THE EVOLUTION OF BINARY STARS INTO CONTACT STATES

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ABSTRACT. Good-quality empirical results on 62 short-period binary stars recently summarised by Hilditch & Bell (1987) and Hilditch, King & McFarlane (1988) are discussed in terms of evolutionary paths from detached to semi-detached and contact states. These data suggest two evolutionary paths to the contact binaries - from detached systems directly into contact to form initially shallow-contact systems, and via case A mass transfer to semi-detached states, thence to contact systems. These empirical results support previous arguments based on evolutionary models and less detailed observational data.

Concern is expressed about the paucity of high-quality spectroscopic data, particularly for low-mass systems displaying EB-type light curves and the resultant limitations on analyses of those light curves. Such systems provide tests of evolution into contact for the first time, or of broken-contact phases for WUMa-type binaries. The crucial importance of long-term monitoring (decades) of times of minima as indicators of mass transfer rates amongst these interacting binaries is also noted.

1. Introduction

It is self-evident that the initial masses and the initial orbital angular momentum will decide which type of binary system is formed. For short-period systems ($P \leq$ few days), the separation and hence the sizes of the Roche lobes will influence very substantially the evolution of both components from an early stage. As a result, such short-period systems may be expected to evolve through extensive mass transfer/loss episodes into semi-detached and perhaps contact states during the main-sequence stages of evolution - case A evolution in the terminology of Kippenhahn & Weigert (1967).

For conservative evolution (no net mass loss from the system), case A was considered to be of only minor importance for massive binaries, and unimportant for low-mass systems since the radius changes across the main-sequence band are small. For example, case A evolution would occur for a $5 + 2.5M_\odot$ binary only if the initial orbital period was less than 1.5 days (Paczynski 1971).

However, increasing amounts of reliable observational data, coupled with improved understandings of mechanisms of mass loss, have altered substantially that picture. For low-mass stars ($\approx 1M_\odot$) magnetic braking plays an important role in their evolution, and provides the key to understanding many of the properties of the WUMa-type contact binaries (see, for example, the summary by Rucinski 1986). For high-mass stars ($\geq 5M_\odot$), stellar-wind mass loss and the consequences of overshooting from the convective stellar cores compete to alter the probability of case A evolution. As a result, the upper limit to the

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initial period for case A evolution to occur increases to ~15 days for a binary with a 20$M_\odot$ primary, almost independently of the mass ratio (Doom 1984, Sybesma 1985a). Hence we may ask how short-period binaries which are observed to be in detached, semi-detached and contact configurations fit together into an evolutionary scheme.

I have been involved for ~10 years in two observational programmes directed to establishing reliable empirical data on such short-period binaries. It is a pleasure to record that this work would not have been completed without the willing efforts of Brian McLean, David King, Tom McFarlane, Steven Bell and Andrew Adamson, whilst they were at St Andrews. And the data analysis would have been substantially less efficient without the software packages *reduce*, *vcross* and *light* written by Graham Hill at the DAO.

These programmes have been (1) a study of 0-B5 binaries with orbital periods less than about 1.8 days, and (2) a study of F-K binaries in the orbital period range of $0.4 \leq P \leq 0.8$ day, that range being chosen to select roughly equal numbers of contact (EW) and non-contact (EB/EA) systems. We have obtained spectroscopic and or photometric data on a total of 39 systems and have published all the data and our analyses of those data in 26 papers in the Monthly Notices of the Royal Astronomical Society. In addition, we have recently published two papers (Hilditch & Bell 1987, Hilditch, King & McFarlane 1988) summarising our results as well as the substantial contributions from other researchers in the field and have been able to draw fairly clear conclusions, based on these empirical results, about evolutionary links between the different types of binaries found in these studies. In both summary papers, we included only binaries with well-determined parameters - typically masses to ±10%, radii to ±5% and log luminosities to ±0.03 $L_\odot$.

I should like to discuss the main conclusions of this work which are relevant to this colloquium, namely evolution from detached states through semi-detached (Algol) configurations and into contact. I will omit discussion of the properties of WUMa-type contact binaries. In addition, it is relevant to make a few comments about problems over uniqueness of photometric solutions, and to discuss what evidence exists for interactions via gas streams between the components in the near-contact systems.

2. The OB systems

Our survey of 31 0-B5 binaries, without regard to the orbital period, which have reliably-determined parameters (Hilditch & Bell 1987) revealed that 16 systems were in detached configurations, 3 of them (Y Cyg, V478 Cyg, CV Vel) being composed of identical components. The evolutionary states of the detached systems may be compared very favourably with the evolutionary models published by Sybesma (1985b, 1986). They range from systems like DI Her in which both components are close to the zero-age line, through AH Cep where a phase of rapid mass transfer may commence within $\sim 2 \times 10^6$ years, to V380 Cyg wherein the primary component is close to the end of the main-sequence phase whilst its companion is not far from the zero-age main sequence.

Eight systems are semi-detached with the less massive component filling its Roche lobe (V Pup, V356 Sgr, SX Aur, AI Cru, DM Per, TT Aur, u Her, Z Vul). In all cases, the primary components are about half-way through their main-sequence lifetimes whilst the secondary components are all oversized and hence overluminous for their ZAMS masses over a rather wide range. In the mass-radius diagram the slope of the line joining each binary pair [$s = \log(R_{pr}/R_{sec})/\log(M_{pr}/M_{sec})$] exhibits an apparently confusing range of values with $s = +0.46$ for SX Aur (the shortest period system with $P = 1.2$ days) to $s = -0.90$ for V356 Sgr (the longest period system with $P = 8.8$ days). This range of values of s indicates simply that the evolved secondary ensures that it always fills the available Roche lobe.

The mean value of the mass ratio for these s-d systems is 0.48±0.11 (sd) which may be compared with 0.83±0.18 (sd) for detached systems and 0.22±0.11 (sd) for the later-type classical Algols listed by Popper (1980). As indicated by the standard deviations of these means, the q-distributions for these three groups form a continuum over the entire range of q.

Nevertheless, application of the Mann-Whitney non-parametric statistical test for the equality of means of two independent distributions (eg Conover 1971) shows that the mean value of q for the classical Algols is less than that for the OB s-d systems at a level of significance of 99.9%.

It would appear that these OB-type semi-detached systems have all evolved into that configuration by means of case A mass transfer, since both components are still within or very close to the main-sequence band and the mass ratios (~0.5) are in accord with the appropriate case A models by Sybesma (1987).

It is worthwhile to comment on the seven contact systems identified in the sample (V348 Car, LY Aur, V382 Cyg, AO Cas, TU Mus, V701 Sco, RZ Pyx). They range across the entire main-sequence band from RZ Pyx in marginal contact on the ZAMS at an age of ~2×10^6 years, through marginal-contact and deep contact systems part way through the region (TU Mus, V701 Sco) to marginal contact systems (LY Aur, V348 Car, AO Cas) in the upper part of the main sequence. Clearly these systems cannot have a common origin. RZ Pyx is the system of lowest total mass ($6 + 5\ M_\odot$) and shortest orbital period (0.66 day) and has presumably had just enough angular momentum to survive the pre-main-sequence phase to form a detached binary which has then evolved within 2×10^6 years into a marginal contact system. By contrast V348 Car is the most massive system ($35+ 35\ M_\odot$) with the longest orbital period (5.5 days) and has had sufficient separation to evolve across most of the main sequence before reaching a marginal-contact state. The other system with equal mass components is V701 Sco ($10+10\ M_\odot$) which is in deep contact and evolved only a little way from the ZAMS. Perhaps RZ Pyx will evolve into a deep-contact state. Sybesma's (1986) models of short-period high mass-ratio systems show that both components evolve 'in parallel' and have a high probability of forming long-lasting contact systems.

The remaining four systems (LY Aur, V382 Cyg, AO Cas, TU Mus) are all very massive - typically $27 + 19\ M_\odot$ - with orbital periods in the range 1.4 - 4.0 days. Although the light-curve analyses are difficult, these systems appear to be in marginal-contact, and the mass ratios and luminosity ratios are anomalous (as first noted in detail by Popper 1982). The mean mass ratio for these four systems is 0.72, from which a mean luminosity ratio of 0.31 would be expected if we adopt the empirical mass-luminosity relationship for main-sequence stars determined by Hilditch & Bell (1987). But the mean observed luminosity ratio is 0.65. Thus the secondaries are overluminous for their masses, which may have resulted from evolution directly into contact, or after the rapid phase of case A mass transfer and during the slow phase. The models by Sybesma (1987) discuss systems of both lower ($<30\ M_\odot$) and higher ($>60\ M_\odot$) total masses than these four systems.

The evolutionary time scales for OB systems are substantially shorter than for the later-type systems and so we are unlikely to observe systems in rapid phases of evolution. For our sample of 31 OB systems none appears to be undergoing any *well-determined* changes in orbital period, though there is evidence from times of minima that some systems are undergoing some period changes, for example AH Cep, SX Aur, V701 Sco, V Pup, V356 Sgr. The available data are not adequate for the task of establishing, unequivocally, values of $P/\dot{P}$ and hence mass transfer rates.

In summary, it appears from these empirical results that there exist two evolutionary paths to a contact binary state, namely (1) directly from a detached system to a contact system, as indicated by RZ Pyx and V701 Sco, and less certainly (2) from a detached system (*viz.* AH Cep) through a semi-detached phase (V Pup) to a contact configuration (LY Aur). I look forward to seeing further detailed comparisons between observed systems and evolutionary models.

3. The F-K Systems

Our observational programme on F-K-type systems with orbital periods in the range $0.4<P<0.8$ day had the specific aims of understanding how initially detached systems might evolve into contact both as a result of evolutionary expansion and of orbital angular momentum loss, and of furthering our empirical knowledge of the properties of the WUMa-type contact binaries.

Of the 31 F-K systems with good-quality data compiled by us (Hilditch, King & McFarlane 1988) 22 are classified as A- or W-type WUMa systems and will not be discussed further here. The remaining nine systems may be divided into three groups, (i) one detached/semi-detached system (RT Scl) which has its primary component close to its Roche lobe and displays substantial evidence for mass transfer from the primary to the secondary component, (ii) five semi-detached systems (CX Aqr, EEAqr, YYCet, FO Vir, RS Ind) which display no complications in their light curves and which have normal detached primary components and Roche-lobe filling secondaries which are oversized and hence overluminous for their ZAMS masses, and (iii) three marginal-contact systems (RV Crv, CX Vir, FT Lup) labelled type B by Lucy & Wilson (1979) where both components just fill their respective Roche lobes and display evidence in their light curves of energy exchange between the components.

The evolutionary time scales for these lower mass stars are sufficiently long that we may expect to see systems at stages of evolution where mass transfer between components is just developing. The system RT Scl (Hilditch & King 1986) has the primary close to its Roche lobe, the secondary oversized for its mass but substantially detached from its Roche lobe, and there is evidence in the light curve (Clausen & Grønbech 1977) for mass transfer from the primary to the secondary via a stream which hits directly the facing hemisphere of the secondary. An excess in luminosity of the system is observed in the phase range 0.20 to 0.45 with a maximum around phase 0.39. The fluid-dynamical calculations of Lubow & Shu (1975) demonstrate that the direction of the stream relative to the line of centres is strongly constrained and equals 20° for the mass ratio of RT Scl. With thermalisation on impact at the surface of the secondary component, the narrow and directed stream produces a localised hot spot which is projected into the line of sight with maximum effect around phase 0.39 before being eclipsed by the primary. Both the work of Clausen & Grønbech and of Duerbeck & Karimie (1979) demonstrate via the *(O-C) vs* time diagram that the orbital period is decreasing indicating a mass transfer rate from the primary of 0.55×10^{-7} $M_{\odot}\ yr^{-1}$.

The resultant accretion luminosity is given by

$$L_{acc} = \frac{G(m_1 + m_2)\dot{m}\Delta C}{2a}$$

where $m_{1,2}$ are the masses of the two components separated by a distance a, $\dot{m}$ is the mass transfer rate, G is the gravitational constant, and ΔC is the normalised potential difference from the inner Lagrangian point to the surface of the secondary component. For RT Scl, $L_{acc} \cong 3.8 \times 10^{25}$ Js^{-1}, or 0.06 of the luminosity of the primary component. In bolometric terms, this excess luminosity would lead to a brightness increase for the system of Δm ~0.06 mag which is close to that observed in V light.

A closely similar system, in terms of total mass, relative stellar radii and orbital period is the type B system FT Lup. Hilditch *et al* (1984) found a spectroscopic mass ratio of 0.43 and analysed an incomplete light curve to find that both components just filled their respective Roche lobes. Mauder (1982) had already shown that the decreasing period indicated a mass transfer rate of ~$3 \times 10^{-7} M_\odot yr^{-1}$ from the primary to the secondary. The system has properties (including the mass transfer rate) in remarkable agreement with an evolutionary model published by Webbink (1976) of evolution of a detached binary directly into contact. Kaluzny (1985) reanalysed the same light curve with a range of fixed mass ratios and both convective and radiative values for the albedo (α) and gravity-darkening exponent (β) for the primary component. He argued that the best solution was that with a small degree of contact (f ~0.9) and convective values for α and β. In order to match the observed depth of secondary eclipse he allowed the albedo of the secondary component to be a free parameter and found a value greater than unity. As we have mentioned previously (Hilditch, King & McFarlane 1988), this is physical nonsense but it provides a convenient procedure within the synthesis code to mimic an enhanced brightness distribution on the facing hemisphere of the secondary if it is symmetric with respect to the line of centres.

Subsequently a more detailed light-curve analysis was made available by Lipari & Sistero (1986) from complete UBV light curves obtained by them. Their analysis preferred a semi-detached solution with the primary at the Roche lobe and the secondary slightly underfilling its Roche lobe. The mass transfer rate was revised to ~$1.3 \times 10^{-7} M_\odot yr^{-1}$. It is worth noting the good agreement between the photometric solutions by Hilditch *et al* (H+), Kaluzny (K) and Lipari & Sistero (LS).

Authors	mean radii		β_{pr}	q	configurations
	r_{pr}	r_{sec}			
H+	0.45	0.30	0.25	0.43 spec	marginal-contact
K	0.45	0.32	0.08	0.45 phot	contact
LS	0.45	0.30	0.25	0.465 phot	semi-detached

The reasons for the changes of description are due entirely to the small change in mass ratio and the value of β_{pr} (to which I will return later). To within errors of observation, these solutions are in very good agreement.

The accretion luminosity inferred from the mass transfer rate is ~1.5×10^{25} Js^{-1} and results in a brightness increase for the system of Δm ~0.03 mag, again in reasonable agreement with the 0.04V magnitude difference between the observed depth of secondary eclipse and that which would be expected from the solution to the primary eclipse curve alone. Note again, however, that the mass transfer rates for RT Scl and FT Lup are being inferred from *(O-C) vs* time diagrams to which have been fitted parabolic curves. One wonders how good our mass transfer rates will look if another 50 years of times of minima will show a reversal in the slope of the parabolic curve and the *(O-C)'s* start looking like a beautiful sinusoid indicating orbital motion about a third body!

The other two type-B systems (RV Crv, CX Vir) have both components just filling their Roche lobes according to our solutions based on spectroscopic mass ratios. In both cases it is impossible to match the observed light curves without allowing the secondary albedo to become greater than unity. Here, however, we cannot appeal simply to a mass transfer rate and a resultant accretion luminosity to explain the hot spot on the secondary.

For RV Crv the available data indicate a possible shortening of the period over the past 40 years, but for CX Vir no change in orbital period has been detected over 80 years of observation! Are we really only witnessing the higher temperature gas from the primary component flowing at a substantially slower rate through L_1 and then floating on the surface of the cooler secondary for a time? Certainly the temperature excess inferred for the hot spots in these systems from the light-curve solutions are ~1500-2000K above normal photospheric values at the substellar point, that is, of the same order as the polar temperature differences between the two stars.

There are now about 15 known type B systems with a variety of published light curves and light-curve analyses. But apart from the three I have already mentioned, none has published spectroscopic data from which reliable minimum masses, separations and mass ratio may be determined. As a result I have not felt able to include them in this review. Attempts to find solutions to the light curves with the mass ratio q as a free parameter usually demonstrate that solutions are anything but unique unless the orbital inclination is close to 90° and total/annular eclipses alternate. This factor is, of course, nothing new to analysers of light curves but it is salutary to study the dependence of a goodness-of-fit parameter like $\Sigma(O\text{-}C)^2$ on mass ratio as published for example by Kaluzny & Semeniuk (1984) or ourselves (McFarlane *et al* 1986 - paper V). These broad minima of $\Sigma(O\text{-}C)^2$ extending over a range greater than 0.2 in q *(sec/pr)* demonstrate unequivocally that, at least for these EB-type light curves, a reliable spectroscopic mass ratio is an essential prerequisite to constrain a photometric solution.

Another factor of interest for these type B systems is the configuration determined according to adopted radiative or convective values for the gravity-darkening exponents and albedos. Lipari & Sistero and Hilditch *et al* have usually found that better solutions are found if we adopt radiative values for the primary components of these systems (which, in any event, have temperatures determined from intrinsic colours and spectral types in the range 6500-7000K); $\Sigma(O\text{-}C)^2$ is reduced by a factor of two over solutions with convective values. In each of these systems, the spectroscopic mass ratio ensures the reliability of the photometric solution, and the systems are found either to be semi-detached or in marginal contact. For other systems, others have adopted convective values only, and consequently in order to reproduce the strongly-curved shapes of the light curves have found solutions with the components in physical contact, that is, more distorted. It may then be argued that these type B systems are really W-type shallow-contact binaries with the components in physical contact with values of $f \simeq 0.9$ ($F \simeq 1.1$) but not in thermal contact. Hence they may be good candidates for WUMa systems in the broken-contact phase of a thermal-relaxation oscillation. I hope I have made it sufficiently clear from the foregoing that, until we have very good spectroscopic data on all 15 known systems (preferably more), any number of sophisticated photometric solutions will not resolve whether these type B systems are to be regarded as just semi-detached, marginal contact, or poor thermal contact WUMa systems.

Evidence for period changes amongst these 15 systems is as limited as that for the OB systems. Only BE Cep, BL Eri, EG Cep and CN And, in addition to RT Scl, FT Lup and RS Ind show clear evidence for period changes but accurate values of $P/\dot{P}$ are not yet forthcoming. Note that AK Her has orbital motion about a third body, as does the short-period RS CVn system SV Cam which will undoubtedly evolve into one of our marginal-contact systems at some later stage.

How do these type B systems and the ordinary-looking and classical semi-detached systems in the same total mass, orbital period range fit together in an evolutionary sequence? From considerations of the locations of the primary and secondary components of these s-d, type B and contact systems in the mass-radius plane and the HR diagram, together with the specific orbital angular momenta of these systems, we have argued that there is sufficient empirical evidence now to consider two paths to the contact state. The first is from short-period detached systems directly into contact forming a W-type contact binary as suggested by the evolutionary model published by Webbink. As observed examples of this sequence, we suggest RT Scl → FT Lup → W-type systems. The second is from longer-period detached systems through case A mass transfer to classical semi-detached systems to marginal-contact systems, to the deeper-contact A-type systems (cf. also Budding 1984). As empirical examples, from the semi-detached state we suggest FO Vir, RS Ind, YY Cet → RV Crv, CX Vir → A-type systems.

That two evolution paths to the WUMa-type binaries are required to explain their properties has been demanded for some time (cf. Moss 1971, Mochnacki 1981, Rucinski 1986). I believe we are now reaching the stage of finding *good quality* empirical evidence to support the views which have been based on a variety of theoretical and rather more circumstantial observational evidence. It seems to me that we may now ask for the detailed calculations of the simultaneous evolution of both stars in a low-mass short-period binary system with due allowance for magnetic braking.

4. Summary

Our empirical knowledge of the properties of short-period binaries with components near the main-sequence has improved very substantially in the last few years. It is now reasonable to identify individual systems or groups of systems with particular stages of evolution, and hence to provide tests of evolutionary models. However, I trust I have made it clear that the available sample is by no means complete and that much remains to be learned about the interactions between the component stars in these interesting binary systems.

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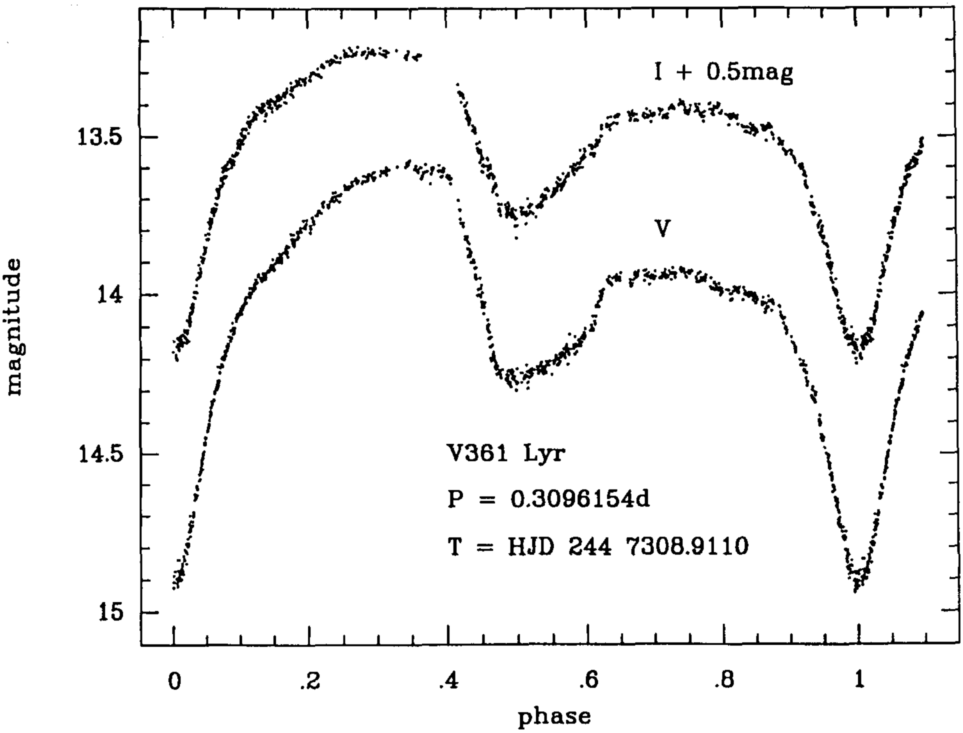
DISCUSSION

Budding felt that other interpretations were possible for RT Scl. Rodgers, for example, had suggested a mass-ratio around unity. Budding and Sullivan had been engaged in a study of RT Scl parallel to Hilditch's, in which they used Duerbeck's photometry and their own spectroscopy carried out with the Cassegrain PDS system at Mt. Stromlo, and could not find any secondary peak in the cross-correlation function. The "bump" in the light-curve is unusual and perhaps quite different solutions are tenable. Budding suggested that the colour-curve might help to decide about the "accretion luminosity".

Hilditch replied that Rodgers' determination of the mass-ratio was based on only three spectrograms whose exposure times were substantial fractions of the orbital period. He and King had been able to measure the secondary peak in the cross-correlation function, even though the luminosity ratio was about 14. The secondary peak is consistent in position with expectations from orbital motion. Hilditch did not feel that he had presented the last word on RT Scl, but rather that it and other systems merited further study, with good resolution in both wavelength and time. Hilditch also noted that the uvby data of Clausen and Grønbech show that the system is slightly bluer during the phases of the "bump".

Rucinski suggested that the system of V361 Lyr supports Hilditch's interpretation. A light-curve obtained by J. Kaluzny, had been on display (see below) and shows very large accretion effects between primary and secondary minima. The colours at these phases indicate a high temperature - (U-B) is negative - but at other phases correspond to a spectral type of F2. The results are quite new and as yet without interpretation. No information about period variations is available and spectrograms were being obtained (at the D.A.O. by D. Johnstone) during the conference.

Eggleton suggested that RT Scl might not be in its very first semi-detached phase (following angular-momentum loss in a detached phase) but in a semi-detached phase of a thermal-relaxation cycle. He and J.A. Robertson (Mon. Not. Roy. Astr. Soc. **179**, 359, 1977) had shown that systems in the two phases would look very similar. As the system continued to lose angular momentum, it would spend less of its time semi-detached and more as a contact system. Such systems would be observed only with periods above the average for contact systems. Hilditch accepted this possibility (which he and D.J. King, Mon. Not. Roy. Astr. Soc. 23, 581, 1986) had noted. He preferred the idea of evolution into contact for the first time because the specific angular momentum of the system was somewhat higher than for W UMa systems with the same mass-ratio, and RT Scl seemed to fit remarkably well with the limited theoretical work on this phase of evolution.



Kaluzny's light-curves of V 361 Lyr