopic ones are represented by circles.

Table 3. O–C from spectroscopic orbits

Mean epoch (JD)	Time interval (year)	O–C (days)	Reference
2426626.4	1931	0.002	Harper (1933)
2428301.8	1935	-0.020 ± 0.030	Young (1939)
2432190.4	1945-48	-0.029 ± 0.006	Sanford (1951)
2445033.3	1979-83	-0.036 ± 0.004	IUE Archive
2446327.6	1985	-0.060 ± 0.003	IUE Archive
2447770.1	1989	-0.098 ± 0.002	IUE Archive
2450449.0	1994-97	-0.153 ± 0.001	Present paper

$P = 1^{\rm d}.983$, yielding $\sigma_{T_0} = 0^{\rm d}.006$. Such a value is in agreement with those given by the CURFIT routine and reported in Table 3, thus showing that the accuracy of T_0 is basically limited by the accuracy of the radial-velocity data.

Photometrically determined epochs of primary minima may be accurate up to $10^{-4} - 10^{-3}$ day, when the eclipses are not distorted by stellar-activity phenomena (Batten 1973). Therefore, we conclude that the determinations of the epochs of conjunction by fitting radial-velocity curves are $5 - 50$ times less accurate than good photoelectrically determined mid-eclipse epochs.

The plot of the O–C reported in Fig. 2 shows a good agreement between the values determined from eclipse photometry and those from radial-velocity curves. Typical differences are $\leq 0^{\rm d}.01$ for modern measurements, confirming the above estimates on the precision of the radial-velocity method. However, the differences are larger for the old measurements obtained in the 1930-1950 period. It is worth noting that the photometric O–C's reported in Fig. 2 were obtained with different techniques and most of the determinations made before 1975 were based on visual or photographic measurements. Moreover, they often cover only a portion of the primary eclipse, leading to a large scatter. Hall & Kreiner (1980) plotted the O–C curve of AR Lac using different symbols for the O–C's determined photoelectrically and those determined visually or photographically, showing that photoelectric photometry gives O–C values with a precision $\leq 0^{\rm d}.01$, whereas the other methods give a precision 2-3 times worse, causing the sizeable scatter of the O–C's before 1975.

We conclude that the O–C values determined from modern radial-velocity curves agree with those determined from photoelectric eclipse timings within $0.01 - 0.015$ days, whereas the determinations based on old photographic data have an estimated precision of ~ 0.03 days.

Surface inhomogeneities, such as spots and faculae, may distort the photometric eclipses and affect the radial-velocity measurements by perturbing line profiles. Hall & Kreiner (1980) gave a formula to estimate the systematic error of the O–C's induced by the distortion caused in the photometric profiles of the eclipses by spots and found that in AR Lac the errors should never exceed $0^{\rm d}.01$. Similar results were also found by Kang & Wilson (1989), who modelled some light curves of AR Lac. They found that it was sometimes necessary to correct the epoch of conjunction with respect to the ephemeris, in order to obtain a satisfactory fit to the light variation during primary eclipses, and attributed such an effect to the presence of spots. However, the correction was never larger than $0^{\rm d}.018$ for AR Lac, i.e., 0.009 in phase units. We found similar results by analysing extended sequences of light curves of RS CVn and AR Lac (Rodonò et al. 1995, Lanza et al. 1998b). Therefore, we conclude that the estimates based on the formula proposed by Hall & Kreiner (1980) are correct and the effect of the spots on the O–C's of primary eclipses is typically smaller than $\sim 0.005 - 0.01$ days for RS CVn binaries. For contact binaries, the effect may be somewhat larger, but it is unlikely to affect significantly the long-term variation of the O–C (cf., e.g., Maceroni & van't Veer 1993).

The presence of spots also affects the photospheric line profiles, causing distortions which migrate in wavelength as the star rotates (cf. Vogt & Penrod 1983) and may influence the measure of the radial velocity. For simplicity's sake, we assume that the line profile is not resolved and the profile distortion induces an apparent sinusoidal variation of the measured radial velocity of amplitude v_s: $\Delta v_r = v_s \sin(\omega t + \chi)$, which is superimposed upon the variation produced by the orbital motion. Stellar rotation and orbital motion are assumed to be synchronized, in such a way that $\omega = 2\pi/P$, where P is the orbital period, but the minimum of the radial-velocity curve is shifted in phase by χ with respect to the minimum of the perturbation induced by spots. The error in the epoch of superior conjunction depends both on the amplitude v_s and the phase difference χ as: $\delta T_0 \sim v_s P \sin\chi/(2\pi K)$. In the case of AR Lac, we may disregard the radial-velocity curve of the secondary K0 IV component, which is mainly affected by spots, and consider only the radial-velocity curve of the primary. The latter shows some evidence of spot activity with a maximum filling factor f_m of 5% of the stellar disk (cf. Lanza et al. 1998b). Therefore, we may estimate v_s roughly as: $v_s \sim f_m(R/a)K$, where R is the radius of the star and a the semi-major axis of the orbit. In the case of the primary component of AR Lac, $R/a \sim 0.2$, which yields $v_s \sim 2$ km s^{-1}. Therefore, the corresponding variation in the epoch of conjunction δT_0 is typically less than $0^{\rm d}.001$. We conclude that when only the spectra of the primary are used for the determination of the O–C, the effects of the spots on the radial-velocity measurements are negligible in comparison with the uncertainty of the radial-velocity data considered in the present study.

The radial-velocity determinations allow us an independent test of a third-body hypothesis, often invoked to explain the observed modulation of the O–C as a light-time effect. We may easily estimate the variation of the radial velocity of the barycentre γ expected in the case of a light-time effect. Considering the observations from 1980 to 1997, the O–C has decreased by $\Delta({\rm O-C}) \sim 0^{\rm d}.1$, which implies that the barycentre of the system has travelled a distance $c\Delta({\rm O-C}) \sim 2.9\times10^9$ km, where c is the speed of light. The average period of the O–C modulation is ~ 36 yr (Jetsu et al. 1997), so that about half a cycle is covered by the 1980-1997 observations and we may assume that the semi-major axis of the light-time orbit is $\frac{1}{2}c\Delta({\rm O-C})$. Therefore, the maximum variation of the radial velocity of the barycentre is $\Delta\gamma \sim 8$ km s^{-1} and the value averaged over the above period is ~ 5.5 km s^{-1}. The accuracy of the determination of the value of γ by our radial-velocity data is $0.5 - 1.0$ km s^{-1} (cf. Marino et al. 1998) whereas the accuracy of the values derived from IUE radial velocities is of the order of $0.7 - 1.0$ km s^{-1}, because the number of measurements is quite large and well distributed in phase. From an inspection of Table 2, we may conclude that the value of γ stayed constant in the 1980-1997 period within ±1 km s^{-1}, contrary to the prediction of the light-time-effect hypothesis. Such a result is based only on four determination of γ and, therefore, it needs further confirmation by future measurements. However, it shows that our observational method is adequate to test the light-time-effect hypothesis for the orbital period changes in RS CVn and Algol binaries.

5. Conclusion

We have shown the possibility of studying the long-term change of the orbital period of an active close binary by means of IUE archive spectra and échelle spectra taken during a long-term program for the monitoring of the chromospheric activity. The epochs of superior conjunctions may be estimated with an accuracy of $0^{\rm d}.01$ from radial-velocity curves obtained by means of cross-correlation techniques, when a good phase coverage is available. The line distortions produced by spots do not significantly increase the error when only the radial-velocity curve of the primary component is used, because photospheric inhomogeneities cover only a few percent of its surface. Therefore, the accuracy of the proposed method is adequate to study cyclical changes of the orbital period which produce O–C modulations with amplitudes of the order of $0^{\rm d}.1$ in some decades, as in RS CVn and Algol binaries. Moreover, intermediate-resolution spectra obtained for chromospheric monitoring are adequate to test the light-time-effect hypothesis for the orbital period modulation and, in the case of AR Lac, together with the IUE radial-velocity data, allow us to draw some preliminary conclusion, suggesting that the cyclic variation of the O–C can not be accounted for by that hypothesis.

Acknowledgements. The authors are grateful to Drs. M. Rodonò and S. Catalano for a critical reading of the paper and interesting discussions.

They are also grateful to the Referee, Dr. R. F. Griffin, for his careful reading of the manuscript and valuable comments.

This research has made use of the ADS-CDS databases, operated at the CDS, Strasbourg, France.

Active star research at Catania Astrophysical Observatory and the Department of Physics and Astronomy of Catania University is funded by MURST (*Ministero della Università e della Ricerca Scientifica e Tecnologica*), CNAA (*Consorzio Nazionale per l'Astronomia e l'Astrofisica*) and the *Regione Siciliana*, whose financial support is gratefully acknowledged.

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