There was a young man whose veracity
Was questioned because his opacity
While given to Stothers
Was held back from others
With a singular show of tenacity.

SESSION 7

EVOLUTION WITH MASS LOSS: DOUBLE STARS

Chairman: D.C. MORTON
Introductory Speaker: I. ZIOLKOWSKI

1. A. TUTUKOV and L. YUNGELSON: Evolution of massive common envelope binaries and mass loss.
2. D. VANBEVEREN, J.P. DE GREVE, C. DE LOORE and E.L. VAN DESSEL: The influence of stellar wind mass loss on the evolution of massive close binaries.
3. A. DELGADO: Common envelope binaries and mass loss.
4. C. FIRMANI, G. KOENIGSBERGER, G.F. BISIACCHI, E. RUIZ and A. SOLAR: HD 50896: an other WR binary star.

EVOLUTION OF BINARY STARS WITH MASS LOSS

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ABSTRACT

Three situations involving mass loss from binary systems are discussed. (1) Non-conservative mass exchange in semi-detached binaries. No quantitative estimate of this mechanism is possible at present. (2) Common envelope binaries. There are both theoretical and observational indications that this phase of evolution happens to many systems, even to some that are not very close initially (orbital periods ~ years). (3) Stellar winds in binaries. Observational evidence suggests that stellar winds from components of close binaries (especially semi-detached) are significantly stronger than from single stars at the same location in the H-R diagram. Theoretical arguments indicate that in some cases stellar wind may stabilize the component of a binary against the Roche lobe overflow. In some cases there is weak evidence of an anisotropy in the stellar wind.

There are two major mechanisms of mass loss from O-type binaries. One of them is non-conservative mass exchange between the components after one of the components overflew its critical Roche lobe. The second mechanism is strong stellar wind from one or both components. The first mechanism can probably operate in any close binary, independent of its mass. The second mechanism is efficient only for massive systems, which practically limits its importance to only O-type binaries (at least one of the components has to be initially an O-type star). A special and very important case of the first mechanism occurs if a common envelope binary is formed during the process of mass exchange. In this paper we shall briefly discuss all three situations: (1) non-conservative mass exchange in semi-detached systems, (2) mass loss from common envelope binaries, (3) stellar winds in binaries.

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1. NON-CONSERVATIVE MASS EXCHANGE

The conservative theory of the evolution of close binaries is summarized in excellent review articles by Plavec (1968), Paczyński (1971) and Thomas (1977). The most controversial among the assumptions on which this theory is based is just the assumption about the conservation of the total mass and the total orbital angular momentum. Certainly this is not a very good assumption. We have observational evidence for mass loss from some binaries undergoing the process of mass exchange at the present moment (Kruszewski 1966, Huang 1966, Batten 1970). Unfortunately no reliable quantitative estimate of this phenomenon is available. The motivation for performing almost all theoretical evolutionary calculations with the conservative assumptions is neither our belief that mass loss is insignificant nor the need for computational conveniency. It is just our ignorance (both observational and theoretical) about the quantitative aspects of the mass loss and orbital angular momentum loss from the system that makes the conservative assumptions appear the most natural. From technical point of view, it is quite easy to incorporate an arbitrary amount of mass and angular momentum loss from the system. We can do so by introducing two parameters defined as follows:

$$f_1 = \frac{\Delta M}{\Delta M_1} \qquad (1)$$

and

$$f_2 = \frac{J_{\Delta M}/\Delta M}{J\ /\ M} \qquad (2)$$

Here $M = M_1 + M_2$ is the total mass of the system at a given moment, J is the total orbital angular momentum, ΔM is the amount of mass lost by the system during one evolutionary time step and $J_{\Delta M}$ is the angular momentum taken away by this matter. We assume that the mass is leaving component M_1 and that ΔM_1 represents the total amount of mass lost by this component during our time step. Part of this mass, equal to $(1-f_1)\Delta M_1$, is accreted by component M_2 and part, $f_1 \Delta M_1 = \Delta M$, leaves the system. In such an approach, the parameter f_1 tells us how large a fraction of the mass lost by the M_1 component, actually leaves the system. Of course, we have $0 \leq f_1 \leq 1$. The parameter f_2 is describing the ratio of the average angular momentum per mass unit for the matter leaving the system to the similar average for the binary system. If we could decide on numerical values for the parameters f_1 and f_2, we could proceed with the evolutionary calculations.

Unfortunately, such a decision has to be quite arbitrary, although some observational and theoretical attempts to estimate the values of f_1 and f_2 have been made. Svetchnikov (1969) was comparing the observed pre-mass exchange and post-mass exchange binaries and tried to deduce the value of parameter f_1 averaged over the entire phase of mass transfer. He found that $f_1 \sim 0.3 \div 0.9$ but his analysis is not very conclusive, since the observational data are quite uncertain and their interpretation is by no means unique. From similar considerations, Ziółkowski (1971) found no substantial evidence of significant mass loss during the past evolution of majority of semi-detached binaries. Hall (1976) suggested that careful investigations of period changes in semi-detached binaries could give us in some cases information about present mass loss from these systems. On theoretical grounds, Drobyshevski and Reznikov (1974) estimated $f_2 \sim 3$ from analysis of the redistribution of angular momentum in the system during the mass transfer. Flannery and Ulrich (1977) used the restricted three-body approximation for particle trajectories and found that for the matter leaving the system from the vicinity of Lagrangiant point L_2, the value of f_2 is $\gtrsim 7$.

Given the situation as described above, the best one can do is probably to make theoretical calculations for different trial values of f_1 and f_2 and in this way to estimate the uncertainties of our conservative evolutionary theory. Such calculations were first done by Paczyński and Ziółkowski (1967). A similar approach was also used by Plavec et al. (1973) and Massevitch and Yungelson (1975). All these calculations confirmed that the evolution of the mass-losing component is determined primarily by its internal structure and is not very sensitive to various assumptions about the mass loss and angular momentum loss from the system. On the other hand, the final orbital parameters are quite sensitive to the values of f_1 and f_2, in particular, the final orbital period can be much shorter in the case of the mass loss from the system.

To summarize our considerations: the mass transfer in semi-detached binaries is not conservative, but we do not know how significant the deviations from the fully conservative process are. The good agreement between the theoretical evolutionary model for β Lyrae (Ziółkowski, 1976a) and the observational data indicates that in some cases the conservative approach does not lead to very bad results.

2. COMMON ENVELOPE BINARIES

Binaries with a deep common envelope are a relatively new idea and I found that they still need some advertisement. Therefore I shall start with a brief summary of theoretical and observational arguments indicating that such objects are really being formed in our Galaxy.

2.1. Theoretical arguments

Benson (1970) was the first who investigated the evolution of the mass-receiving component of a close binary and found that already at an early stage of mass transfer the secondary (mass-receiving) component expanded so much that it filled its own Roche lobe and a contact system was formed. Similar calculations were later done by many other authors (Yungelson 1973, Webbink 1975, Kippenhahn and Meyer-Hofmeister 1976, Ulrich and Burgher 1976, Flannery and Ulrich 1977, Neo et al. 1977). The common result of all these investigations was that even in the binaries that were initially relatively wide (with initial periods $\gtrsim$ 10 days) a contact system was formed after only a few percent of the initial mass of the primary were transferred. The evolutionary tendency indicated the built-up and expansion of the common envelope during the subsequent evolutionary phase. Flannery and Ulrich (1977) followed the evolution of their binary system up to the moment when the common envelope reached the equipotential surface passing through the outer Lagrangian point L_2. One may expect that as the surface of the common envelope expands further beyond the L_2 point, mass loss from the system might occur. Flannery and Ulrich investigated this problem using the restricted three-body approach for particle trajectories. They found that particles ejected from a co-rotating atmosphere through the L_2 point with low velocities would indeed leave the system, carrying away considerable angular momentum. The parameter f_2 as defined above is in this case given by:

$$f_2 = C(1+q)^2/q \qquad (3)$$

where $q = M_1/M_2$ and $C = 1.7 \div 2$ depending on the degree of asynchronism and the mass ratio. A very similar formula for f_2 was found independently by Tutukov and Yungelson (1978). Let us note that the minimum value of f_2 is ~ 7 and that for large mass ratios (X-ray binaries) we have $f_2 \approx 2q$. This means that mass outflow from L_2 is a very efficient mechanism for angular momentum loss from the system. Due to this loss the orbit of the binary will shrink very rapidly. It is easy to show that the separation between the mass centers A will change with the total mass of the system according to the approximate formula:

$$d \log A/d \log M \approx 2f_2 \qquad (4)$$

It appears that under typical conditions ($f_2 \sim 10$) the loss of only 12 percent of the mass by the system will decrease the size of the orbit by one order of magnitude! Due to this rapid shrinking, the point L_2 will sink deep into the common envelope and soon the surface of the envelope will be far outside this point and at a large distance from two rotating mass centers. At such a large distance the rotation is certainly very asynchronous and there is no longer any compelling reason for the matter to leave the system. As a result a binary with a deep, roughly spherical and still expanding common envelope forms.

2.2. Observational arguments

Observational arguments can be divided into three categories.

A) The statistics of observed Algol-type systems evolving in Case A and B and comparison with theoretical evolutionary time scales indicates a strong deficit of systems evolving in Case A. The most likely explanation of this deficit is that binaries evolving in Case A quickly form deep common envelope configurations and as such are lost from the statistics of Algol-type systems (Ziółkowski, 1976b).

B) Some systems like SV Cen and probably V 367 Cyg are now observed to be in the very process of building up a common envelope (Kreiner and Ziółkowski, 1978). These common envelopes are not very thick yet (otherwise we would not observe them as binary systems) but the observed evolutionary trend (mass transfer) indicates that they might become quite thick after only a few thousand years.

C) We observe many close binaries the origin of which can be understood only by assuming dramatic angular momentum loss (and some mass loss) from the systems during their past evolution. One can mention here a broad class of cataclysmic binaries (novae and dwarf novae) and some interesting individual systems like: (1) the binary pulsar PSR 1913+16 (e.g. Smarr and Blandford, 1976), (2) UU Sge (Bond et al., 1978), (3) V 471 Tau (e.g. Paczyński, 1976), (4) PG 1413+01 (Green et al., 1978), (5) UX CVn = HZ 22 (Schönberner, 1978), (6) LB 3459 (Dearborn and Paczyński, 1978) and (7) BD $-3^{\circ}5357$ (Dworetsky et al., 1977). The common feature of all these systems is that they have very short orbital periods but contain components which are very advanced from the evolutionary point of view (white dwarfs, hot subdwarfs or neutron stars). From the theory of evolution of single stars we know that such objects could be incubated only inside red giants or supergiants of large radius and luminosity. This implies that the initial separations between the components of the systems discussed above had to be much larger than at present and that their initial orbital periods had to be of the order of years. For example, in the case of V 471 Tau, Paczyński (1976) found the initial orbital period of the order of 10 years, while the present period is only 12 hours. The only known way to decrease so dramatically the size of the orbit is to evolve the system through the phase of a deep common envelope which is subsequently lost by the system (see the next section).

2.3. Mass loss from common envelope binaries.

Common envelope binaries undergo mass loss probably during two phases of their evolution. The first of these - discussed earlier - occurs soon after formation of the common envelope, at the moment when its surface reaches the L_2 point. As described earlier, some matter will escape from the vicinity of L_2, but due to the considerable angular momentum loss accompagnying this process, the binary orbit will shrink rapidly and mass loss will probably have to cease soon. The fraction of the mass lost at this phase is unknown but might be quite small - perhaps of the order of few percent.

The subsequent evolution of a common envelope binary was discussed qualitatively by Paczyński (1976). Numerical calculations of this phase of evolution were carried out by Taam et al. (1978), Tutukov and Yungelson (1979) and Delgado (1978) for somewhat different systems in which one of the components is a neutron star or a white dwarf. However uncertain the details of such evolution, the basic results can be summarized as follows. The main mechanism responsible for the evolution is the drag force experienced by the components of the binary system (or their dense cores) moving through the matter of the common envelope. The action of this drag force will transfer energy and angular momentum from the orbital motion to the common envelope. This will have two effects: (1) rapid shrinking of the binary orbit and (2) increase in the luminosity of the envelope (during most of the evolution the drag luminosity is much larger than the intrinsic luminosity of both stars) and its further expansion. When the luminosity and the dimensions of the envelope are large enough, different instabilities similar to those responsible for planetary nebulae ejections from single stars (e.g. Iben, 1974) will appear and as a result the common envelope will be lost. The development of these instabilities is easier than in single stars due to large energy generation (drag luminosity) at the base of the envelope. An additional mechanism facilitating the loss of mass from the envelope is the generation of acoustic waves by two dense cores orbiting each other inside the envelope.

If the two cores are not merged prior to the loss of the envelope, then the final product will be a low-mass binary with very short orbital period. In some cases one or both components of such a system could be in an advanced phase of evolution (white dwarf, neutron star). The existence of the objects discussed in section 2.2.(C) indicates that the evolutionary scenario as described above is indeed realized by stars. In at least one case (UU Sge) we even observe the remnant of the ejected common envelope, in the form of a planetary nebula around the binary system.

3. STELLAR WINDS IN BINARIES

The evolution of single stars with mass loss due to stellar wind was discussed in detail in previous talks by de Loore and Chiosi. Their analysis covered wide ranges of stellar masses and of stellar wind strengths and was based on extensive numerical calculations. Similar calculations for stars which are members of binary systems are rather scarce. I know about only two papers which might be relevant: Ziółkowski (1977) and Vanbeveren et al. (1978). The first of these papers is essentially dealing with problems of X-ray binaries and only the latter one is fully devoted to evolution of binaries with stellar winds. Fortunately, the evolution of single stars with mass loss due to stellar wind is very similar to the evolution of the same star in a close binary, assuming that the strength of the stellar wind is the same. Usually this is not the case, and we shall discuss this problem later; but if we know (or assume) the proper rate for binaries, then we can use calculations for single stars to describe quite adequately the evolution of the components of binary systems. For this reason I shall not discuss the evolution of the components (for this purpose, see papers by de Loore and Chiosi after selecting the proper rate of mass loss) but I shall rather comment on some problems that are specific for stellar winds in binaries. Among these problems are: (1) the effects of stellar wind on orbital parameters, (2) the difference in stellar wind strength between single and binary stars and (3) possible anisotropy of stellar winds in binaries.

3.1. The effects of stellar wind on the orbital parameters

As far as the changes of the orbital parameters are concerned, the mass loss due to stellar wind can be well approximated by the Jeans' mode of mass loss. Jeans' mode assumes that the specific (per mass unit) angular momentum of the matter lost from the system is equal to the specific angular momentum of the mass-losing component. Since the stellar wind is roughly spherically symmetric and has high velocity, this assumption is well satisfied. It is well known that for the Jeans' mode of mass loss, the orbital period P and the separation of the components A are changing with the total mass of the system according to the relations:

$$d \log P = - 2 \, d \log M \tag{5}$$

and

$$d \log A = - d \log M \tag{6}$$

This means that both the orbital period and the separation of the components are increasing due to mass loss via stellar wind. It means also that the radius of the critical Roche lobe around the mass-losing component:

$$R_1^{cr} = A(0.38 + 0.2 \log q) \tag{7}$$

will increase as well although slightly slower than A (because q is decreasing). In the case of the binary system discussed by Ziółkowski (1977) the strong stellar wind decreased the mass of the primary from 35 $M_\odot$ to 13.5 $M_\odot$ by the end of the core hydrogen burning. During that time the orbital period increased by a factor of ~ 6, the separation of the components increased by a factor ~ 2.5, and the radius of the Roche lobe around the primary increased by a factor ~ 2. As we see, the expansion of the Roche lobe may be quite substantial. Let us recall, in addition, that strong stellar wind tends to decrease the stellar radius starting from a certain point of the main sequence evolution. These two effects together mean that in some systems the presence of the stellar wind may prevent the Roche lobe overflow which would happen otherwise. This fact has great importance for the lifetimes of massive X-ray binaries (Ziółkowski, 1977). An additional mechanism that might help to stabilize massive components of X-ray binaries against Roche lobe overflow is the "evaporative" stellar wind proposed by Basko et al. (1977). They suggested that strong X-ray heating by the compact companion will stimulate the stellar wind and increase the rate of the mass loss enough to prevent the overflow of the Roche lobe.

3.2. Are stellar winds in binaries stronger than for single stars?

Asking such a question we have in mind stars that have the same location in the H-R diagram and are either single or members of binaries. The answer is definitely affirmative and is based on the following arguments.

A) Direct observational evidence. Hutchings (1976) found in his survey of mass loss due to stellar wind that mass loss is systematically higher for stars that are proven or suspected members of binaries. To give a clear example, the mass loss rate from Krzemiński's star was recently estimated (Hutchings et al., 1978) to be of the order of $\sim 5 \times 10^{-6}$ $M_\odot$/year, while the typical rate for single stars at the same location in the H-R diagram is $\sim 10^{-7}$ $M_\odot$/year (Hutchings, 1976).

B) Analysis of the O-B components of massive X-ray binaries. Masses and luminosities of some of these stars are known well enough to permit quantitative analysis. In every well investigated case, the O-B component appears to be significantly overluminous for its mass or significantly undermassive for its luminosity (Ziółkowski, 1977). We are reasonably sure that this mass deficit could not result from the Roche lobe overflow, because in a massive X-ray binary the mass ratio is usually so high ($q \sim 15$) that any outflow from the L_1 (or L_2) point will cause such dramatic shrinking of the orbit that a common envelope configuration will form almost immediately. It follows then that the mass deficit in the O-B components of X-ray binaries is due to mass loss via stellar wind during their past evolution. From the known evolutionary time-scales, we can estimate the stellar wind strengths necessary to produce the observed mass deficits. For two of these stars (Krzemiński's star and Sk 160) evolutionary models were constructed by Ziółkowski (1976c, 1978). He found that the initial masses of these stars had to be respectively ~ 36 $M_\odot$ and ~ 31 $M_\odot$ (present masses are about 18 $M_\odot$ for both stars) and that both stars are still in the main sequence (core hydrogen burning) phase of evolution. The average rate of mass loss during the past evolution had to be for both stars of the order of 3×10^{-6} $M_\odot$/year. This value is consistent with the estimate of the present rate of mass loss from Krzemiński's star ($\sim 5 \times 10^{-6}$ $M_\odot$/year). Now, let us compare this picture with the mass loss calculated for single stars with similar initial masses. Using observational rates determined by Hutchings (1976), Czerny (1978) found that stars with initial masses < 40 $M_\odot$ will lose less than ~ 0.3 $M_\odot$ during their entire main sequence evolution. Using another set of empirical data, given by Barlow and Cohen (1977), Chiosi et al. (1978) found that a star with initial mass of 36 $M_\odot$ will lose only 3 to 5 $M_\odot$ during its main sequence evolution. This comparison suggests that stellar winds in binaries might be stronger by an order of magnitude than those in similar single stars. A similar conclusion was reached by de Loore's group (de Loore et al. 1977, Vanbeveren et al. 1978). They determined the value of a parameter N, which is proportional to the rate of mass loss, for different observed O-B stars. For O-B components of X-ray binaries they found the value $N \sim 400 \div 500$. At the same time, inspection of Fig. 1 of de Loore et al. (1977) implies that for single stars in the relevant part of the H-R diagram the value of N is of the order of $30 \div 50$.

C) Analysis of undermassive O-type components of other close binaries. Altogether we know about 40 O-type binaries. Only few of them have mass determinations and in some of these (UW CMa, V 729 Cyg, LY Aur and perhaps also the others) one of the conponents seems to be undermassive (Conti 1978, 1979). In all these cases we observe evidence of strong stellar winds at present, but we cannot also exclude some large scale mass exchange in the past. For this reason, the analysis of these systems is not very conclusive.

D) Theoretical arguments. A semi-detached component of binary system has lower average surface gravity than the similar single star. This lower gravity (especially near the L_1 point) might increase the efficiency of whatever mechanism is responsible for the stellar wind. No quantitative analysis of this problem has been done. In X-ray binaries, the additional mechanism stimulating the stellar wind might be due to X-ray heating (the "evaporative" stellar winds of Basko et al., 1977).

3.3. Are stellar winds in binaries anisotropic?

The information concerning this problem is very scarce so far. We know one system (HD 47129) that is observed to change its rate of mass loss over the range $2 \div 8 \times 10^{-6}$ $M_\odot$/year as a function of the orbital phase (Hutchings and Cowley, 1976). From the theoretical side, one could argue that the area on the surface of the star near the L_1 point has much lower gravity than the rest of the surface and this could produce an asymmetry in the stellar wind. Also the explanation of the large X-ray luminosity of SMC X-1 might be easier if Sk 160 (its optical companion) had an anisotropic stellar wind (Ziółkowski, 1978), but this is only one of the possible solutions.

On the other hand, it might appear that also some single stars have anisotropic stellar winds. Pismis (1979) investigated three emission nebulae excited by central stars of Of or WN-type with strong stellar winds. She found that the mass loss responsible for formation of the nebulae was anisotropic and suggested that also the present stellar winds from the central stars might be anisotropic.

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DISCUSSION FOLLOWING ZIOLKOWSKI

Cowley: Although the observations of the X-ray binaries show they have undergone a very large percentage of mass loss (more than 50%), in only one system (3U1700-37=HD 153919) do we now see evidence of an exceptionally strong stellar wind in the optical spectrum. This is not to say there is no wind, but that it is not nearly large enough at present to account for the earlier mass loss. For example SMC X-1 is the most luminous X-ray binary, but we see none of the characteristic signatures (as discussed by Hutchings) in the spectrum to infer a strong stellar wind. The present rate of mass loss is typical for a single star of the same T_{eff} and L.

Conti: Mass loss deduced from the optical spectrum probably only detects the highest rates. We need the UV line analysis to get better numbers for rates. 9 Sgr, an O4 main-sequence star, might have a substantial rate.

Cowley: I would suppose your mass loss rates for the companions of X-ray sources are lower limits, because some material may have been transfered from the X-ray progenitor to the present OB companion. This affects how much mass needs to have been lost.

Conti: I should probably modify Ann Cowley's statement HD 153919 (=3U1700-37) might have an anomalous carbon abundance. The λ4650 CIII emission, and λ5701, 5812 CIV lines are stronger than in any other Of star (save one). Unfortunately there is not yet a detailed analysis as the relevant line atomic physics is not available, nor are Of envelopes wholly satisfactory. There exists only a possibility that carbon is enhanced.

Morton: I do not think we can be sure that the absence of strong visual mass loss features in a star requires that the mass loss rate be less than from a star having such features. For example 9 Sgr (O4V) has only relatively mild visible emission features and λ4686 is in absorption, whereas the UV spectrum shows a highly saturated NV profile and one of the largest terminal velocities. Clearly, some direct estimates of $\dot{M}$ are needed from the UV spectra.

van den Heuvel: I think that for SMC X-1 and Cen X-3 you do not need a strong wind, as the high mass transfer rate can also be explained by Roche lobe overflow, as can in fact be inferred partly from your own work. You have shown that due to the mass loss the star can look like a giant while it is still burning hydrogen. It has been shown by several authors (McCray et al.1977, preprint; Savonije 1978, Astron.Astrophys. and: in press) that such a star can remain near its Roche lobe and transfer mass at a moderate rate for as much as 10^5 years, and in this way power a strong X-ray source. In fact the agreement between this prediction and the observations is very good in the cases of Cen X-3 and SMC X-1.

Wilson: In SV Cen it appears that the envelope will reach the outer contact surface when the masses are approximately equal. This is a coincidence which might have some interesting consequences for the further evolution of the system. In particular it should affect the efficiency of ejection of mass from the outer Lagrangian point and thus the formation or non-formation of a non-synchronous common outer envelope. Have you looked into this point?

Ziolkowski: No, I have not.

Hutchings: V453 Sco (HD 163181) is very relevant to your discussions. It is a B0Ia+O8V system in which the B star at 13 $M_\odot$ is undermassive by a factor ~3. It shows mass transfer via Roche lobe and stellar wind characteristics. Also, at this level of mass loss we see CNO abundance anomalies. We do not see such anomalies in the X-ray systems which have lost only ~ half of their mass.

Dearborn: It should be noted that the very low mass of Krzemenski's star, and most X-ray binaries require ^{14}N enhancements by a factor of 3 to 5. In some extreme cases where the star is reduced to 1/3 of its original mass, a region is reached where ^{16}O is partially converted to ^{14}N, and ^{14}N is enhanced by 10 times. Also in mass transfer systems, if mass is currently deposited on a star by one showing chemical peculiarities, both should show the same peculiarity.

Cowley: As nearly as we can tell from spectroscopic data which we have for all of the X-ray supergiant binaries, the only one which shows peculiar abundances is SMC X-1. However, although in that system the heavy elements are greatly weakened, this seems to be a general property of the Small Cloud as a whole and probably has nothing to do with the fact the system is an X-ray binary in which there has been much mass lost.

Vanbeveren: One has to be very careful with the argument about the X-ray luminosity of SMC X-1. The theoretical X-ray luminosity is very critically dependent on the value of the wind velocity in the vicinity of the neutron star.

Lamb: What is the maximum mass that can be lost from the binaries you have been discussing that will allow them to remain gravitationally bound?

Ziolkowski: I believe that if we have gradual,not instantaneous, mass loss, we can lose any amount of matter without disrupting the binary.

Plavec: Disruption of a binary system can occur in the case of a supernova explosion, where the sudden mass loss occurs on a time scale short even compared to the orbital period of the system. Dr. Ziolkowski has been talking here about an uncomparably much slower mass loss.

de Loore: Just a remark concerning your discussion about the calculation of evolutionary tracks with stellar wind: according to you one should stick as much as possible to the observations rather than using an equation for the mass loss. Nevertheless, the final products of our mass loss evolution with the Barlow and Cohen equation (for N=100) are comparable with those that were carried out with $\dot{M}$ values related immediately to the observations. So I do not see why one should not use a mass loss equation.

Sreenivasan: A few comments regarding the specific mass loss rate used for a given calculation are perhaps in order in response to what you said. I agree that it is desirable to use specific observed empirical rates when they are available. Unfortunately they are not always available. In addition, it is not appropriate to use a property of the flow to predict characteristics of that flow. It is better to employ reasonable physical arguments to estimate any parameters involved such as: ε or (α,k) or N in $\dot{M}=\frac{\varepsilon L}{V_{escape}\cdot V_{sound}}$; or in Castor et al.'s rate for mass loss, which is a function of L, Γ, k and α; or in $\dot{M}=\frac{NL}{c^2}$ used by de Loore et al. and then compare the results with observations. "Appropriate" values of these parameters are often employed by model makers to claim that mass loss rates so used, agree with observations! Perhaps, we should not be so afraid of the observers. It's just probable that observed estimates are subject to uncertainties in or limitations of the measurements. They are also often incomplete.