OBSERVATIONAL EVIDENCE FOR MASS EXCHANGE IN CLOSE BINARY SYSTEMS

Horst Drechsel
Jürgen Rahe
Gudrun Wolfschmidt

Remeis-Sternwarte Bamberg
Astronomisches Institut der Universität Erlangen-Nürnberg/F.R.G.

Yoji Kondo

Goddard Space Flight Center, Greenbelt, Maryland/U.S.A.

George E. McCluskey, Jr.

Division of Astronomy, Lehigh University, Bethlehem, Pa./U.S.A.

Introduction

In 1925 a photographic search for new variable stars was begun at the Remeis-Observatory in Bamberg. Initially the sky patrol covered only the northern hemisphere, but in 1964 it was also extended to the southern sky. At the individual observing stations, the sky is systematically photographed with several wide-angle patrol cameras which are attached to the same mounting, and which have f/6 Tessar lenses of 4-inch aperture. Each camera covers a 13-by-13 degree field. The plates are usually exposed for one hour and a photographic magnitude of 14^m is reached.

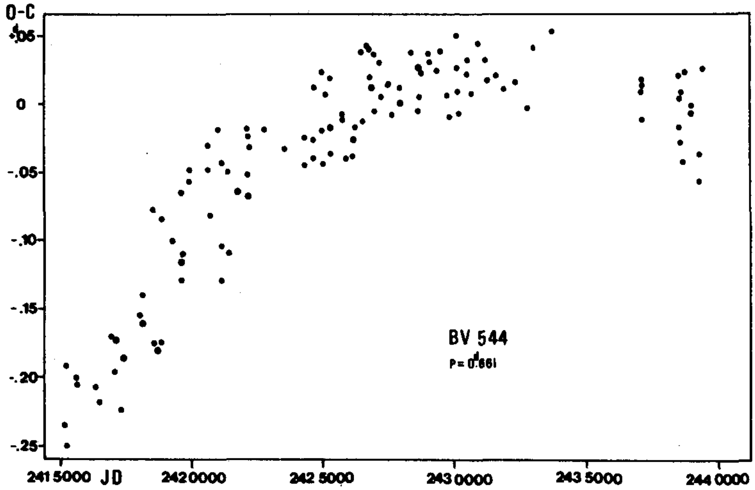
Until now, a total of about 40 000 patrol plates has been obtained and nearly 1800 new variables have been discovered, most of them brighter than 12^m. After discovery, the new variables are classified, and - if possible - their period is determined.

Period Study for Bamberg Variables

The physical conditions relevant to the problem of mass exchange in close binary systems, the correlation between mass transfer rates and period changes, and the particular problems connected with it have been discussed by many investigators (for references see e.g., Herczeg and Frieboes-Conde, 1973). Typical period changes amount to a few seconds per year; classical examples are U Cephei with a period of 2.5 days and a period increase of about 0.2 sec yr^{-1} (Hall, 1975) or Beta Lyrae with a period of 12.5 days and a period increase of about 20 sec yr^{-1} (Hack et al., 1975). If these period changes are interpreted through mass exchange, the corresponding mass transfer rates amount to 10^{-7} and 10^{-8} M_0 yr^{-1}.

Figures 1 and 2 show the (O-C)-diagram for four eclipsing binaries discovered in Bamberg. Photographic observations of the sky patrol programs of Bamberg, Sonneberg/D.D.R. and Harvard/U.S.A. have been analyzed and the period behavior

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press



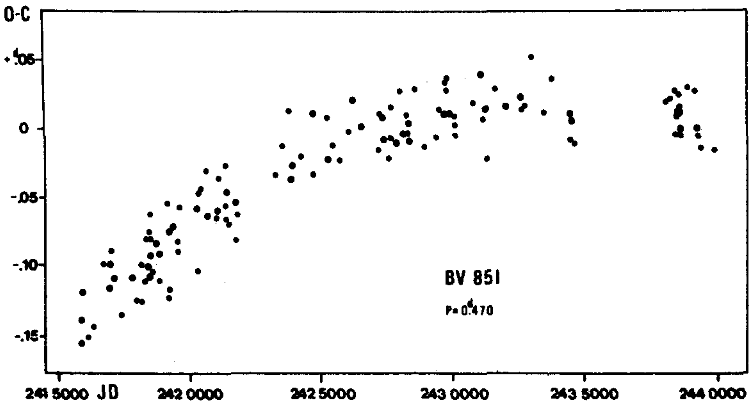
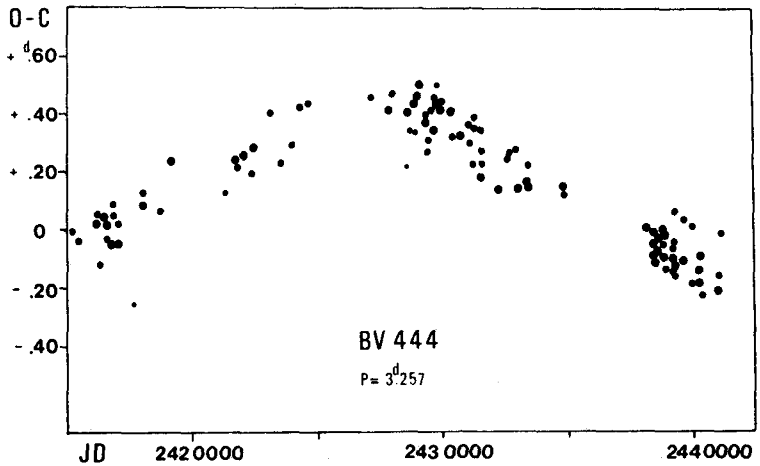


Figure 1. (O-C)-diagram for the eclipsing binaries BV 544 (= V 1010 Oph) ($P = 0\overset{d}{.}661$) and BV 851 (= FT Lup) ($P = 0\overset{d}{.}470$) discovered in Bamberg as determined from sky patrol plates of Harvard/U.S.A., Sonneberg/D.D.R. and Bamberg.

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press



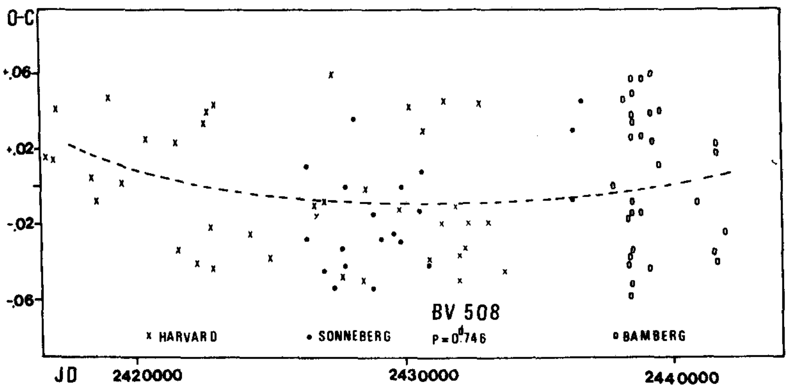


Figure 2. (O-C)-diagram for the eclipsing binaries BV 444 (= AT Cir) (P = 3^{d}.258) and BV 508 (= CX Vir) (P = 0^{d}.746) discovered in Bamberg.

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press

during the last 70 or 80 years has been studied for these and several other stars (e.g., Bauernfeind, 1969; Wälder, 1975). The figures give the Bamberg variable number which is assigned in order of discovery, the period in days, and the (O-C)-value for the corresponding Julian Date (JD). Most eclipsing binaries show of course period changes and one has also to be very careful not to overinterpret determinations of minima that are based on photographic plates. Only those systems that appear to exhibit interesting properties are selected, and then photoelectric and spectrographic observations are made at the European Southern Observatory (ESO) in Chile and at the South African Astronomical Observatory (SAAO) in South Africa for objects on the southern sky, and at the Wise Observatory in Israel for objects on the northern hemisphere. In addition, we are carrying out ultraviolet observations with the COPERNICUS satellite. One outcome of this study is the derivation of absolute dimensions of these stars. But the main aim of the present investigation is, to get information on mass exchange between the components.

For BV 851 (= FT Lup) ($P = 0^{d}.470$), the period change found is $dP/dt = 1.06 \cdot 10^{-9}$ days/day and $(dP/dt) \cdot P^{-1} = 8.24 \cdot 10^{-7}\ yr^{-1}$. For BV 544 (= V 1010 Oph) ($P = 0^{d}.661$), one finds $dP/dt = 1.83 \cdot 10^{-9}$ d/d. According to Leung and Wilson (1977), this system is likely to be an evolved system with $M_1 = 1.40\ M_o$, $M_2 = 0.68\ M_o$; $R_1 = 2.05\ R_o$, $R_2 = 1.46\ R_o$; and a separation $a = 4.53\ R_o$. For BV 444 (= AT Cir) ($P = 3^{d}.258$), there are indications for a third component. BV 508 is discussed in the next paragraph.

CX Virginis

The eclipsing binary CX Vir (= BV 508 = HD 123 660) is a W UMa-system. UBV-observations by Schöffel (1974) with the ESO 50 cm photometric telescope have been used for an analysis of the system (Wolfschmidt, 1975) and the main results are compiled in table 1.

A few anomalies appear in the U, B, V light curves: The two maxima differ by $0^{m}.03$ in height; the depth of the secondary minima in the B and U colors is too

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press

Table 1

Properties of CX Virginis

		larger comp.	smaller comp.
Period	$0^d.746\ 077$		
Amplitude	$0^m.65$ (prim.min.)		
	$0^m.30$ (sec.min.)		
B - V	$0^m.49$ (max)	$0^m.54$	$0^m.48$
U - B	$-0^m.11$ (max)	$-0^m.10$	$-0^m.01$
Spectral Type		F 8	F 6
Mass Ratio	0.16 (?)		
Inclination	$70^\circ \pm 3^\circ$		
Radius		0.55 $\pm$0.01	0.23 $\pm$0.01
Luminosity		0.74 (tr) $\pm$0.01	0.24 (occ) $\pm$0.01
Ratio of the Surface Luminosity	$I_l/I_s = 0.53$		
dP / dt	$7.4 \cdot 10^{-11}$ d/d		
$(dP/dt) \cdot P^{-1}$	$3.6 \cdot 10^{-8}\ yr^{-1}$		
dM / M	$1.8 \cdot 10^{-8}\ yr^{-1}$		

small as compared to the theoretical curves; and symmetrically to the secondary minimum at phase 0.5 $\pm$ 0.16 there is an increase in brightness of about $0^m.08$ in B, and a decrease of about $0^m.06$ in U; this is even more noticeable in the (B-V)- and especially in the (U-B)-curve.

Several methods used in deriving orbital elements lead practically to the same results (see table 1). Both components fill their Roche lobes.

A mass ratio of 0.16 was taken from the Roche model since there were no spectra available. A period change of $dP/dt = 7.4 \cdot 10^{-11}$ days/day has been derived from 91 minima found on Harvard, Sonneberg and Bamberg sky patrol plates, using a least-square fit of the (O-C)-diagram and taking $P = 0^d.746\ 077$ and $JD_0 = 242\ 6092^d.450$ (figure 2). With $dP/P = -2\ dM/M$ and assuming a total mass of the system of 2.5 $M_\odot$ which is a value often found for contact systems, a mass loss rate of $dM/M = 1.8 \cdot 10^{-8}\ yr^{-1}$ or $dM/dt = 4.5 \cdot 10^{-8}\ M_\odot\ yr^{-1}$ can be determined. The preliminary analysis indicates the necessity of a better solution. This is planned by Schöffel and Wolfschmidt when spectra of the system are available.

SV Centauri

The chance of observing a close binary system during its first phase of interactive evolution (rapid mass loss) is extremely small due to the relatively short time scales involved. As was first pointed out by Wilson and Starr (1976) and by Rucinski (1976), one of these rare early-type contact systems which are in the stage of mass transfer prior to reversal of the mass ratio seems to be the Beta Lyrae - type eclipsing binary SV Centauri (= HD 102 552).

In 1970 Irwin and Landolt (1972) made photoelectric and spectrographic observations of this system which was subsequently extensively discussed by Wilson and Starr and by Rucinski. Initiated by these studies, simultaneous photoelectric and spectrographic observations were recently carried out at ESO with the 50 cm photoelectric and the 152 cm spectrographic (20 Å/mm Coudé spectra) telescopes. A preliminary evaluation of this material essentially confirms the results obtained earlier.

SV Cen has a period of $P = 1\overset{d}{.}659$ which shows very pronounced variations with time (e.g., Dugan and Wright, 1939; Wood and Forbes, 1963; Irwin and Landolt, 1972). Figure 3 illustrates the observed period change since 1894. It is based on previously published 49 photographic and 37 photoelectric data (O'Connell, 1951; Irwin and Landolt, 1972; Landolt, 1973; Kvíz, 1976), 39 photographic minima determined on Bamberg sky patrol plates, and recent photoelectric measurements. Making a least-square fit and choosing $P = 1\overset{d}{.}659\ 5649$ and $JD_0 = 243\ 3053\overset{d}{.}217$, a period decrease of about $dP/dt = -8.9\cdot10^{-8}$ days/day $((dP/dt)\cdot P^{-1} = -1.96\cdot10^{-5}\ yr^{-1})$ is found; it is one of the largest values known and indicates a characteristic life time of $P\cdot(dP/dt)^{-1} = 50\ 000$ years. Other pertinent properties of the system are listed in table 2 which is compiled according to Irwin and Landolt (1972), Wilson and Starr (1976) and the present investigation.

The period changed from $1\overset{d}{.}661$ in 1894 to $1\overset{d}{.}659$ in 1976. If the observed rate of period change is interpreted through mass exchange between the components with mass flowing from the more massive but cooler secondary ($dP/dt < 0$) to the less massive and hotter primary (Wilson and Starr, 1976; Rucinski, 1976), the resulting transfer rate dM/dt can be derived under the assumption of conservation of mass and angular momentum from (e.g., Wilson and Starr, 1976)

$$\frac{dM}{dt} = \frac{M_2}{3\cdot(q-1)} \cdot \frac{1}{P}\frac{dP}{dt} \quad .$$

dM/dt turns out to be of the order of several $10^{-4}\ M_\odot\ yr^{-1}$. It thus seems to be at least one order of magnitude higher than that derived e.g. for Beta

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press

Table 2

Properties of SV Centauri	
Period	$1\overset{d}{.}659\ 5649$
M_p (B1 - star)	$9.4\ M_o$
M_s (B4 - star)	$11.1\ M_o$
R_p	$6.9\ R_o$
R_s	$7.2\ R_o$
dP / dt	$-8.9 \cdot 10^{-8}$ days/day
$(dP/dt) \cdot P^{-1}$	$-1.96 \cdot 10^{-5}\ yr^{-1}$
dM / dt	$3.8 \cdot 10^{-4}\ M_o\ yr^{-1}$

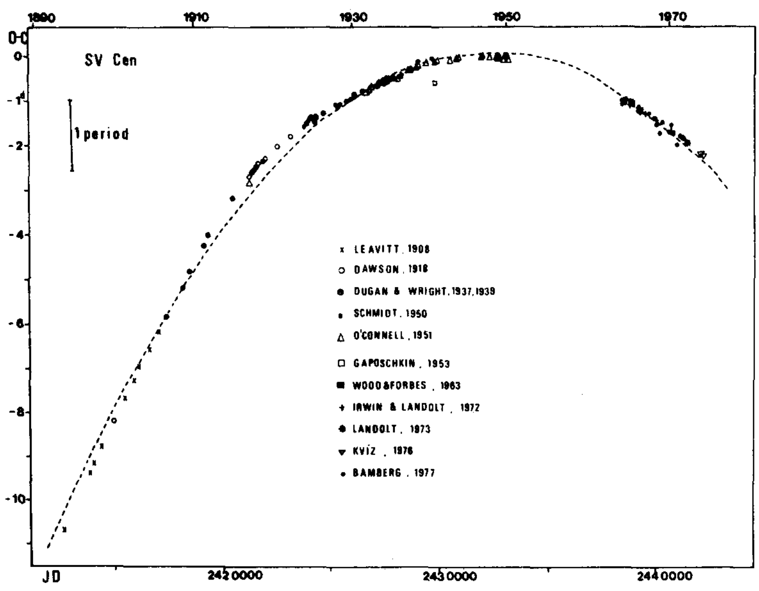


Figure 3. Observed period change of the eclipsing binary SV Cen between 1894 and 1977. The length of one period is illustrated in the upper left corner. A pronounced period decrease is apparent, indicating a mass exchange rate of about $4 \cdot 10^{-4}\ M_o\ yr^{-1}$ and a characteristic life time of the system of only 50 000 years.

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press

Lyrae ($5\cdot10^{-5}$ M_0 yr^{-1}; Hack et al., 1975), and about three orders of magnitude higher than the mass loss rate of $dM/dt = 4.5\cdot10^{-7}$ M_0 yr^{-1} determined for V 1010 Oph (see above).

In the spectra, emission features pointing to the presence of circumstellar matter cannot be detected on our, nor on Irwin's and Landolt's plates; they give also no indication that a third component is present. According to the studies of Wilson and Starr (1976) and Rucinski (1976), the absence of emission lines is, however, understandable if SV Cen is indeed a contact binary with a volume very close to, but still inside the outer critical volume and with the mass transfer occurring inside the common envelope of the system.

SZ PISCIUM

SZ Piscium (= HD 219 113) seems to be another member of this small group of early type contact binaries (Wilson and Starr, 1976). Photoelectric and spectrographic observations have been obtained and analyzed by Jakate et al. (1976). According to this investigation, it is a double-line spectroscopic and eclipsing binary of spectral types K1 IV and F8 V with a period of P = $3^{d}.9663$. The K-subgiant is more massive than the F-dwarf (which is eclipsed during primary minimum) and exhibits strong Ca II H and K emission lines; it nearly fills its Roche volume.

Figure 4 shows the period behavior of SZ Psc since 1927 as determined by a least-square fit solution with JD_0 = 242 $6334^{d}.365$ from 19 photographic observations by Jensch (1934), 2 by Gaposchkin (1943, 1952), 34 minima found on Bamberg sky patrol plates; and from 3 photoelectric observations of Jakate et al. (1976).

The period is highly variable and shortened from $3^{d}.966$ in 1927 to $3^{d}.965$ in 1976; it appears to decrease with time according to $dP/dt = -5.95\cdot10^{-8}$ days/day, resulting in a characteristic life time of about $P\cdot(dP/dt)^{-1} = -1.8\cdot10^{5}$ years. Assuming a linear decrease of the period leads to a mass transfer of about 10^{-6} M_0/yr.

UW Canis Majoris

Ultraviolet observations of UW CMa (= HD 57 060) are presently carried out with the COPERNICUS satellite. The system has been observed in 1973 and in 1975 near phases 0.25 and 0.75 (P=$4^{d}.39$), and is presently monitored during one

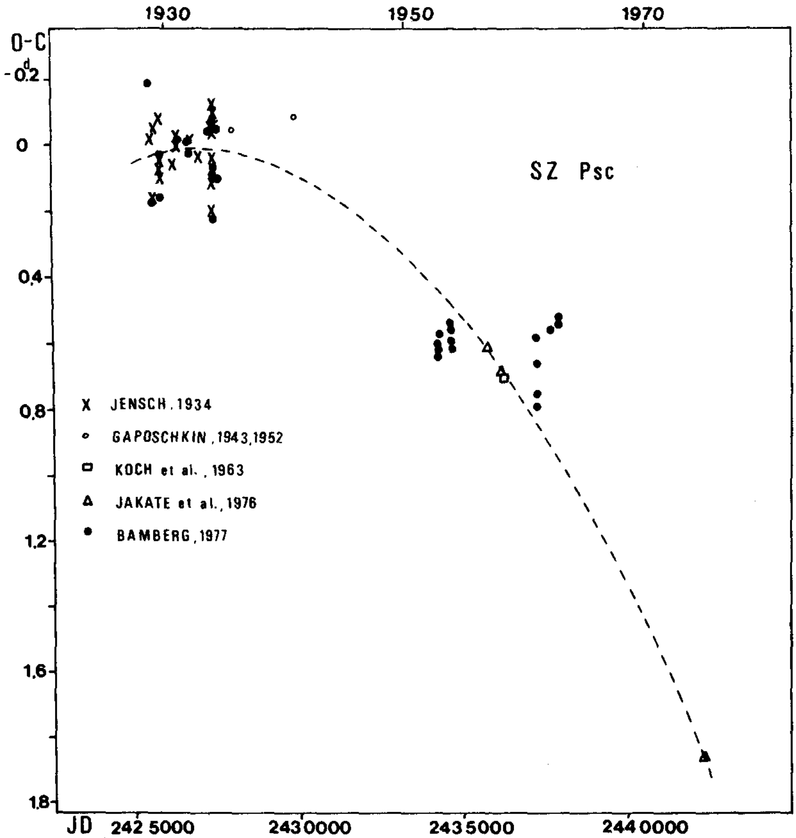


Figure 4. The observed period change of SZ Psc between 1927 and 1976. A period decrease of $(dP/dt) \cdot P^{-1} = 5.48 \cdot 10^{-6}\ yr^{-1}$ can be derived.

orbital period in order to obtain a more definite understanding of the mass flow, and to search for any secular variations in its pattern.

In the ultraviolet spectrum several P Cygni type line features of, e. g., C III (977, 1175 Å), S IV (1062, 1072 Å), P V (1117, 1128 Å) and N V (1238, 1242 Å) can be detected. According to earlier studies of McCluskey et al. (1975) and McCluskey and Kondo (1976), some of these lines exhibit shortward shifted absorption components with mean velocities greater than the escape velocity of the system ($v_e \approx$ 650 $km \cdot s^{-1}$); in addition, all P Cygni features have short-wavelength edges which correspond to velocities sufficiently high for an escape

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press

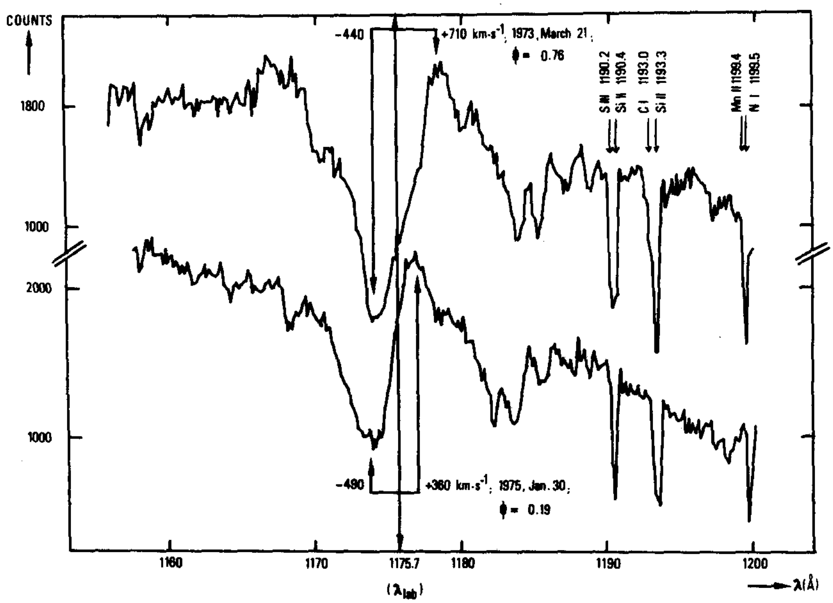


Figure 5. P Cygni line profile of C III (1175.7 Å) as observed in the ultraviolet spectrum of the O7f binary UW CMa on 1973, March 21 (orbital phase ϕ = 0.76) and on 1975, January 30 (ϕ = 0.19). Variations of the redshifts of the emission components and of the absorption strengths are clearly discernible.

of matter. The rate of mass loss can be estimated from the strengths of the absorption components, and McCluskey et al. (1975) derive a rate of about $3 \cdot 10^{-6}$ $M_{\odot}$/yr. Figure 5 shows the profiles of the P Cygni line of C III (1175.7 Å) as observed on 1973, March 21 and on 1975, January 30, i.e., at orbital phases 0.76 and 0.19, respectively. As can easily be seen, the redshifts of the emission components have considerably different values and the strengths of the absorption features have also changed. It is presently investigated whether these variations are related to phase or due to effects with longer time scales. The sharp lines between 1190 and 1200 Å are interstellar.

Detailed studies of these and similar objects are presently carried out. It is hoped that such investigations will in the long run lead to a better understanding of the evolution of early-type binary systems.

https://doi.org/10.1017/S0252921100069566 Published online by Cambridge University Press

Acknowledgements

It is a pleasure to thank Drs. Z. Kvíz, E. Schöffel, and R.E. Wilson for helpful discussions. Dr. Schöffel also obtained the photoelectric measurements of BV 508 at ESO and kindly made the material available for analysis by one of us (G.W.). Other material was obtained by J.R. at ESO, SAAO (invitation by Sir Richard Woolley / CSIR; additional observing time was supplied by Dr. Brian Warner / UCT) and Wise Observatory (Wise Observatory and Smithsonian Research Foundation Grant SFC-0-3005); part of the work was supported by the Deutsche Forschungsgemeinschaft.

References

Bauernfeind,H. 1968, Veröff. Remeis Sternw. Bd. VIII, Nr.81
Dawson, B.H. 1918, La Plata Publ. 6, 3
Dugan, R.S. and Wright, F.E. 1939, Princeton Obs. Contr. No.19, 32
Gaposchkin, S. 1952, HA 115, 86 and HA 118, 41
1953, HA 113, 72
Hack, M., Hutchings, J.B., Kondo, Y., McCluskey, G.E.Jr., Plavec, M. and Polidan, R.S. 1975, ApJ 198, 453
Hall, D.S. 1975, Acta Astronomica 25, 1
Irwin, J.B. and Landolt, A.U. 1972, PASP 84, 686
Jakate, S., Bakos. G.A., Fernie, J.D. and Heard, J.F. 1976, AJ 81, 250
Jensch, A. 1934, AN 252, 393
Koch, R.H., Sobieski, S. and Wood, F.B. 1963, Publ. Univ. Pennsylv. Vol. IX
Kvíz, Z. 1976, IBVS No. 1162
Landolt, A.U. 1973, PASP 85, 117
Leavitt, H.S. 1908, HA 60, 109
Leung, K.C. and Wilson, R.E. 1977, ApJ 211, 853
McCluskey, G.E.Jr., Kondo, Y. and Morton, D.C. 1975, ApJ 201, 607
McCluskey, G.E. Jr. and Kondo, Y. 1976. ApJ 208, 760
O'Connell, D. 1951, Riverview Coll. Obs.Publ. 2, 69
Rucinski, S.M. 1976, PASP 88, 244
Ruegemer, H. 1934, AN 255, 180
Schmidt, M. 1950, BAN 413, 200
Schöffel, E. 1974, *private communication*
Wälder, M. 1975, Veröff. Remeis Sternw. Bd. X, Nr. 108
Wilson, R.E. and Starr, T.C. 1976, Mon. Not. R.A.S. 176, 625
Wolfschmidt, G. 1975, Zulassungsarbeit, Universität Erlangen-Nürnberg
Wood, D.B. and Forbes, J.E. 1963, AJ 68, 257
Wright, F.W. 1937, HA 89, 172 .

D I S C U S S I O N of paper by DRECHSEL, RAHE, WOLFSCHMIDT, KONDO, and McCLUSKEY:

WILSON: SV Cen is telling us something about mass transfer which needs telling, in that the mass rates have not yet reversed, yet the system is not overfilling its outer contact surface. The evolutionary calculations by Flannery and Ulrich showed mass loss from the outer Lagrangian point after only about 0.1 $M_\odot$ was transferred at the beginning of rapid transfer. Two obvious questions then arise, assuming this computational result is correct: First, how does the binary get out of this desperate situation, in which it is bleeding away its angular momentum so efficiently and quickly? Second, how long does it take to do this? SV Cen shows us a case where the star has solved its problem before reaching equal masses (i.e., quite early in the transfer episode). Perhaps this will help in understanding also how this has happened.

WEBBINK: I have done evolutionary calculations very similar to those of Flannery and Ulrich to which Dr. Wilson refers (see Ap. J. Suppl, Dec. 1976), and as they do, I find the binary rapidly swelling to fill its outer critical surface. This behaviour is found by imposing the boundary condition that, in the contact state, the photospheres of both components lie on a common potential surface. No allowance has been made for a closed circulation with the common envelope, however, though this is obviously important in the more familiar W UMa systems; these assumptions are precisely the same as those made by Flannery and Ulrich. However, when I later performed a detailed hydrodynamical calculation of the mass flux through a plane passing through L_1, given the envelopes of each of the components calculated previously far from L_1, I obtained a total mass transfer rate 10^6 times greater than that obtained under the simplified assumptions used in the evolutionary calculations, and opposite in sign. I must therefore strongly caution against accepting at face value any of the calculations of massive contact binary evolution done so far.

HERCZEG: We should keep in mind that period changes are only giving - in a sense - preliminary results and without using some additional hypothesis (isotropic or directional ejection, etc.) the results may even remain ambiguous, for instance, mass exchange or mass loss from the system are not always distinguishable. It is highly desirable to supplement surveys like those done here in Bamberg by the photoelectric (and possibly spectroscopic) following-up of some more interesting objects. Perhaps this meeting can be used to work out and publish a "list of desiderata".

RAHE: We completely agree with Dr. Herczeg's remark. In a "first step" we have indeed studied the period behaviour of a number of eclipsing binaries using the photographic plates of the sky survey programs of Bamberg, Sonneberg, and Harvard. In a second step, of the most interesting objects, photoelectric and spectrographic observations - in part obtained simultaneously - have been made, and these observations are for a few bright objects then supplemented by UV-satellite observations.

H.C. THOMAS: There is an alternative explanation of the period decrease, as suggested by Refsdal, Roth and Weigert and by Eggleton, namely a magnetically coupled stellar wind reducing the angular momentum of the system. It seems worthwhile to check, whether the numbers come out right.

RAHE: In Algol-like systems, stellar winds from the subgiant to the hot component are probable, but mass loss has to be of the order of 10^{-7} $M_\odot$ yr^{-1} in order to cause an angular momentum effect as large as needed (Biermann and Hall, A & A 27, 249, 1973). Ulrich and Popper (BAAS 6, 461, 1974) explain mass exchange in binaries with H and $\bar{K}$ emission through stellar winds from the K-component; the estimated mass loss rate for these objects amounts to 10^{-9} $M_\odot$ yr^{-1} and is thus several orders of magnitude smaller than what is observed in some systems.