OBSERVATIONS OF BINARIES AND EVOLUTIONARY IMPLICATIONS*

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Abstract. Comparison of the characteristics of groups of stars in various evolutionary phases and the study of individual systems allow to make estimates of the parameters governing mass loss and mass transfer. Observations enable us in a few cases to determine geometric models for binaries during or after the mass transfer phase (disks, rings, common envelopes, symbiotics, interacting binaries, compact components).

From spectra taken at different phases, radial velocity curves can be derived and masses and radii can be determined. In special cases spectra in different spectral ranges (visual, UV, X-ray) are required for the determination of the radial velocities of the two components (for X-ray binaries, for systems with hot and cool components). Information on parameters related to the mass transfer process enables us to consider non conservative evolution – i.e. the computation of evolutionary sequences with the assumption that mass and angular momentum not only are transferred from one of the components towards the other one, but that also mass and angular momentum can leave the system. Careful and detailed analysis of the observations allows in certain cases to determine the parameters governing this mass and angular momentum loss, and for contact phases, to determine the degree of contact.

1. Introduction

The values of the conservative evolution and the influence of the various parameters was examined by De Grève *et al.* (1978). Non-conservative evolutionary computations were performed by the Brussels group (Vanbeveren *et al.*, 1979) for massive systems, taking into consideration stellar wind mass loss and mass and angular momentum loss during the Roche lobe overflow stages. In all these cases the fractional mass and angular momentum losses were determined by parametrization of general character, and used for groups of systems.

A strong argument against conservative evolution is found in studying total masses M and total angular momenta of binaries as a function of their mass ratios. This has been done by Giannuzzi (1981). For detached systems the regression lines are straight lines parallel to the coordinate axes, since these quantities are independent parameters; for semi-detached systems however the masses (or angular momenta) and the mass ratios are correlated. The mass ratio distribution in detached systems is peaked near 1, hence the semi-detached systems with small mass ratio can be assumed to be in a more advanced evolutionary phase (Giannuzzi, 1981) (see Figures 1 and 2).

Hence, it may be concluded that mass and angular momentum can leave the system. The difficult point for non-conservative evolutionary computations is to

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determine what mass fraction leaves the system as a function of the time during the mass transfer phase, and what happens to the angular momentum. We can try to find values by statistical methods, or by observing individual systems. For a number of binaries the observations reveal that matter expelled by the primary is not immediately accreted by the companion, but is stored in disks, streams, clouds. Observational evidence for the presence of circumstellar matter in close binaries has been reviewed by Batten (1970, 1973).

Disks are usually detected by their emission spectra, which are best seen at primary eclipse, when the star within the disk is hidden behind its companion. Disks are known in systems of different type: short period systems with high temperature components, Algol-type systems, systems with giant and supergiant components like SX Cas or VV Cep. Starting from two ZAMS components we can consider both conservative and non-conservative evolution, and for the latter case we can consider a variety of models and the corresponding possible configurations for solutions in view of the computation of evolutionary sequences. Different evolutionary possibilities are shown in Figure 3.

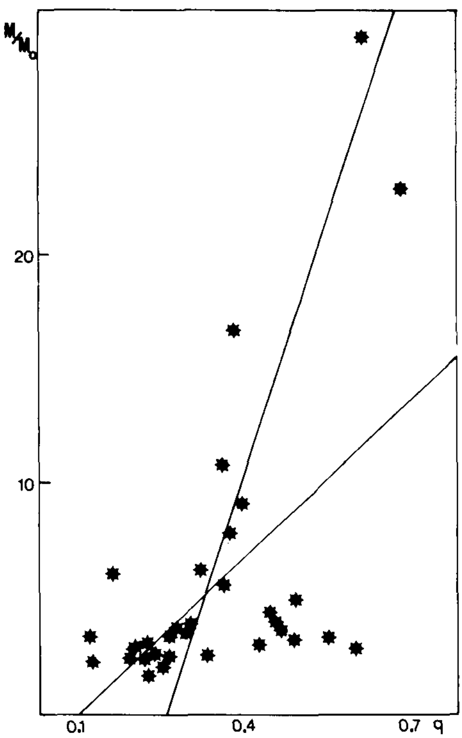

Fig. 1. Total mass as a function of the mass ratio q $(= M_2/M_1)$ for semidetached systems. These quantities are independent, hence the regression lines should be parallel to the axes. In reality the regression lines show a correlation coefficient of 0.6 (from Gianuzzi, 1981).

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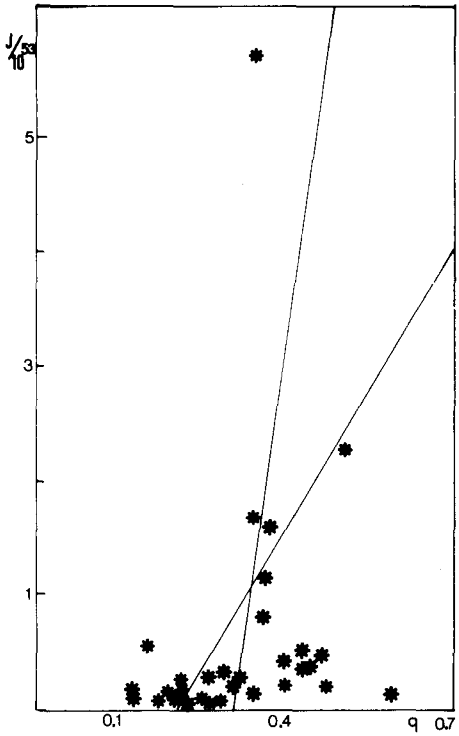

Fig. 2. Total angular momentum as a function of the mass ratio q. See further the explanation by Figure 1.

2. Historical Overview

In this overview I will try to indicate the milestones marking the progress in binary research, observations and theory.

Theoretical astrophysicists and observers have mutually helped each order in solving problems, but have also contributed from both sides to pose new problems to the other part of the astronomical community, and this challenge has lead on one hand to a considerable progress in the study of binaries, but on the other hand shows that the problems are far from solved. This will be discussed in the next section.

Successive contributions of theoretical work and observations to our actual knowledge of binary evolution

Theory	Observations
1941: Kuiper mentions the importance of the critical Roche-surface.	
	1942: Joy and Struve.
	1947: discover gaseous rings in binaries.

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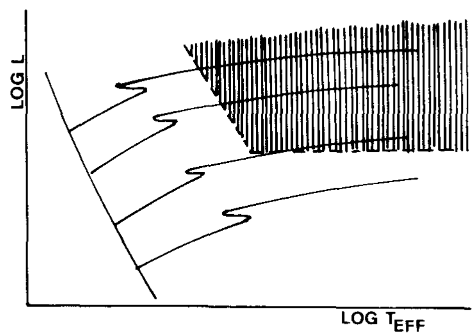
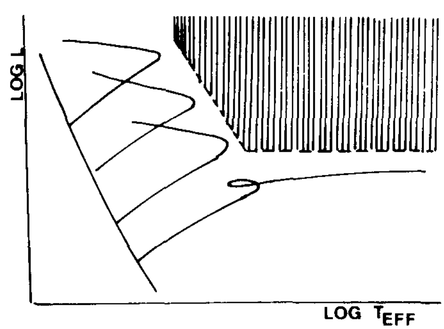
Theory	Observations
More massive stars evolve faster than lower mass stars. 1952: Sandage and Schwarzschild show that after core hydrogen burning stars evolve towards the red giant region.	1950: Study of Parenagó of 54 Algolsystems: subgiant components less massive than the Main Sequence components, hence less massive star is more evolved = Algol-paradox.
1955, 1956: Kopal shows the existence of a group of eclipse-variables, semidetached systems, in which one of the components fills its Roche lobe, for the Algols this is the less massive star. Subdivision of binaries: – detached systems: both components smaller than their Roche-volume; – semidetached systems: one component fills its Roche-lobe; – contact systems: both components fill their Roche-lobe. 1955: Crawford: solution of the Algol-paradox: dog eats dog; more massive component is fast evolving volume increases and exceeds its Roche volume; mass loss of primary; mass transfer towards secondary, accretion by secondary. 1960: Computations by Morton.	
1967: Computation of close binary evolution: evolution with mass loss of primary of close binaries. Kippenhahn *et al.* 1967: Paczynski. 1968: Plavec. 1969: Paczynski explains the Wolf-Rayet abundances for binaries: mass transfer removes the outer layers; the helium core with the products of nuclear burning appears at the suface.	Wolf–Rayet stars have abnormal abundances: overabundance of N in WN stars, of C in WC stars. Explanation?
	1962: Discovery of X-ray binaries. 1962: Sco X-1. 1970: Uhuru-catalogue of X-ray binaries: optical identifications; luminous stars + compact object.
1972: Van den Heuvel and Heise: X-ray binaries are an evolutionary phase in the evolution of massive close binaries; the mass transfer from the rejuvenated secondary produces the X-rays.	

Theory	Observations
1977: Evolutionary computions for massive close binaries from ZAMS through two supernova-explosions to two runaway neutron stars. De Loore, De Grève-evolution of accreting stars (= accreting secondaries) Tutukov. Explanation: stellar wind mass loss.	
1977: Computation of evolutionary sequences with mass loss for single stars: de Loore, De Grève, Lamers; Chiosi, Nasi, Sreenivasan; Chiosi, Bressan Bertelli.	
	Humphreys 1978: Study of luminous stars in nearby galaxies. Lack of evolved supergiants at very high luminosities: region of avoidance in the HRD.



Conflict with evolutionary tracks.



Inclusion of overshooting: larger convective cores
1981: Bressan, Bertelli, Chiosi.
1982: Doom.

Star counts: MS band not wide enough – too many B and A – stars.

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Theory	Observations
Study of OB associations (mass and age). 1983: Doom, de Loore, De Grève. – Birth of stars in different waves: a wave producing stars with mass $< 15\,M_{\odot}$; a next wave producing more massive stars.	

Conclusion: for the evolution of close binaries, computation programmes taking into account mass loss by stellar wind (massive stars, overshooting by the Roxburgh criterion) and semi-convection for the accreting component give satisfying results.

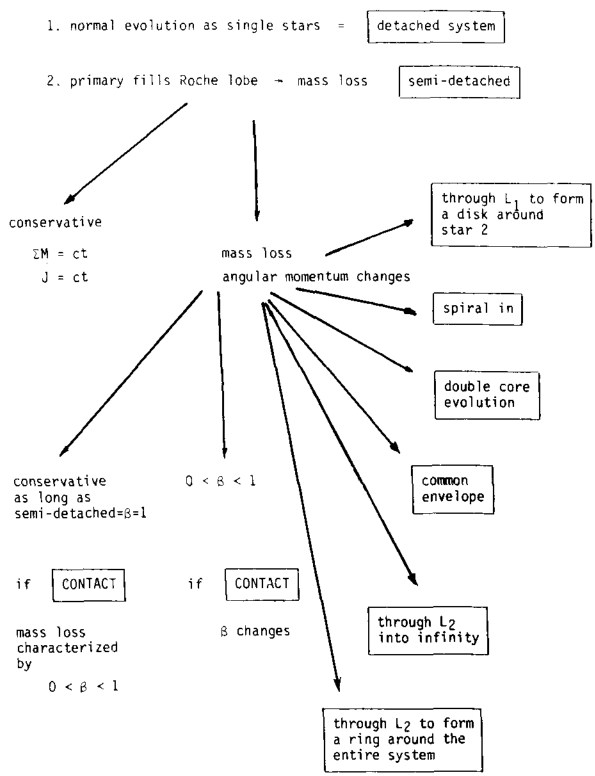

Fig. 3. Possible evolutionary scenarios for close binaries.

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3. Observations

(1) From a detailed and careful analysis of spectra, radial velocities can be derived, leading to the determination of mass ratios, and, in special cases, in combination with other observations, to masses, mass luminosity relations, radii.

The spectral range required for the optimum information is determined by the spectral emission range of the components: if both components are of the spectral types *A* to *M*, most information can be derived from spectra in the visual. For binaries with hot and cool components, different spectral ranges are needed to collect information on the system, i.e. observations in the visual for the cool component, and in the UV for the hot component. For X-ray binaries the radial velocity curve for the normal star is obtained from optical spectra, while the radial velocity curve for the neutron star component is given by the X-rays.

(2) Recent detailed observations in the visual as well as in the UV (Plavec, 1982) show that a modification of the classical model for semi-detached systems (binary at the end of the mass transfer with little interaction) is necessary. The observations point to large activity during that phase and perhaps to a relationship between Algols and symbiotics.

(3) Structure of the components. – The mass transfer in binaries modifies drastically the structure of both components. In the mass losing star deeper layers, hence with chemical compositions modified by nuclear burning, show up at the surface.

(4) In systems consisting of a normal star and a supergiant, information of the outer layers of the supergiant can be discovered in the UV spectrum of the system in and outside eclipses, by subtraction of the spectra in both phases.

Information concerning the chemical composition by analysis of spectra in various wavelengths is also necessary to compare more advanced model calculations of stellar evolution with observations. As was already mentioned, during the mass transfer phase, more and more nuclear burning products appear at the surface of the mass losing primary, while due to the transferred mass the composition of the outer layers of the accreting secondary changes. In the first phases hydrogen rich matter will be mixed in with the outer layers. Still more complex phases can be imagined when after core helium burning of the remnant of the primary this star fills again its Roche lobe, hence a second phase of mass transfer occurs. This phase has been calculated already (De Grève and de Loore, 1976; Delgado and Thomas, 1981). During this phase pure helium is tranferred towards the secondary. It would be very interesting if observations could give information about these theoretically expected, but not confirmed phases. An upper limit for the primary mass of binaries where two successive stages of mass transfer can occur has been determined by De Grève and de Loore (1976). It would also be very interesting to determine a lower limit for this special case.

During further evolution reversed mass transfer can occur, from the original rejuvenated secondary to the remnant of the primary, i.e. a helium star, or even a white dwarf. Comparison of the theoretical profile of H and He in the two components, calculated with evolution programs, with the observed chemical composition from high resolution spectra, can provide us important clues on mass transfer and mass loss. In Figure 4 is shown how the chemical profile of the mass losing star changes during the mass loss phase, and different possibilities for the behaviour of the chemical profile of the gainer (de Loore and De Grève, 1981) are indicated.

IUE spectra obtained by Plavec and Koch (1980) appear normal and agree with the spectral classification in the optical range.

According to Plavec this is not so surprising since the mass transfer rate in Algols is probably low. However, an abundance analysis of the atmosphere of the primary, mass losing star should reveal an overabundance of helium. During the last phases of the mass transfer, as matter from deeper layers of the primary is expelled, the atmosphere of the secondary should also be enriched in helium if matter is accreted.

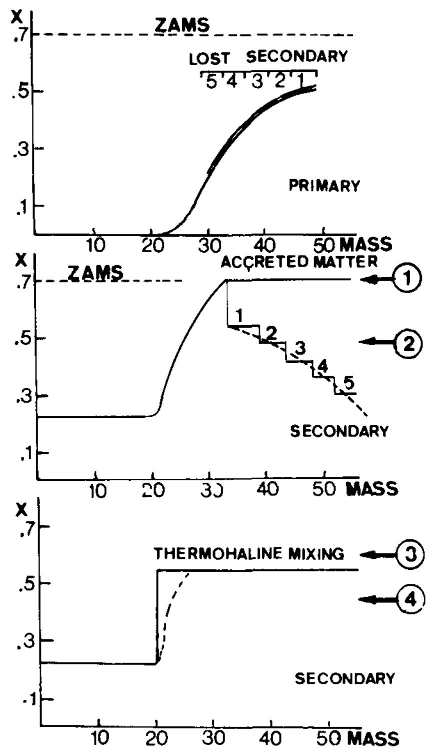

Fig. 4. The chemical profile of the loser (top) and of the gainer (middle and bottom). The figure shows four possible solutions: (1) assuming that the hydrogen profile remains unchanged ($X = 0.7$); (2) stratification and no mixing; (3) thermohaline mixing with a discontinuity; (4) thermohaline mixing with a smooth transition.

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4. Differences in Time Scales for Evolutionary Computations and Time Scales for Observations

The aim of the computation of evolutionary sequences for binaries is to explain, starting from an initial ZAMS system i.e., given masses for primary and secondary and an initial period, and applying the exact physical laws for nuclear burning, energy transfer (radiative or convective), the treatment of convection and semiconvection, the treatment of the atmosphere (plan-parallel, spherical, hydrostatic, or dynamic) to calculate successive models for the detached phase, to determine what happens durning semi-detached and possible contact phases, i.e. again calculating successive evolutionary models, for primary and secondary, but

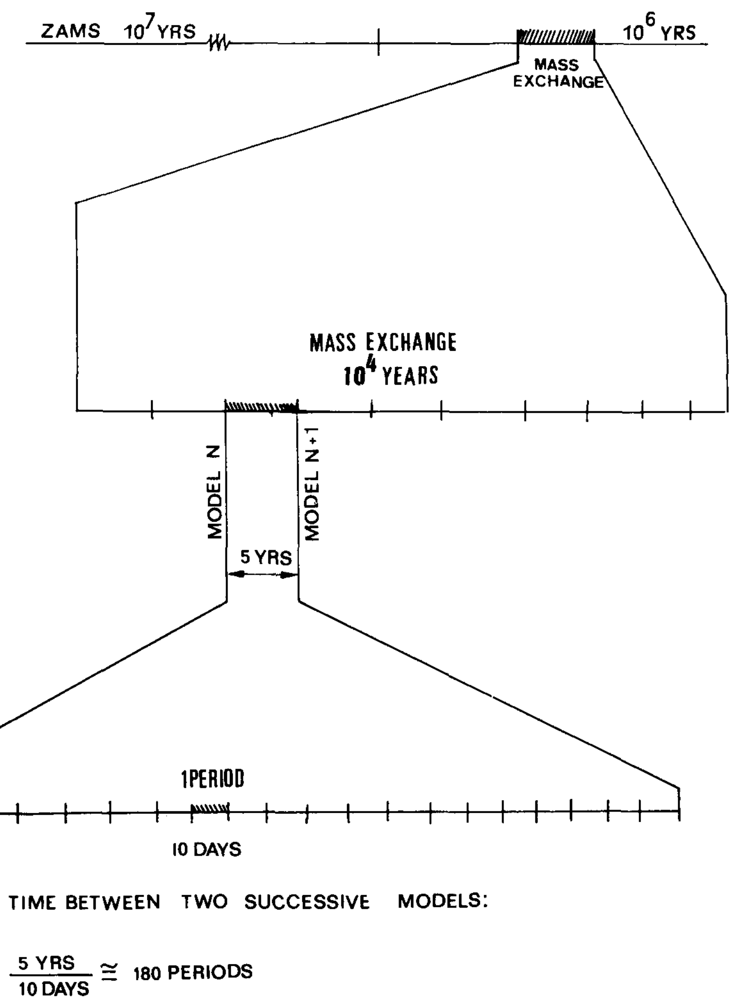

Fig. 5. Time scales for evolutionary computations and observations of binaries.

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now with interaction between the material of the two stars, and then to calculate successive evolutionary models for the phase when the contact is interrupted and the system again becomes semidetached and later on detached.

The evolutionary timescale for the various phases, i.e. the time which enters the evolutionary code to calculate two successive models is different.

In Figure 5 are depicted different evolutionary stages for a massive close binary (say a 30 $M_\odot + 20\ M_\odot$ system). The core hydrogen burning lifetime is of the order of 10 million years, the subsequent stages are $\sim 10\%$ of this time.

Roche lobe overflow starts during shell hydrogen burning.

The mass transfer occurs on the Kelvin–Helmholtz time scale, which is in this case, of the order of 10^4 yr. While the time step for successive evolutionary models during core hydrogen is of the order of 10^5 yr, and during shell hydrogen of the order of 10^4 yr, the time step for successive models during the mass transfer phase drops to the order of 10 yr.

Let us now turn to the observations, to the lower part of Figure 5. The figure shows clearly that two successive models, model N and model $(N+1)$ are about 5 yr apart, which means that these two models depict two phases in the life of the binary with a time interval of 5 yr, corresponding to two observations, also 5 yr apart. What is happening between these two phases can be observed but not calculated. This makes the comparison of theory and observations very difficult.

This becomes even clearer when we compare this time lapse between two successive models with the orbital period. In our example 180 orbits fill in the gap between two successive models!

5. Non-Conservative Evolution

Since not always the conditions for conservative evolution-total mass and total angular momentum are constant – are satified, computations of evolutionary sequences have been carried out with assumptions on mass and angular momentum losses.

TABLE I

The remaining masses of primary (M_1), secondary (M_2) final period and time of the mass exchange of an initial $40\ M_\odot + 20\ M_\odot$ system with a ZAMS period of 10.2 d for various parameters related to the mass loss (β) and angular momentum loss (α)

β	α	M_1	M_2	P(d)	Time mass exchange (in years)
1	0	11	29	18.8	12200
0.5	1	10.7	23.1	6.8	11150
	3	10.3	23.2	2.9	7700
0	0	11.2	16.9	62.5	11200
	1	11.0	16.9	22.3	13300
	3	10.2	16.9	2.4	14100

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As an example the non-conservative evolution of a $40+20\ M_\odot$ system is shown in Figure 6 and Table I (Vanbeveren *et al.*, 1979).

In the computations were included:

(1) Mass loss by stellar wind during core hydrogen burning and shell hydrogen burning (detached phase).

(2) During the Roche lobe overflow stage it was assumed that a fraction β of the mass expelled by the primary is accreted by the companion, and that also a given fraction of the angular momentum is transferred towards this companion, related to α.

6. Survey of Theoretical Conservative Evolutionary Computations

A. Computations

During the last two decades a large number of evolutionary sequences for close binaries have been carried out.

Figures 7 and 8 show the initial masses, mass ratios and periods of systems for which computations exist.

(Cases (A), (B), and (C) are defined according to Kippenhahn; i.e.:

(A) mass transfer starts during core hydrogen burning;

(B) during shell hydrogen burning;

(C) after the start of He-burning.

Figure 7 shows clearly that:

(a) computations with extreme mass ratios ($q < 0.3$) have practically not been carried out;

(b) case (C) is not yet thoroughly investigated;

(c) contact systems (indicated with (★) have been computed as far as the contact phase, not through the contact phase.

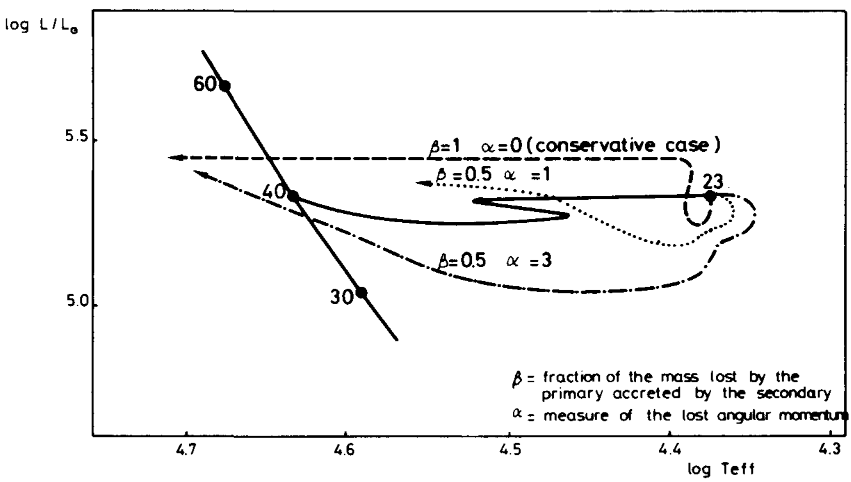

Fig. 6. Non-conservative evolution of a $40\ M_\odot+20\ M_\odot$ system, for various values of the parameters related to mass loss (β) and angular momentum loss (α).

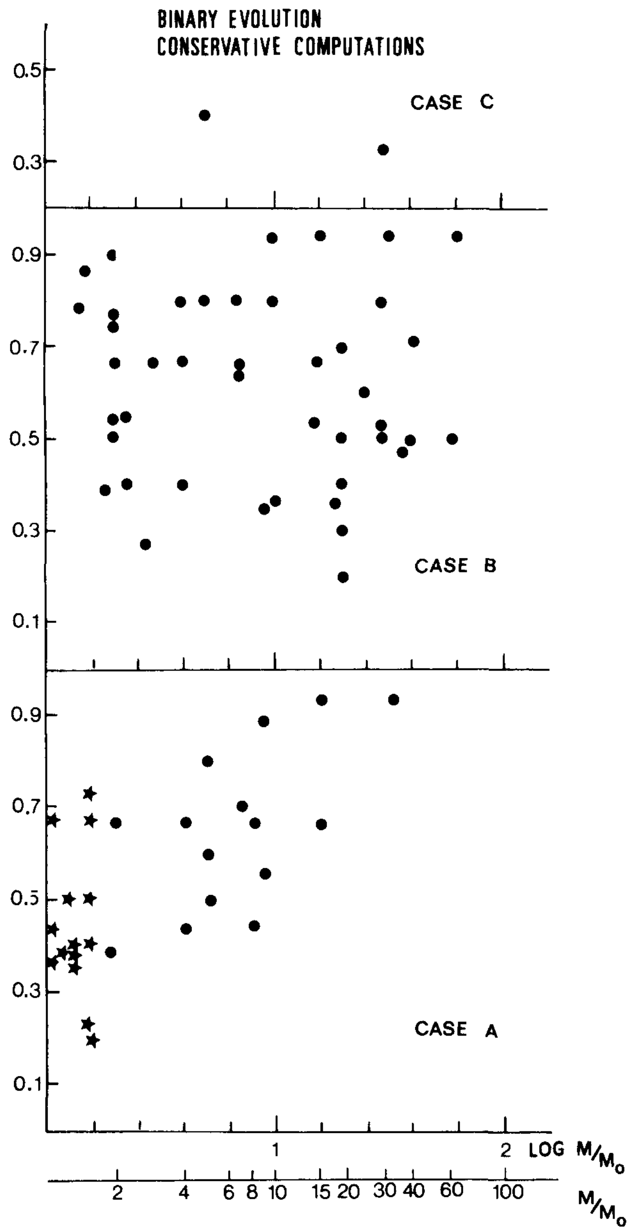

Fig. 7. Survey of initial masses and mass ratios of computed close binary systems. Vertically are displayed the mass ratios q. The dots represent ZAMS-systems for which evolutionary computations were carried out through semi-detached phases; the asterisks represent systems evolving into contact and here the calculations end.

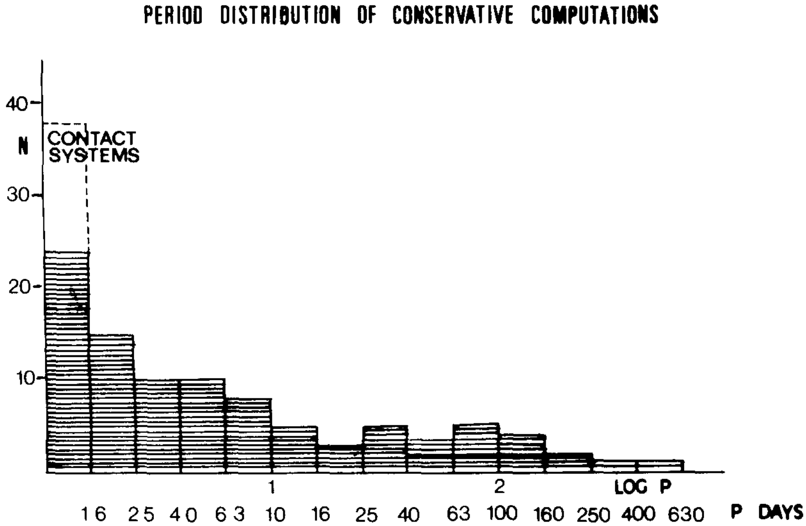

Fig. 8. Survey of initial masses and periods of computed close binary systems.

Figure 8, where the period distribution is depicted, reveals clearly that most computations were performed for systems with small periods.

B. Treatment of the mass transfer

Successive phases, in the evolution of close binaries are:

(1) *detached phase*;

(2) *semi-detached phase*: i.e. the primary fills its Roche lobe while the secondary lies deeply within its Roche volume;

(3) *contact-phase*: where the two stars are overflowing their Roche lobe, hence filling volumes limited by a common equipotential surface.

In a first approximation the mass exchange was treated in the following way:

(1) *detached phase*: only stellar wind losses;

(2) *semi-detached phase*: conservative mass transfer from primary to secondary;

(3) contact phase: a fraction β of the mass expelled by the primary is accreted by the secondary, determined in such a way that the secondary keeps filling its Roche lobe, the rest leaving the system in a spherically-symmetric way ($\beta < 1$) (Plavec, 1981).

After a certain time the secondary becomes detached from this contact volume, the system becomes again semidetached and the mass transfer occurs again in a conservative way ($\beta = 1$).

The mass transfer comes to an end when the primary shrinks back within its Roche lobe.

Another way to treat the contact phase has been investigated by Packet (1983) in the following sense: the mass transfer rate is determined such that both stars fill a common equipotential surface, outside their Roche lobes. Until now luminosity transfer has been omitted; in the future this will be investigated.

Mass exchange is thus treated in a conservative way, only when the surface of the system corresponds with the equipotential surface through L_2, mass loss has to be considered. Test computations carried out by Packet for a binary system, with a primary of 9 $M_\odot$, and secondaries with mass ratios of 0.9 and 0.6 show that the latter situation is not reached, and that the total binary evolution occurs in a conservative way.

7. Algols

7.1. Short-period systems ($P \lesssim 14$ d)

Algol binaries are semi-detached close binaries. The less massive component, which appears to be more advanced in its evolution by its position in the HRD (on the giant or subgiant branch of the evolutionary track) is filling its Roche lobe. The more massive component lies in most cases within the Main Sequence band. This component is of an earlier spectral type. Such systems are supposed to be the results of mass transfer and mass loss. The initially most massive one is now the less massive one as a consequence of this mass transfer process. The timescale of the mass transfer is the Kelvin-Helmholtz time scale. Although the Algols are beyond the most important phase of the mass transfer, some mass flow still exists, at rates different from one system to the other. The Algol binaries with subgiant secondaries are very difficult to treat, since as a rule one can only observe the spectrum of the primary component, and in that case the radial velocity curve leads only to the mass function

$$f(m) = \frac{m_2^3 \sin^3 i}{(m_1 + m_2)^2}.$$

For the derivation of the mass ratio complementary information or additional assumptions are needed.

For a number of Algol systems spectroscopic orbits were obtained by Popper (1980a, b). For the systems with periods less than 6 days the orbits found by Popper are without complications. For a number of systems with longer periods the velocities deviate from sinusoidal variations. In the case of U Cep and U Sge these deviations of the velocity curves might be the consequence of absorption in gas streams in the system.

Strong double H emission in the spectra of the longer period systems points to the presence of extra-photospheric matter. The masses and radii of the primaries lie in the range for Main Sequence stars of the same spectral type (except TW And, cooler than predicted by mass and radius).

Table II shows that masses as low as 0.2 $M_\odot$ and 0.3 $M_\odot$ are common for Algols.

TABLE II

Well-known SD systems

Name		M_p	M_s	P
V Pup	HD 65818	$M_1 = 9$	$M_2 = 17$	$P =$ 1.5 d
V 356 Sgr	HD 173787	4.7	12.1	8.9 d
u Her	HD 156633	2.7	7.3	2.1 d
Z Vul	HD 181987	2.3	5.4	2.5 d
RZ Cnc	HD 73343	0.5	3.2	21.6 d
AR Mon	HD 37364	0.8	2.7	21.2 d
RV Lib	HD 128171	0.4	2.2	10.7 d
RT Lac	HD 209318	1.5	0.6	5.1 d
RY Per	HD 17043	0.8	5.0	6.9 d
RS Vul	HD 180939	1.4	4.5	4.5 d
U Sge	HD 181182	1.9	5.7	3.4 d
Algol	HD 19356	0.8	3.7	2.9 d
S Cnc	HD 74307	0.2	2.4	9.5 d
RY Gem	HD 58713	0.6	2.6	9.3 d
TT Hya	HD 97528	0.7	2.6	7.0 d
XY Pup	HD 67862	0.3	2.3	13.8 d
AS Eri	HD 21985	0.2	1.9	2.7 d
TW Dra	HD 139319	0.8	1.7	2.8 d
AW Peg	HD 207956	0.3	2.0	10.6 d
RY Aqr	HD 203069	0.3	1.3	2.0 d
TW And	+32 4756	0.4	1.8	4.1 d
U Cep	HD 5679	2.8	4.2	2.49 d
V 701 Sco		9	9	0.76 d

Evolutionary calculations show that it is not easy to explain these systems.

Packet (1980) found that if no mixing occurs the gainer, after the mass transfer, has a position in the HRD hotter than the Main Sequence band, in contradiction with observations. Hence a mixing mechanism has to be involved. Packet suggests differential rotation or pulsational instabilities.

The Interacting Binary U Cephei and the mass losing system HR 2142

According to Plavec (1982) the system consists of a B9V primary and a G8III secondary. The masses are 4.2 $M_\odot$ and 2.8 $M_\odot$ with radii of 2.9 $R_\odot$ and 4.7 $R_\odot$, respectively. The G star is evolved and is losing mass; some returns to the G star.

IUE spectra reveal that the effects of the gas stream are most distinctly visible in the resonance line of Fe II at 2599.395 Å and the resonance M_g doublet at 2795.523 Å and 2802.698 Å. The absorption lines of Si II, III, IV, C II, C IV, Fe III, Al II, III are probably also affected. Most of these absorption lines are broad and shallow and point to rapid rotation of the B star, of $\sim$ 300 km s^{-1}. A geometric model was presented by Kondo *et al.* (1980) and is shown in Figure 9.

The gas stream leaves the G star from the hemisphere directed towards the B star, circles around the B star; some of the gas probably falls onto this star. The rest leaves the system after orbiting 3/4 of the B star. Some of the matter can fall

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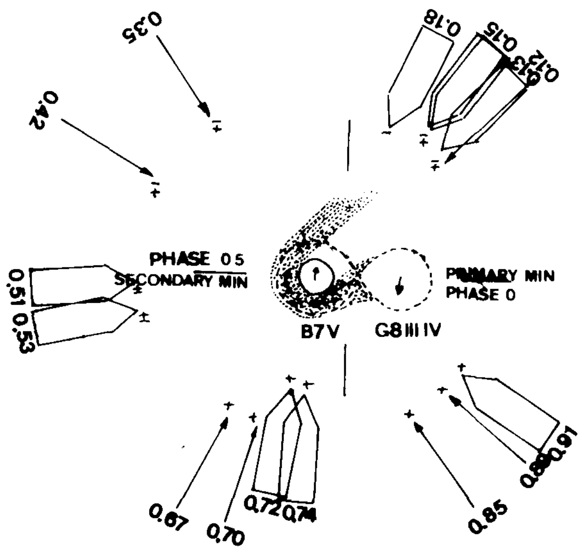

Fig. 9. Schematic representation of the gas stream as observed in the Fe II and Mg II resonance lines. The broad arrows are the data from 1978 June and September and the thin arrows are the data from 1979 March and June: the phases of observation are also given. The + sign indicates that the radial velocity of the gas stream projected against the B-star is away from the observer, the − sign that the radial velocity is toward the observer; the ± sign both away and toward the observer, and the ∓ sign mostly toward, but with a minor component away from, the observer. The + sign at phases between 0.67 and 0.91 is probably due to the combination of the gas streaming around the B-star and the gas falling onto that star creating a hot spot which faces the observer shortly after phase 0.75. The ∓ sign at phases between 0.12 and 0.15 is probably due to the partial occulation of the B-star by the matter leaving the G-star (from Kondo *et al.*, 1980).

back onto the G star. The gas in the stream is hot enough to keep most of the Fe, Si, and Mg atoms ionized.

Observations of HR 2142 (Polidan and Peters, 1980) in the UV show that most of the material that leaves the primary is ejected from the system and not accreted. Evidence of mass ejection from the system can be seen in C II 1335 where rather strong, sharp absorption components are present, not from interstellar origin. As most probable origin for these components a circumsystem cloud or disk is suggested. Also in HR 7084 and λ Tauri gas streams are detected.

7.2. Long-period systems ($13 < P < 600$ d)

A number of Algol systems with longer periods have been studied by Plavec and Koch (1978), in the visual as well as in the UV.

As mentioned before the chemical structure of both components can provide important information on the mass transfer process, on mass loss and mass storage. We know reasonably well how a star losing mass reacts to this mass loss, but how the accretion process works is still not understood. The systems studied by Plavec (1980) display emission lines in the visual (Balmer lines, He I, Fe II); they imply the presence of a much hotter source.

One of these systems, β Lyrae was observed by Hack *et al.* (1975, 1977) with Copernicus. They found that β Lyr has a unique spectrum in the far UV, with strong emission lines.

Koch and Plavec (1978) discovered 6 binaries with the same type of emission line spectra in the far UV. All these W Serpentis stars show emission lines (Balmer lines) in the optical spectra compatible with the optical continuum of a star, too cool (A9) to excite the emission, hence suggesting a hot source. Observations of Plavec and Koch (1978) revealed five of these systems.

The spectra of 'Serpentides' show as common characteristic that:

(a) in the UV we see strong emission lines superposed on;

(b) a hot continuum of 11 500 K.

The optical companions are cooler:

B8II for β Lyr, A6III for SX Cas, F5II for W Ser.

The UV is produced in a region smaller than the observed stellar surface, as shown in Figure 10.

The IUE spectrum of SX Cas out of eclipse, partially and totally eclipsed (Plavec, 1980) is shown in Figure 11.

Optical spectra show that when the eclipse is total, the A6III spectrum disappears completely and the G5III spectrum remains. In the UV during the eclipse also the continuum disappears while the lines remain.

The explanation is that a hot source is present.

This hot source is the hot component.

In these interacting binaries emission lines of C II, C IV, N V, Si II, III, IV, Fe III, Al II, III are present. These emission lines are probably related to the mass flow, and the accretion; the ionization is most likely connected with a hot spot or a hot radiative region in the interior of the thick disk. The matter surrounding the hot component is not completely eclipsed when the star itself disappears behind the companion, and certain components of the shell lines remain visible against the background of continuous hydrogen radiation. The period of SX Cas is variable, and decreases at a rate of $\dot{P}/P = -7.6 \times 10^{-8}\,\mathrm{yr}^{-1}$ (Guinan and Tomczyk, 1979).

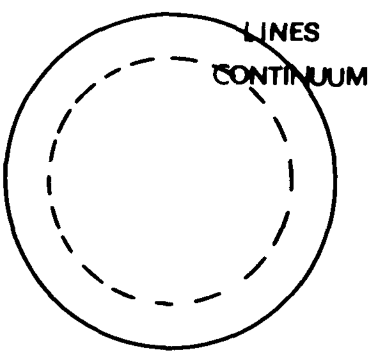

Fig. 10. Explanation in the text.

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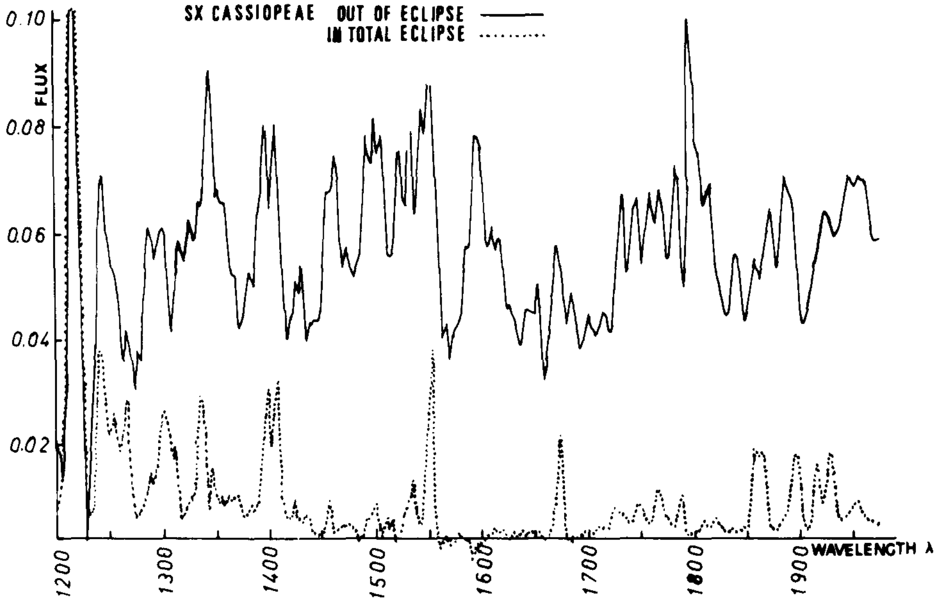

Fig. 11. IUE spectra of SX Cas in- and outside eclipse. During eclipse the continuum disappears, but the UV lines remain.

This period change is comparable to those of β Lyr or W Ser, but the sign is opposite. Simple mass transfer from the less massive component to the other one increases the period. In SX Cas the loser is certainly the less massive one. Probably strong mass loss from the system in the form of a strong stellar wind occurs. A disk model for SX Cas is shown in Figure 12.

8. A Contact System: SV Centuari

SV Centauri has been studied in great detail in the optical and the UV by Drechsel *et al.* (1982), and orbital and absolute dimensions could be derived. A radial velocity curve was found by Irwin and Landolt (1972) leading to a mass ratio of $M_2/M_1 = 1.19$ and a systemic velocity $\gamma = -33.4 \pm 7.5$ km s^{-1}. The improved values determined by Drechsel *et al.* (1982) are $M_2/M_1 = 1.25$ and $\gamma = -27.7 \pm 6.3$ km s^{-1}.

From a combination of spectroscopic and photometric data they found the absolute dimensions and system parameters of SV Cen (see Table III). The analysis reveals that SV Cen is a contact binary, with the less massive component the more luminous star. The period decrease is $\dot{P}/P = -2.15 \times 10^{-5}$ yr^{-1}. Both components are filling their Roche lobes, and the common stellar surface is very close to the outer critical Roche surface. The UV spectroscopic observations point to the presence of an expanding circumbinary envelope, and to a large mass loss from the system. The period decrease can be explained by means of angular momentum

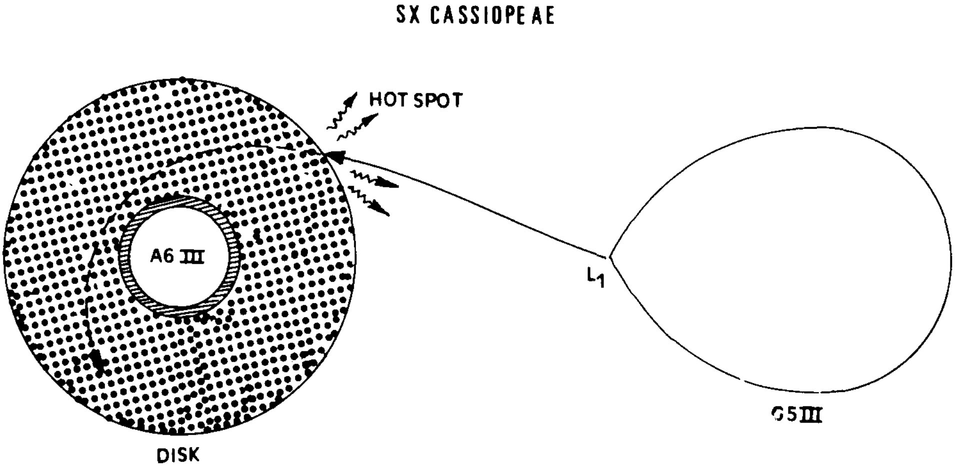

Fig. 12. Model of a close binary during the mass transfer phase, with an accretion disk and a hot spot where the flow of matter, leaving the mass losing star, impinges on the disk. Model for SX Cas by Plavec, Weiland and Koch. According to Plavec (1982) the correct spectral types are probably B7III for the gainer and K3III for the loser.

carried away by matter leaving the system. A geometrical model for the system is shown in Figure 13.

It is suggested that matter is flowing from the less massive component through L_1, near the inner critical equipotential surface. The kinetic overshoot energy of the inflowing material allows a part to escape through L_3. The matter is accelerated by radiation pressure and leaves the system.

Evolutionary computations to reproduce the actual parameters of SV Cen were carried out by Nakamura and Nakamura (1981). They started from ZAMS masses

TABLE III

Absolute dimensions and systemparameters of SV Cen

$a_1 = 8.5\,R_\odot$	$M_1 = -5\overset{m}{.}4$
$a_2 = 6.8\,R_\odot$	$M_2 = -3\overset{m}{.}4$
$a = 15.3\,R_\odot$	
	$BC_1 = -2\overset{m}{.}3$
$m_1 = 7.7\,m_\odot$	$BC_2 = -1\overset{m}{.}1$
$m_2 = 9.6\,m_\odot$	
	$M_1(V) = -3\overset{M}{.}1$
$R_1 = 6.8\,R_\odot$	$M_2(V) = -2\overset{M}{.}3$
$R_2 = 7.4\,R_\odot$	$M_{tot}(V) = -3\overset{M}{.}5$
$L_1 = 11\,700\,L_\odot$	$E(B-V) = 0\overset{m}{.}27$
	$A_V = 0\overset{m}{.}9$
$L_2 = 1900\,L_\odot$	$d = 1800$ pc
	$Sp_1 =$ B1 V
	$Sp_2 =$ B6.5 III

of 13.4 $M_\odot$ and 7 $M_\odot$, with an initial period of 2.21 days. The evolutionary tracks, with calculation of the contact condition according to Robertson and Eggleton (1977) are depicted in Figure 14. The authors conclude that SV Cen is actually in the rapid phase of mass transfer preceding the mass ratio reversal. The mass loss rate in the theoretical computations decreases when the system evolves into contact.

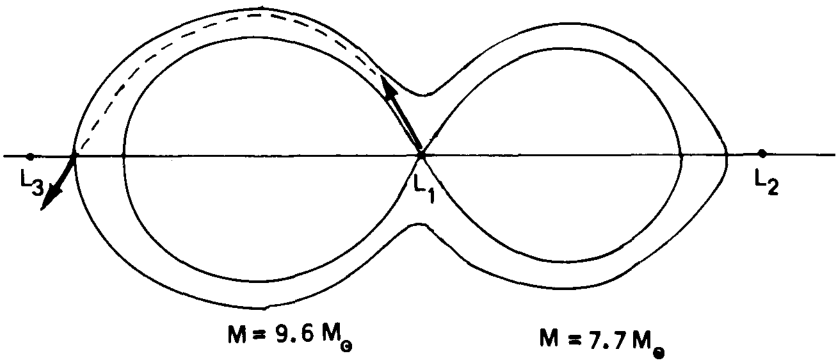

Fig. 13. Geometrical model for SV Cen. L_1, L_2, L_3: Lagrangian points.

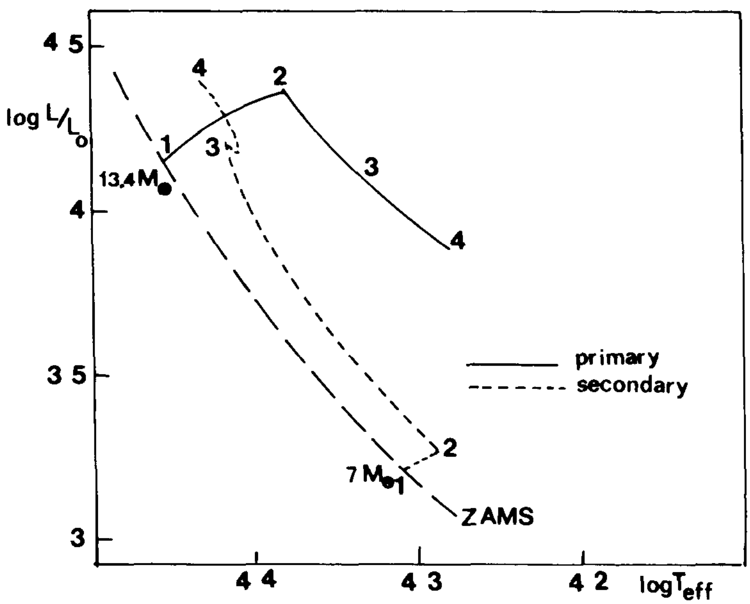

Fig. 14. Evolutionary tracks leading to the SV Cen system: (1) start of the ZAMS; (2) start of the mass transfer; (3) beginning of the contact phase; (4) actual stage.

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9. Supergiant Systems

A few binary systems are known where one of the components is a hot star, much smaller than its companion. Such systems are extremely interesting if they can be observed when the hot star travels behind the outer layers to the supergiant, an atmospheric eclipse. The most famous binaries of this group are listed in Table IV.

TABLE IV

Supergiants

Name	Hot star	Supergiant	Period	
φ Aurigae		K4 Ib		
31 Cygni	B	K4 Ib		
32 Cygni	B	K4 Ib		
VV Cephei		M2 Ia	20 years	
μ Sagittarii	OV?	B8 Ia		$f(m) = 2.64$
ε Aurigae	B?	F2 Ia	27 years	

The optical is completely dominated by that of the red supergiant component. The hot companion is only marked by the Balmer lines and a couple of He-lines, blended with the late type spectral lines of the supergiants (metals, molecules). The hot component can be studied by ultraviolet during eclipses and outside eclipses. Studies of such systems have been carried out by Stencel *et al.* (1980) for 31 and 32 Cygni. Their observations reveal a hot turbulent region near the B component and a cool fast moving wind farther out. μ Sagittarii has been investigated a.o. by Plavec (1980), who, by substraction of the in- and out eclipse spectra, made an estimate of the nature of the hot companion, possible an O Main Sequence star, with log $T_{\rm eff} \sim 4.60$. Hack and Selvelli (1978) found from IUE spectra indications for a B-spectrum for the hot component, with a radius of $2\,R_\odot$. The most astonishing fact is that during the eclipse the supergiant disappears behind the hot star, hence this star should have an envelope of $\sim 850\,R_\odot$. Huang (1965), Morris (1965) suggested that the eclipse is caused by a flat disk, seen edge-on, and formed by material expelled from the F-star. There seem however to remain difficulties, since the F-star is not yet filling its Roche lobe.

10. Cataclysmic Variables

(1) Orbital period $\lesssim 1$ d;
(2) one of the components is a highly evolved star, WD or NS;
(3) the companion has a low mass and low luminosity $M \lesssim 1\,M_\odot$, $L \lesssim 1\,L_\odot$; may also be highly evolved.

The observational characteristics have been reviewed by Robinson (1976) and Warner (1976). Observational and theoretical aspects of novae can be found in Gallagher and Starrfield (1979). One of the components of binaries belonging to this group is a white dwarf surrounded by an accretion disk. The system is in a Roche-lobe overflow phase, and matter flows from the secondary through the inner Lagrangian point L_1 towards the disk. The evolution of cataclysmic variables has been discussed by Paczynski (1981). Observational and theoretical aspects of low mass X-ray sources are discussed by Lewin and Joss (1981) and by van Paradijs (1981). In this group the evolved object is a neutron star instead of a white dwarf. Evolutionary aspects of these objects were reviewed by Ritter (1982a). A list of all cataclysmic binaries and related objects and of the relevant literature is collected by Ritter (1982b).

11. Symbiotic Stars

Symbiotics form a inhomogeneous group of stars, probably representing various evolutionary phases. A number of symbiotics are long-period binaries with one of the components being a hot star. In many cases this hot star is variable, and this is perhaps a common property of symbiotics. An excellent review of symbiotics is given by Plavec (1981) and evolutionary aspects of symbiotics are discussed by Paczynski (1980).

The symbiotics are poorly known. According to Plavec (1981) their evolutionary status could be:

(a) binary systems in the beginning of a second mass transfer stage, with a cool component which is a red giant in expansion but still within its Roche lobe, and a companion situated in the HRD in the same region as the central stars of planetary nebulae (could be a helium star, remnant of an Algol after the first mass transfer stage);

(b) the hot subdwarf can also be a white dwarf where accretion of matter leaving the red giant as stellar wind re-ignites nuclear burning shells (novalike symbiotics);

(c) a system in the first stage of mas transfer in which an accretion disk around a Main Sequence star furnishes the photons required for the ionization of the nebula (Algol-symbiotics).

12. Wolf–Rayet Binaries and OB-Type Binaries

The general characteristics of Wolf–Rayet stars can be summarized as follows:

(1) they are hydrogen poor or they contain no hydrogen at all;

(2) the spectrum is dominated by strong emission lines;

(3) they can be divided into two subgroups, the WC stars, having a strong carbon and oxygen spectrum, and the WN stars, having a nitrogen spectrum;

(4) WR stars are losing mass in a spherically symmetric way (stellar wind); the mass loss rates are of the order of $3 \times 10^{-5}\, M_\odot\, \mathrm{yr}^{-1}$;

(5) single WR stars as well as WR binaries exist.

(For a complete review see Conti (1982).)

Problems connected with the origin of WR stars are:

(1) how are single WR stars formed? By mass loss, during the core hydrogen burning stage, so that the products of nuclear burning appear at the surface (overshooting models, or models with increased mass loss?), or did these stars pass through the red giant stage where a sudden and large mass loss forced them back to the blue part of the HRD or do both scenarios exist?

(2) how are WR binaries formed? Here is the problem simpler, since due to mass transfer during the RLOF stage, the WR characteristics appear in a natural way: enough mass is removed so that the products of nuclear burning appear at the surface:

$$\mathrm{OB1} + \mathrm{OB2} \rightarrow \mathrm{WR1} + \mathrm{OB2}$$

$$\mathrm{C.S.} + \mathrm{OB2} \rightarrow \mathrm{C.S.} + \mathrm{WR1}$$

(C.S. means compact object, e.g. neutron star)

$$\mathrm{OB1} \lesssim 30\text{–}40\, M_\odot;$$

(3) very important is the number of WR stars which are binaries.

Detection of the Binarity

(1) Photometric observations, showing eclipses;
(2) variation of the absorption lines.

In a number of WR stars absorption lines are seen. This has been used until recently as proof for the binarity. There are no systems with companions other than of O-type. In the seventies (Niemela, 1973; Conti, 1976) it was realized that absorption lines could originate in the WR stars as well. Massey (1980), Massey and Conti (1981), Massey *et al.* (1981) have shown that in certain cases the absorption lines could be intrinsic to the Wolf–Rayet star itself, so that the presence of absorption lines is not necessarily a proof for the binarity (e.g. in HD 927407 WR emission lines and absorption lines vary in phase). Hence reliable WR binaries are only those systems for which an orbit has been established. Only 20 of the 159 WR stars in the catalogue of van der Hucht *et al.* (1981) are true WR binaries.

Number of known WR stars (Pop. 1):

159	WR in the Galaxy	(van der Hucht *et al.*, 1981)
100	WR in the LMC	(Breysacher, 1981)
8	WR in the SMC	(Azzopardi and Breysacher, 1979)
40	WR in M33	(Way and Corso, 1972)
20	WR in M31	(Shara and Moffat, 1982)
	WR in NGC 604, M101,	(Boksenberg *et al.*, 1977)
	Tol 3, II Zw 40	(Conti and Massey, 1981).

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Hence only 10% of the galactic WR stars are yet established as WR + O systems (SB2) and only 2.5% have optically invisible companions (SB1). This has been examined by Massey (1980, 1981); he concludes that the percentage of close WR + O binaries seems to be maximum 25%, and the overall binary frequence less than 50%.

All WR stars in the SMC show absorption lines. In the LMC the overall fraction of binaries is ~ 40%.

A list of well defined Wolf–Rayet binaries is given in Table V. For a number of OB-type binaries masses could be determined from binary motion and evolutionary computations. The two components must have the same age and the same sin *i*; using stellar structure models for OB stars and Of stars allows the determination of consistent *t* and sin *i*, hence the masses can be determined for a number of cases (Doom and de Loore, 1984). Masses of OB stars are shown in Table VI.

TABLE V

Wolf–Rayet binaries; well defined systems

Name	P (d)	Type	q	$M_1 \sin^3 i$	$M_2 \sin^3 i$	M_{WR}	M_{OB}
HD 90657	8.2	WN4–O4–6	0.5	6.8	13.6	25	58
HD 152270	8.89	WC7–O6	0.36	1.8	4.9	~ 20	~ 60
HD 94546	4.9	WN4–O7	0.34	8	23	> 8	
HD 168206	29.7	WC8–O8–9V	0.37	7	24	~ 9	25
MR 42	6.3	WN6–O5	0.86	43	50	50	60
HD 186943	9.55	WN4–O9V	0.42	3.36	7.94	13	25
HD 190918	112.8	WN4.5–O9I	0.27	0.7	2.6	9	35
HD 214419	1.6	WN7–O?	1.20	23	19	> 40	> 23
HD 193576	4.21	WN5–O6	0.39	10	25.6	12(17)	45
HD 211853	6.68	WN6–O	> 22	11.5	33	10–25	> 50–60
HD 68273	78.5	WC8–O9I	0.54	17	32	20	35
MR 114	2.13	WN4 + O8	0.43	5.3	12.2	5–11	12–25
HDE 311884	6.34	WN6–O5V	0.84	40		~ 50	~ 60
HD 192641		WC7 + abs					
HD 193793		WC7 + abs					
HD 92740	80.34	WN7 + abs					
HD 97152	7.86	WC7–O5–7	0.59	3.6	6.1	20	35
HD 63099	27.63	WC5–O7	0.16	17			
HD 113904	18.34	WC6–O9.5Ia					
HDE 320102	8.83	WN3 + O7	0.33	1.8		11	35
RUNAWAYS							
HD 50896	3.76	WN5					
HD 96548	4.80	WN8					
HD 76536	4.00	WC6					
HD 192163	4.50	WN6					
HD 197406	4.30	WN7					
HD 164270	1.80	WC9					
HD 86161	10.70	WN8					
HD 177230	1.80	WN8					
209 BAC	2.40	WN8					

TABLE VI

Well defined O-type binaries

Name	Type	P(d)	$M_1 \sin^3 i$	$M_2 \sin^3 i$	$t/10^6$ yr	M_{1i}	M_{2i}	M_1	M_2	Remarks
AO Cas	O9III+O9III	3.5	10.1	12.9	6.5	25	33	23	29	3% overcontact
	O9.5III+O9III	3.5	10.1	12.9	6.7	19	26	19	24	
HD 19820	O9IV+O9IV	3.4	18.9	9.18						
ι Ori	O9III+O9III	29.1	15.9	9.4	6.1	42	24	35	21	
29 CMa	O8.5If+O7	4.4	20	24						23% overcontact
HD 93205	O3V+O8	6.1	39	15	0.0	63	24	63	24	
HD 93403	O5f+O7.5	15.1	5.2	3.4	5.4	57	33	45	29	
HD 159176	O7V+O7V	3.4	10.8	11.4	5.7	35	38	32	34	
HD 191201	B0III+B0III	8.3	13.8	12.9	11.1	19	17	17	16	
HDE 228766	O5. 5If+O7.5I	10.7	16.3	15.7	6.0	47	44	38	37	
HD 228854	O6.5V+O7.5	1.88	37.3	32.7	5.7	44	37	37	33	both fill RL
HD 206267	O6.5V+O9	3.7	18.3	6.37						
14 Cep	O9V+O9V	3.1	6.16	2.91						
HD 215835	O6+O6	2.1	23.4	19.1	5.0	51	39	43	35	both fill RL
HD 166734	O7If+O9I	34.5	29	31	6.7	41	40	32	34	
HD 149404	O8.5I+O7IIIf	9.8	1.58	2.66	5.7	24	45	23	39	
HD 165052	O6.5V+O6.5V	6.1	2.5	2.2	5.4	45	38	38	33	
HD 167771	O7IIIf+O9III	4.0	2.7	2.3	6.4	43	33	32	29	

13. Massive X-Ray Binaries

13.1. Radial Velocities and Mass Determinations

From a collection of 92 blue spectrograms of HD 77581 taken with the 152 cm spectrographic telescope of ESO, heliocentric radial velocities were determined. Using the observed pulse arrival times of Rappaport *et al.* (1976) the orbital elements for the compact object were derived. Combination leads to the masses of the components of the Vela X-1 system:

$$M_x \sin^3 i = 1.67 \pm 0.12\, M_\odot,$$

$$M_{\text{opt}} \sin^3 i = 20.5 \pm 0.9\, M_\odot.$$

If we adopt an average value of $\sin^3 i = 0.96$, as 'best value' for the masses, $M_x = 1.74\, M_\odot$ and $M_{\text{opt}} = 21.3$ were obtained (van Paradijs *et al.*, 1977).

13.2. Variations in the Profiles of Hβ and He II 4686

The observed periodic variation of the Hα emission profile is commonly interpreted as due to gaseous streams in the system. Also the profile of Hβ is phase dependent and consists of two absorption components, superimposed on one another. One of these components is the steady photospheric profile, the other is variable in strength and velocity (Zuiderwijk, thesis, 1979). The profile of He II 4686 is of the P Cygni type around phase 0.7 and in absorption with variable strength between $\phi = 0.9$ and 0.5. These observations point to a gaseous stream in the system, and an asymmetrically expanding atmosphere.

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13.3. Detailed analysis of the Hα line

The wide undisplaced emission component of Hα is clearly produced far from the stellar surface in an extended envelope outflowing radially. The absorption component is formed in the part of the envelope between observer and stellar surface, hence the absorption line velocity reflects the outflow velocity of the envelope at the mean Hα forming level into the direction of the observer. An analysis of the Hα profile as a function of phase was carried out by Zuiderwijk *et al.* (1974). Figure 15 shows the variation of the Hα profile.

Already in the case of a circular orbit the outflow pattern is expected to be asymmetric as a consequence on the asymmetric gravitational field of the neutron star. The eccentricity ($e = 0.096$) makes this still worse. The figure shows that the

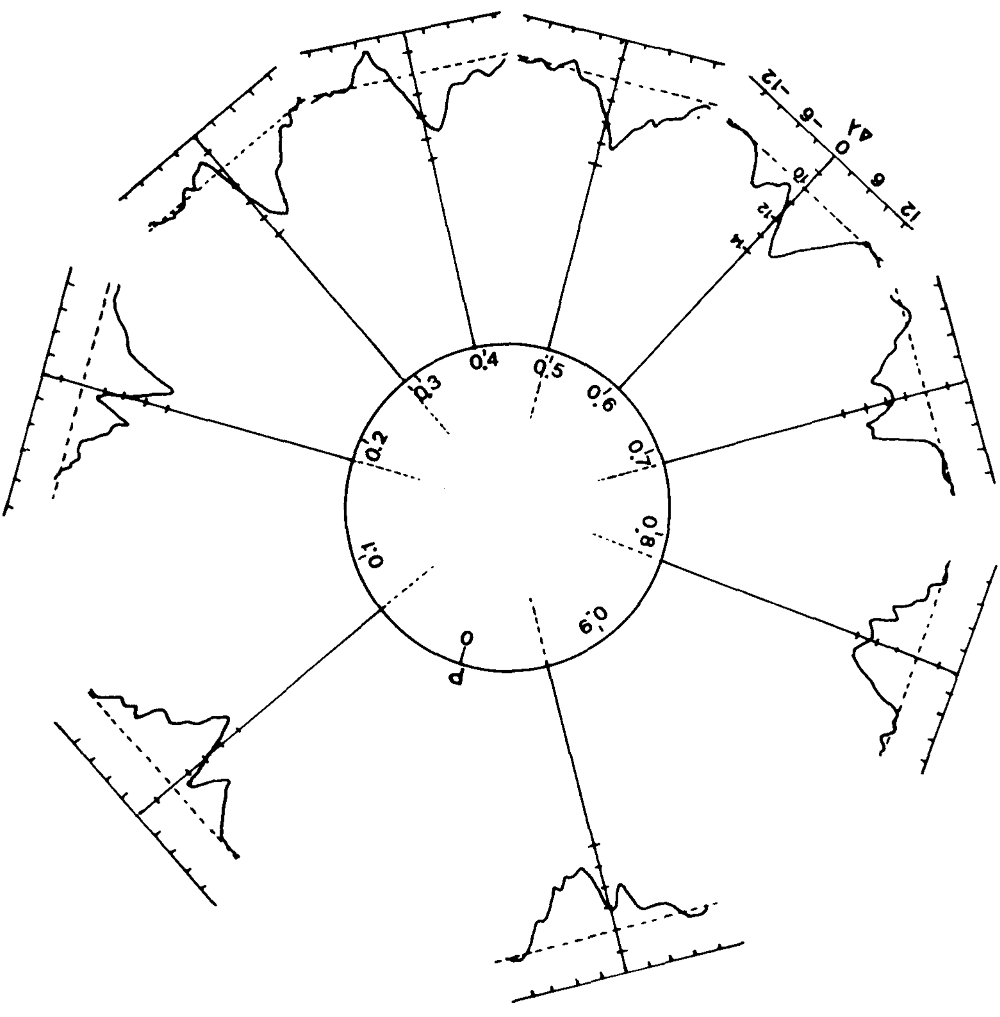

Fig. 15. The variable Hα profile of HD 77 581 as a function of phase (from Zuiderwijk, 1974).

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largest outflow occurs between the phases 0.25 and 0.50. The figure suggests that the outflow is not very strongly dependent on the size of the Roche lobe as the Hα profiles before and after apastron passage are different although the sizes of the lobes are the same. Probably the B0.5Ia star is well within the Roche lobe, so that the mass loss process is probably due to stellar wind, not to Roche lobe overflow.

14. Barium Stars

According to McClure *et al.* (1980) all stars with a Ba II anomaly vary in radial velocity and could be binaries. In a couple of cases they could even go farther and could derive a mass function, indicating companions of 1 to 2 solar masses. The low masses, low luminosities and small radial velocity ranges suggest that the systems are reasonably wide and that the companions probably are degenerate (Plavec, 1982).

The Ba II star ζ Cap (G5II) has such a component (Böhm–Vitense, 1980). From the observed flux distribution is derived that $T_{\rm eff} \sim 22\,000$ K, and the mass is $\sim 1\ M_\odot$. These observations strongly suggest that the Ba II anomaly may be due to mass transfer.

15. Conclusions

Many problems concerning the evolution of close binary systems remain unsolved. More detailed and accurate observations are needed, as well as more evolutionary computations, allowing comparison between theory and observations. For more systems should be derived the masses of the components, the rates of mass flows, a geometric picture of the mass flow, the evolutionary status.

We have a considerable amount of information on the final stages of binary evolution, massive X-ray binaries, binary pulsars, cataclysmic variables, X-ray bursters and on advanced phases of the evolution of massive stars, e.g. Wolf–Rayet binaries, and we have good ideas about the progenitors of such systems. Observations in different wavelength regions, optical, UV, X-ray, IR, radio, in many cases simultaneously, have especially for these cases provided relevant information. For more normal cases, the mass transfer phase itself which is very short, especially the rapid phase, but also for the phases following the mass exchange, more information is required.

Very important for the determination of the evolutionary status is the chemical composition of the atmosphere. The hydrogen to helium ratio of the atmosphere of the two components of a close binary can give us information on the mass loss and accretion processes as explained in Section 3. A contaminated atmosphere for the gainer is a proof for accretion; the hydrogen to helium ratio, combined with a theory on accretion and mixing of accreted material and existing material tells us how much is accreted. The same analysis of H/He gives information on the internal structures of the loser and the amount of expelled matter.

Systems with well defined masses, periods and information on the abundances for primary and secondary, compared with evolutionary computations can provide important contributions to our ideas on the evolution of close binaries.

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