W Crv: The shortest-period Algol with non-degenerate components? *

Slavek M. Rucinski and Wenxian Lu

David Dunlap Observatory, University of Toronto, Box 360, Richmond Hill, Ontario L4C 4Y6, Canada
e-mail: rucinski@astro.utoronto.ca, lu@astro.utoronto.ca

Accepted Received in original form 1999 July

ABSTRACT
Radial velocity data for both components of W Crv are presented. In spite of providing full radial-velocity information, the new data are not sufficient to establish the configuration of this important system because of large seasonal light-curve variations which prevent a combined light-curve/radial-velocity solution. It is noted that the primary minimum is free of the photometric variations, a property which may help explain their elusive source. Photometrically, the system appears to be a contact binary with poor or absent energy exchange, but such an explanation – in view of the presence of the mass-transfer effects – is no more plausible than any one of the semi-detached configurations with either the more-massive or less-massive components filling their Roche lobes. Lengthening of the orbital period and the size of the less-massive component above its main-sequence value suggest that the system is the shortest-period (0.388 days) known Algol with non-degenerate components.

Key words: stars: variables – binaries: eclipsing

1 INTRODUCTION
Contact binary stars are common: According to the only currently available unbiased statistics – a by-product of the OGLE microlensing project – as discussed in Rucinski [1997a] and Rucinski [1998b], the spatial frequency of contact binaries among the main-sequence, galactic-disk stars of spectral types F to K (intrinsic colors 0.4 < V − I_C < 1.4) is about 1/100 to 1/80 (counting contact binaries as single objects, not as two stars). Most of them have orbital periods within 0.25 < P < 0.7 days, and they are very rare for P > 1.3 – 1.5 days (Rucinski 1998a). These properties, as well as the spatial distribution extending all the way to the galactic bulge, with moderately large z distances from the galactic plane, and the kinematic properties (Guinan & Bradstreet 1988) suggest an Old Disk population of Turn-Off-Point binaries, i.e. a population characterized by conditions conducive to rapid synchronization and formation of contact systems from close, but detached, binaries. The contact binaries are less common in open clusters which are younger than the galactic disk (Rucinski 1998b), a property indicating that they form over time of a few Gyrs. It is obviously of great interest to identify binaries which are related to, or precede the contact system stage, as the relative numbers would give us information on durations of the pre- and in-contact stages.

Lucy (1976) and Lucy & Wilson (1979) were the first to point out the observational importance of contact systems with unequally deep eclipses as possible exemplification of binaries which are to become contact systems or are in the “broken-contact” phase of the theoretically predicted Thermal Relaxation Oscillation (TRO) evolution of contact binary stars, as discussed by Lucy (1976), Flannery (1976) and Robertson & Eggleton (1977). Lucy & Wilson called such contact systems the B-type – as contrasted to the previously recognized W-type and A-type contact systems – because of the light curves resembling those of the β Lyrae-type binaries. While the A-type are the closest to the theoretical model of contact binaries with perfect energy exchange and temperature equalization, the W-type show relatively small (but still unexplained) deviations in the sense that less-massive components have slightly higher surface brightnesses (or temperatures). Systems of the B-type introduced by Lucy & Wilson show large deviations from the contact model in that more massive components are hotter than predicted by the contact model. Thus, the energy transfer is inhibited or absent and the components of the B-type systems behave more like independent (or thermally de-coupled) ones. While light-curve-synthesis solutions suggest good geometrical contact, it has been suggested that these may be semi-detached binaries with hotter, presum-
ably more-massive components filling their Roche lobes (we will call these SH following Eggleton (1996)).

The same OGLE statistics that gave indications of the very high spatial frequency of contact binaries suggests that short-period binaries which simultaneously are in contact and show unequally-deep eclipses are relatively rare in space: Among 98 contact systems in the volume limited sample, only 2 have unequally deep minima indicating components of different effective temperatures (Rucinski 1997b). Both of these systems (called there "poor-thermal-contact" or "PTC" systems, but which could be as well called B-type contact systems) have periods longer than 0.37 day and both show the first maximum (after the deeper eclipse) relatively higher of the two maxima. This type of asymmetry is dominant in the spatially much larger (magnitude limited) sample of systems available in the OGLE survey. As already pointed by Lucy & Wilson (1979), this sense of asymmetry can be explained most easily as a manifestation of mass-transfer from the more-massive to the less-massive component. We add here that this can happen also in a non-contact SH system, with the continuum light emission from the interaction volume between stars contributing to the strong curvature of the light-curve maxima and mimicking the photometric effects of the tidally-elongated (contact) structure. Exactly this type of asymmetry is observed in a system which is absolutely crucial in the present context, V361 Lyr: it has been studied by Kaluzny (1990) and Kaluzny (1991), and later convincingly shown by Hilditch et al. (1997) to be a semi-detached binary with matter flowing from the more massive to the less-massive component. The light curve asymmetry in the case of V361 Lyr is particularly large and stable. A similar asymmetry and somewhat similar mass-transfer effects (albeit involving much more massive components) are observed in the early-type system SV Cen (Rucinski et al. 1992) where we have a direct evidence of a tremendous mass-transfer in a very large period change.

The subject of this paper, the close binary W Crv (GSC 05525–00352, BD=12 3565) is a relatively bright (V = 11.1, B − V = 0.66) system with the orbital period of 0.388 day. For a long time, this was the short-period record holder among systems which appear to be in good geometrical contact, yet which show strongly unequally-deep eclipses indicating poor thermal contact. It was as one of the systems exemplifying the definition of contact systems of the B-type by Lucy & Wilson (1979), although most often its type of variability has been characterized as EB or β Lyrae-type. A system photometrically similar to W Crv was collected and discussed in a five-part series by Kaluzny, concluding with Kaluzny (1986), and in studies by Hilditch & King (1986), Hilditch et al. (1988) and Hilditch (1989).

The radial velocity observations of W Crv were obtained in February – April 1997 at David Dunlap Observatory, University of Toronto using the 1.88 metre telescope and a Cassegrain spectrograph. The spectral region of 210˚ was centered on 5185 Å was observed at the spectral scale of 0.2 Å/pixel or 12 km s^{-1}/pixel. The entrance slit of the spectrograph of 1.8 arcsec on the sky was projected into about 3.5 pixels or 42 km s^{-1}. The exposure times were typically 10 to 15 minutes. The radial velocity data are listed in Table I and are shown graphically in Figure 1. The component velocities have been determined by fitting gaussian curves to peaks in the broadening function obtained through a de-convolution process, as described in Lu & Rucinski (1999). The mean standard deviations from the sine-curve variations are 7.7 km s^{-1} for the primary (more-massive, subscript 1) component and 17.2 km s^{-1} for the secondary (less-massive, subscript 2) component. These deviations give the upper limits to the measurement uncertainties because they contain the deviations of the component velocities from the simplified model of circular orbits without any proximity effects (i.e.

![Figure 1. The radial velocity observations of W Crv versus the orbital phase. The hotter, more massive component eclipsed in the primary minimum is marked by filled circles. The data are listed in Table 1 and the sine-curve fits (broken lines) correspond to elements given in Table 2.](image-url)
the spectroscopic data, as given in Table 2, describe the following system: The more-massive component is eclipsed in the deeper eclipse and hence is the hotter of the two. Judging by the relative depths of the eclipses, and noting the small light contribution of the secondary component (even if it fills its Roche lobe), we estimate – on the basis of the systemic colour at light maxima \((B - V) = 0.66\) – that the effective temperatures of the components are approximately 5700 K and 4900 K. The mass of the primary component is \(M_1 \sin^3 i = 1.00 M_\odot\), so that the primary is apparently a solar-type star, and the orbital inclination cannot be far from \(i = 90^\circ\), although not exactly so as total eclipses are not observed. Obviously, the spectroscopic data cannot provide any constraint on the degree of contact in the system, i.e. whether it is a contact system with poor thermal contact or a semi-detached configuration with one of the components filling the Roche lobe or perhaps even a detached binary. There are no spectroscopic indications of any mass-transfer either, although – with the mutual proximity of components – one would not expect such obvious signatures of this process as a stream or an accretion disk; besides, the spectral region around 5185 Å would not normally show them in any case. We must seek for constraints on the system geometry in the light curve and its variations.

3 ATTEMPTS OF A COMBINED LIGHT CURVE AND RADIAL VELOCITY SOLUTION

Four light curves discussed by Odell (1990) are currently available: the first from 1966 was obtained by Dycus (1968), the remaining three in 1981, 1988 and 1993 were by Odell. The light curves were obtained with the same comparison star permitting direct comparison of the large curves. The large seasonal variations of the light curves were interpreted by Odell by star spots. We do not support the spot hypothe-

Table 2. Radial velocity observations of W Crv

| JD(hel) | Phase | V_{pri} | O-C | V_{sec} | O-C |
|---------|-------|---------|-----|---------|-----|
| 2450000+ |       | km s^{-1} | km s^{-1} | km s^{-1} | km s^{-1} |
| 489.811 | 0.564 | 38.8 | 1.7 | -109.5 | -10.9 |
| 489.822 | 0.591 | 57.7 | -0.9 | -136.4 | -6.3 |
| 489.835 | 0.624 | 76.0 | -5.9 | -175.0 | -11.0 |
| 489.846 | 0.653 | 97.5 | -0.6 | -187.4 | 0.4 |
| 489.858 | 0.685 | 113.7 | 1.6 | -205.4 | -10.5 |
| 489.860 | 0.713 | 121.9 | 1.9 | -208.3 | 11.5 |
| 489.881 | 0.744 | 120.4 | -3.4 | -257.9 | -32.6 |
| 489.892 | 0.772 | 114.3 | -8.2 | -228.2 | -4.7 |
| 489.903 | 0.802 | 130.1 | 13.6 | -215.1 | -0.5 |
| 489.914 | 0.830 | 113.5 | 7.1 | -198.7 | 1.2 |
| 520.674 | 0.091 | -84.1 | 10.3 | 130.9 | 37.2 |
| 520.684 | 0.118 | -118.2 | -4.5 | 147.7 | 25.8 |
| 520.697 | 0.149 | -140.0 | -7.6 | 162.7 | 13.5 |
| 520.707 | 0.177 | -154.1 | -8.8 | 169.3 | 1.3 |
| 520.721 | 0.212 | -156.7 | -0.8 | 205.7 | 22.1 |
| 520.732 | 0.240 | -153.7 | 5.9 | 187.4 | -1.6 |
| 520.744 | 0.271 | -153.1 | 5.6 | 166.6 | -21.0 |
| 520.756 | 0.303 | -160.0 | -7.9 | 157.5 | -20.5 |
| 520.769 | 0.335 | -141.7 | -0.8 | 145.7 | -15.1 |
| 520.779 | 0.363 | -111.0 | 14.8 | 153.2 | 13.6 |
| 535.675 | 0.746 | 120.8 | -3.0 | -237.4 | -12.1 |
| 535.686 | 0.774 | 116.1 | -6.2 | -233.6 | -10.5 |
| 539.716 | 0.159 | -124.0 | 13.3 | 133.4 | -22.9 |
| 539.728 | 0.190 | -163.9 | -14.0 | 148.6 | 26.2 |
| 539.741 | 0.223 | -160.2 | -2.4 | 153.7 | -32.6 |
| 539.752 | 0.252 | -160.8 | -0.9 | 178.4 | -11.0 |

Figure 2. Four seasonal V-filter light curves of W Crv as discussed by Odell (1990) are shown here together, in intensity units, assuming the difference of 0.37 mag between the comparison and the variable star. Note the good repetition of the light curves in primary minima and large variations elsewhere. The codes are: 1966 – crosses, 1981 – filled circles, 1988 – filled squares, 1993 – triangles.

Table 2. Circular orbit solution for W Crv

| Parameter | Units | Value | Comment |
|-----------|-------|-------|---------|
| \(T_0\) | JD(hel) | 2450489.9781 ± 0.0015 | |
| \(P\) | days | 0.388081 | assumed |
| \(K_1\) | km s^{-1} | 140.8 ± 2.0 | |
| \(K_2\) | km s^{-1} | 206.4 ± 3.7 | |
| \(V_0\) | km s^{-1} | -20.1 ± 1.8 | |
| \(q\) | | 0.682 ± 0.016 | derived |
| \((a_1 + a_2) \sin i\) | \(R_\odot\) | 2.66 ± 0.04 | derived |
| \(M_1 \sin^3 i\) | \(M_\odot\) | 1.00 ± 0.06 | derived |
| \(M_2 \sin^3 i\) | \(M_\odot\) | 0.68 ± 0.05 | derived |

without allowance for non-coinciding photometric and dynamic centres of the components).

The individual observations as well as the observed minus calculated \((O-C)\) deviations from the sine-curve fits to radial velocities of individual components are given in Table 2. When finding the parameters of the fits, we assumed only the value of the period, following Odell (1990), and determined the mean velocity \(V_0\), the two amplitudes \(K_1\) and \(K_2\) as well as the moment of the primary minimum \(T_0\). The remaining quantities in that table have been derived from the amplitudes \(K_i\). The errors of the parameters have been determined by a bootstrap experiment based on 10,000 solutions with randomly selected observations with repetitions.

Among the spectroscopic elements in Table 2, the mass-ratio, \(q = 0.682 ± 0.016\), is the most important datum for proper interpretation of the light curves. Without external information on the mass-ratio, strong inter-parametric correlations in the light-curve analyses are known to frequently produce entirely wrong solutions (except for cases of total eclipses).

Before attempting a combined solution, we note that the spectroscopic data, as given in Table 2, describe the following system: The more-massive component is eclipsed in the deeper eclipse and hence is the hotter of the two. Judging by the relative depths of the eclipses, and noting the small light contribution of the secondary component (even if it fills its Roche lobe), we estimate – on the basis of the systemic colour at light maxima \((B - V) = 0.66\) – that the effective temperatures of the components are approximately 5700 K and 4900 K. The mass of the primary component is \(M_1 \sin^3 i = 1.00 M_\odot\), so that the primary is apparently a solar-type star, and the orbital inclination cannot be far from \(i = 90^\circ\), although not exactly so as total eclipses are not observed. Obviously, the spectroscopic data cannot provide any constraint on the degree of contact in the system, i.e. whether it is a contact system with poor thermal contact or a semi-detached configuration with one of the components filling the Roche lobe or perhaps even a detached binary. There are no spectroscopic indications of any mass-transfer either, although – with the mutual proximity of components – one would not expect such obvious signatures of this process as a stream or an accretion disk; besides, the spectral region around 5185 Å would not normally show them in any case. We must seek for constraints on the system geometry in the light curve and its variations.

3 ATTEMPTS OF A COMBINED LIGHT CURVE AND RADIAL VELOCITY SOLUTION

Four light curves discussed by Odell (1990) are currently available: the first from 1966 was obtained by Dycus (1968), the remaining three in 1981, 1988 and 1993 were by Odell. The light curves were obtained with the same comparison star permitting direct comparison of the large curves. The large seasonal variations of the light curves were interpreted by Odell by star spots. We do not support the spot hypothe-
sis by pointing out a curious property: A comparison of the seasonal light curves (Figure 2) indicates that all changes take place at light maxima and during the secondary eclipse when the cooler component is behind the hotter one, but that primary eclipse is surprisingly similar in all four curves. This constancy of the primary-eclipse shape remains irrespectively whether one considers the intensity or magnitude (relative intensity) units. We feel that we have here a strong indication that mass-exchange and accretion processes are operating between the stars. These processes would produce large areas of hot plasma, most probably on the inner face of the less-massive secondary component which is invisible during the primary minima. One can of course contrive a scenario involving dark spots appearing in certain areas, but never appearing on the outer side of the less-massive component, but the dark-spot hypothesis seems to be the most artificial of all possibilities. We note that an argument of the diminished brightness being accompanied by a redder colour is a weak one as such correlation is expected when plasma temperature effects are involved, irrespectively whether the spots are cool or hot.

With strong mass-transfer effects modifying its light curve, W Crv is not a typical contact system. In this situation, a blind application of light-curve synthesis codes may have led us to entirely wrong sets of parameters. For that reason, we did not attempt to obtain a light-curve solution of the system and used the popular light-curve synthesis program BinMak2 (as described by Bradstreet (1994) and Wilson (1994)) to explore reasonable ranges of parameters in different geometrical configurations.

Attempts of conventional light-curve synthesis solutions of W Crv encounter several problems. First of all, the large amplitudes at both minima totally exclude a detached configuration. At least one of the components or possibly both contribute to the strong ellipticity of the light curve, which would not be surprising in view of the short orbital period and little space for expansion of components in the system. The system must be a contact one or must be described by the Roche model (Lucy & Wilson 1979), but even above its physically allowed upper limit – including the case of W Crv – and by Kuzny (1986), as attempts of conventional light-curve synthesis solutions make it abundantly clear that the strong curvature of light maxima and large amplitude of light variations require two properties: a large orbital inclination and a moderately strong contact, at least $i \approx 0.15 - 0.25$. However, the inclination cannot be exactly 90 degrees as then we would see a total eclipse in the secondary minimum. The contact-model fit is far from perfect because of the large seasonal changes, but also indicates a need of a “super-reflection” effect, with increased albedo not only above but also below the currently most popular value of 0.5 for convective envelopes (Rucinski 1969), but even above its physically allowed upper limit of unity. This is clearly visible in Figures 2 and 3 in the branches of the secondary minimum. Cases of the abnormal reflection were already discussed by Lucy & Wilson (1973) – including the case of W Crv – and by Kahuzy (1980), as indicating some abnormal brightness distribution between the stars (most probably, on the inner side of the secondary component) which could be linked to a mass-exchange pheno-

| Parameter | C | SH | SC |
|-----------|---|----|----|
| $\Omega_1$ | 3.156 | 3.215 | 3.4 |
| $\Omega_2$ | 3.156 | 3.4 | 3.215 |
| $r_1$ (deg) | 88 | 90 | 90 |
| $r_2$ | 0.424 | 0.412 | 0.380 |
| $R_1/R_2 \sin^i$ | 1.13 | 1.10 | 1.01 |
| Comment | $f = 0.15$ primary | secondary | fills R. lobe | fills R. lobe |

**Figure 3.** The three configurations of W Crv considered in the text, with parameters as listed in Table 3, are shown here as sections in the orbital plane. The Roche critical equipotentials (dotted lines) and the position of the mass center (cross) are shown to scale. Note how little space separates the components; this leads to our hypothesis that strong mass-transfer phenomena between the components are the source of additional light which produces the seasonal variations of the light curve.

© 1999 RAS, MNRAS 000. 3
nomenon. Obvious presence of such effects would make the standard, light-curve synthesis model – which hides all energy and mass transfers deep inside the common contact envelope – entirely invalid.

**Semi-detached configuration (SH):** This is the preferred configuration for B-type systems, either in terms of a system before forming contact or in the broken-contact phase of the TRO oscillations. Photometrically, the model does not provide enough of the light-curve amplitude and curvature at maxima, even with $i = 90^\circ$. The dotted line in Figures [4] and [5] shows this deficiency. However, in this configuration, it would be natural to expect departures from the simple geometric model due to the mass exchange phenomena. The increased reflection effect could be then explained through an area on the secondary component which is visible only at the quadratures, as is most likely the case for SV Cen ([Rucinski et al. 1992]). Although such a configuration cannot be modeled with the existing light-curve synthesis codes, it offers a prediction of the shortening of the orbital period; in Section 4 we present indications that the period is in fact getting longer. It is also consistent with the light curve variations almost entirely limited to the light maxima, with very small seasonal differences between portions at light minima. If the mass-transfer phenomena between the stars increase the light-curve amplitude, then the inclination could take basically any value. For $i < 90$ degrees, the inner side of the secondary component would be partly visible at secondary minima explaining large light-curve variations at these phases.

**Semi-detached Algol configuration (SC):** Of the three geometrical models considered here, this one best fits the 1981 light curve in all parts except in the upper branches of the primary minimum which are wider than predicted. The large amplitudes of the light variations find a better explanation in this model than in the SH case. Also, most of the reflection effect can be explained with the conventional value of the albedo by the relatively larger area of the illuminated secondary component. The mass-transfer in this model should lead to a period lengthening, as in other Algols. This is what we apparently see in the times of minima of W Crv (see Section 4). If the light-curve maxima contain a light contribution of mass-transfer and/or accretion effects, then the second maximum (after the secondary minimum) would be expected – on the average – to be more perturbed by the Coriolis-force deflected stream, and this seems to be the case for W Crv (see Figure 3). Within the SC hypothesis, only one of the two components, the secondary, would be abnormal (oversize relative the main-sequence relation, see Tables [2] and [3]), whereas the C and SH models predict mass-radius inconsistencies for both components. Thus, we feel that all the current data suggest that the short-period Algol configuration is the correct explanation for W Crv. The major problem, however, is with the theoretical explanation for such a configuration: There is simply no place for Algols with periods as short as 0.388 days within the present theories. We return to this problem in Section 4.

### Table 4. New and corrected moments of minima for W Crv

| $E$     | $T_0$     | $(O - C)$ | Comment |
|---------|-----------|-----------|---------|
| 54750.0 | 49108.7920| +0.0028   | correction |
| 54752.5 | 49109.7626| +0.0032   | correction |
| 58309.0 | 50489.9781| +0.0093   | spectroscopy |
| 60364.5 | 51287.6757| +0.0067   | new |
| 60411.0 | 51305.7230| +0.0082   | new |
| 60413.5 | 51306.6938| +0.0088   | new |
| 60416.0 | 51307.6639| +0.0087   | new |

### 4 PERIOD CHANGES

Although known for almost 65 years, W Crv has not been extensively observed for moments of minima. Practically all extant data have been presented by Odell (1996). Dr. Odell kindly sent very new, unpublished data and corrections to a few data points listed in Table 1 of his paper. These are given in Table 4. We have added to these the moment of minimum inferred from our new spectroscopic determination of $T_0$ (see Table 3). What follows, we will use the ephemeris of Odell: $JD(min) = 2427861.3635 + 0.3880(8034 × E)$. The observed minus calculated $(O - C)$ deviations from Odell’s ephemeris are shown in Figure 3. The moments secondary minima, which are based on shallower eclipses with stronger light-curve perturbations, are marked in the figure by open circles. Our spectroscopic result gives a significant, positive deviation of $(O - C) = +0.0093 ± 0.0015$ days, in agreement with the newest data of Odell.

The available times-of-minima contain information about orbital period changes that have taken place over the 65 years. Disregarding presumably random and much smaller shifts in the eclipse centres caused by stellar-surface perturbations (whether we call them spots or mass-transfer affected areas), the observed deviations from the linear elements of Odell (1996), in Figure 3, can be interpreted as consisting of at least two straight segments or as forming a parabola. We do not consider a possibility that the discov-
Figure 5. The four V-filter light curves of W Crv (in magnitudes) are shown here together with three different fits for a contact model (C) with a mild degree-of-contact ($f = 0.15$, continuous line), for two semi-detached configurations discussed in the text (SH, dotted line and SC, broken line). The fits have been based on the 1981 light curve (see Figure 4). Note the small differences between the theoretical curves when compared with the large seasonal variations in the observed light curves.

Table 5. Quadratic fits to the time-of-minima ($O-C$) deviations and the evolutionary time scales $\tau$

| Value | $a_0$ | $a_1$ | $a_2$ | $\tau$ |
|-------|-------|-------|-------|--------|
| days  | $10^{-7}$ days | $10^{-12}$ days | $10^7$ years |
| $-95\%$ ($-2 \sigma$) | -0.0025 | -8.28 | +3.87 | 5.33 |
| $-68\%$ ($-1 \sigma$) | -0.0002 | -6.44 | +5.93 | 3.48 |
| median | +0.0023 | -3.79 | +7.98 | 2.58 |
| $+68\%$ ($+1 \sigma$) | +0.0072 | -2.36 | +11.06 | 1.86 |
| $+95\%$ ($+2 \sigma$) | +0.0097 | -1.04 | +13.44 | 1.53 |

Figure 6. The ($O-C$) deviations in the observed moments of eclipses (in days) from the ephemeris of Odell (1996). The secondary minima are marked by open circles. The new spectroscopic determination is marked by the large filled square. Its error has been obtained by a bootstrap experiment and is well determined, but – obviously – systematic effects in photometric and spectroscopic determinations may be different. The quadratic fit discussed in the text is shown by a continuous line. The histogram of the bootstrap results for the quadratic coefficient $a_2$ (in units of $10^{-12}$ days) is shown by the small insert.

Table 5. Quadratic fits to the time-of-minima ($O-C$) deviations and the evolutionary time scales $\tau$

The quadratic coefficient $a_2$ is proportional to the second derivative of the times of minima hence to the period change through $dP/dt = 2a_2/P$. For comparison with the theory of stellar evolution, it is convenient to consider the time-scale of the period change given by $\tau = P/(dP/dt) = P^2/2a_2$. The values of $\tau$ are given in the last column of Table 5. The data given in Table 5 indicate that the or-
bital period is becoming longer with the characteristic time scale of \((1.5 - 5.3) \times 10^7\) years, with the range based on the highly secure 95 percent confidence level. The sense of the period change is somewhat unexpected as it indicates – for the relative masses that we determined – that the mass transfer is from the less-massive component to the more-massive component, i.e. as in Algols (the configuration designated as SC). One would normally expect the other semi-detached configuration (SH) for the pre-contact or broken-contact phases of the TRO cycles. The period-lengthening argument for the Algol (SC) configuration is a stronger one than any based on the light curve analysis which seems to be hopelessly difficult for W Crv. The time-scale is exactly in the range expected for the Kelvin-Helmholtz or thermal time-scale evolution of solar-mass stars, \(\tau_{KH} = 3.1 \times 10^7 (M/M_\odot)^2 (R/R_\odot)^{-1} (L/L_\odot)^{-1}\), which is characteristic for systems in the rapid stage of mass exchange such as \(\beta\) Lyrae or SV Cen.

5 DISCUSSION AND CONCLUSIONS

The present paper contains results of spectroscopic observations confirming the assumption of Odell [1996] that the more massive, hotter star is eclipsed in the primary minimum. However, this information and the value of the mass-ratio are not sufficient to understand the exact nature of the system mostly because of the strong light curve variability which may be interpreted as an indication of mass-exchange and accretion phenomena producing strong deviations from the standard binary-star model. We suggest – on the basis of the absence of light-curve perturbations within the primary minima – that the system is not a contact binary with components which mysteriously have different temperatures, but rather a semi-detached system. Furthermore, we suggest that W Crv, similarly to systems like V361 Lyr or SV Cen, has a light-producing volume between the stars or – more likely – on the inner face of the secondary component. In the case of V361 Lyr, there is apparently enough space for the stream of matter to be deflected by the Coriolis force and strike the less-massive on the side; in SV Cen, the photometric effects of a strong contact are probably entirely due to the additional light visible only in the orbital quadratures. In contrast to V361 Lyr and SV Cen, the mass-transfer phenomena in W Crv are visible at all orbital phases except at primary minima, that is when the inner side of the cooler component is directed away from the observer.

The general considerations of the light-curve fits in the presence of large brightness perturbations make both semi-detached configurations almost equally likely, but the semi-detached configuration of the Algol type for W Crv, i.e. the one with the less-massive, cooler component filling the Roche lobe (SC) is preferable for two reasons: (1) it is simpler, as it leads to only one component deviating from the main-sequence relation (since the inclination must be close to 90 degrees, the secondary would have 0.92R\(\odot\) and 0.68M\(\odot\), whereas the primary would be a solar-type star with 1.01R\(\odot\) and 1.00M\(\odot\)), and (2) it can explain the observed lengthening of the orbital period in the thermal time-scale. This way, W Crv joins a group of well-known stars – such as SV Cen, V361 Lyr or the famous \(\beta\) Lyrae – where large, systematic period changes are actually the final proof of our hypothesis of the Algol configuration. W Crv would be then the shortest-period (0.388 days) known Algol consisting of normal (non-degenerate) components. With such a short period, the system presents a difficulty to the current theories describing formation of low-mass Algols, as reviewed by Yungelson et al. [1989], and of binaries related to contact systems, as reviewed by Eggleton [1996]. One can only note that Sarna & Fedorova [1989], who considered formation of solar-type contact binaries through the Case A mass-exchange mechanism, pointed out the importance of the initial mass-ratio: For mass-ratio sufficiently close to unity, the rapid (hydrodynamical) mass exchange can be avoided and the system may evolve in the thermal time-scale. Although the mass-reversal has not been modeled, it is likely that W Crv is the product of such a process.

ACKNOWLEDGMENTS

We thank Dr. Andy Odell for providing the light curve and time-of-minima data and for extensive correspondence, numerous advices and suggestions and Drs. Bohdan Paczyński and Janusz Kalužny for a critical reading of the original version of the paper and several suggestions that improved the presentation of the paper.

REFERENCES

Bradstreet D. H., 1994, in Milone E. F., ed., Light Curve Modeling of Eclipsing Binary Stars. Springer-Verlag, p. 151
Dycus R. D., 1968, PASP, 80, 207
Eggleton P. P., 1996, in Milone E. F., Mermilliod J.-C., eds, The Origins, Evolution, & Destinies of Binary Stars in Clusters, ASP Conf., 90, 257
Flannery B. P., 1976, ApJ, 205, 217
Guinan E. F., Bradstreet D. H., 1988, in Dupree A. K., Lago M. T., eds, Formation and Evolution of Low-Mass Stars. Kluwer, Dordrecht, p. 345
Hilditch R. W., 1989, Space Sci. Rev., 50, 289
Hilditch R. W., King D. J., 1986, MNRAS, 223, 581
Hilditch R. W., King D. J., MacFarlane T. M., 1988, MNRAS, 231, 341
Hilditch R. W., Collier Cameron A., Hill G., Bell S. A., Harries T. J., 1997, MNRAS, 291, 749
Kalužny J., 1986, PASP, 98, 662
Kalužny J., 1990, AJ, 99, 1207
Kalužny J., 1991, Acta Astron., 41, 17
Lu W., Rucinski S. M. 1999, AJ, in press (July 1999)
Lucy L. B., 1976, ApJ, 205, 208
Lucy L. B., Wilson R. E., 1979, ApJ, 231, 502
Odell A. P., 1996, MNRAS, 282, 373
Robertson J. A., Eggleton P. P., 1976, MNRAS, 179, 359
Rucinski S. M., 1969, Acta Astr., 19, 245
Rucinski S. M., 1985, in Eggleton P. P., Pringle J. E., eds, Interacting Binaries, Reidel, Dordrecht, p. 13
Rucinski S. M., 1997a, AJ, 113, 407
Rucinski S. M., 1997b, AJ, 113, 1112
Rucinski S. M., 1998a, AJ, 115, 1135
Rucinski S. M., 1998b, AJ, 116, 2998
Rucinski S. M., Baade D., Lu, W. X., Udalski, A., 1992, AJ, 103, 573
Sarna M. J., Fedorova A. V., 1989, A&A, 208, 111
Tsesevich V. P., 1954, Odessa Izv., 4, 231
Wilson R. E., 1994, PASP, 106, 921
Wilson R. E., Devinney E. J., 1971, ApJ, 166, 605
Rucinski and Lu

Yungelson L. R., Tutukov A. V., Fedorova A. V., 1989, Sp.Sci.Rev., 50, 141