MASS LOSS FROM INTERACTING CLOSE BINARY SYSTEMS

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ABSTRACT

Mass outflow from interacting close binary systems, accompanied by loss of orbital angular momentum, appears to be a very important process affecting the evolution of binary stars. Together with accretion on the mass-gaining component, it is the least understood aspect of the general complex process we call "evolution with mass transfer and/or mass loss", or, more briefly, "interaction". It is therefore very imperative to assemble and examine all available facts or hints about mass loss.

Three well-defined classes of evolved binary systems show evidence of present and/or past mass loss. The cataclysmic variables probably would not exist at all without it. Wolf-Rayet stars and Algols can in principle be modeled in a conservative scenario, but comparison with observed systems shows that actually a large-scale mass outflow from the system must have accompanied the mass transfer between the components, and that probably more material escaped than was captured. In the Wolf-Rayet stars, mass loss appears to be associated with exceptionally strong stellar wind. In the Algols, we suspect that mass loss was heavy particularly in the rapid phase of mass transfer, but that phase is still poorly understood. The proposed transformation of supergiant binary systems into the very short-period cataclysmic variables must have been a complex process, whose outlines can be only sketched, and for which observational evidence is very desirable.

Observationally, considerable new evidence has recently been obtained from the far ultraviolet spectra that a certain subclass of the Algols (called here the Serpentids) are undergoing fairly rapid evolution. The remarkable mass outflow observed in them is probably connected with a strong wind powered by accretion. Typical Algols are more quiescent, yet even in them mass loss apparently continues. Circumbinary clouds or flat disks probably surround many strongly interacting binaries, but their origin is not yet clear. Attention is also called to binary systems with hot white dwarf or subdwarf components, such as the symbiotic objects, the BQ stars, and the like, since in them both components may be prone to an enhanced stellar wind.

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1. "NO MASS TRANSFER, PLEASE!"

When my talk was discussed by the Scientific Organizing Committee, I was repeatedly and urgently asked to talk about mass loss from binary systems, not about mass transfer within the systems. Apparently, the astronomical community (or at least the Organizing Committee) are fed up with hearing about cases A, B, C again. This gives me an excuse to use these terms without defining them. Those in need of an explanation are best advised to read the recent excellent review by Webbink (1979). Nevertheless, I must protest here the discrimination against the secondary components in the semi-detached Algol systems. For this is a Colloquium on Mass Loss from Stars, and those stars are losing mass and therefore should be mentioned here. It is not their fault that the material they lose is captured by the other component.

As a compromise, I will devote them one brief paragraph. Some of them must be quite interesting stars. They can have relatively large radii and luminosities associated with quite small masses. I will quote a few examples from a recent compilation by Popper (1980). The K0 subgiant in AS Eridani has a well-established mass of only 0.2 solar masses, but it still radiates 2.5 solar luminosities. The period of AS Eri is only 2.7 days. In wider systems, the subgiants are larger, since they always fill the critical Roche lobe. The less well determined system of S Cancri probably has a subgiant of about the same mass as in AS Eri, but its radius is 5 $R_\odot$ and its luminosity more than 10 $L_\odot$. Very similar to it is the secondary in RY Gem, but its mass is about 0.6 $M_\odot$, i.e. less extremely small. All these components must be very near the end of the mass transfer process. How the Roche lobe overflow proceeds is probably well understood nowadays, thanks to the papers by Lubow and Shu (1975) and Shu (1976). They also show how the transferred material arrives to the accreting star, which I will simply call the <u>gainer</u>. If the gainer's radius is relatively large with respect to the separation of the components, the stream will impact directly; if the gainer is relatively small, an accretion disk will be formed. Apart from the inevitable losses of part of the mass and orbital angular momentum resulting from an outward transport through the disk as viscosity enables the bulk of the material to spiral inwards to the gainer, the Lubow and Shu picture on the whole supported theoretical calculations based on conservation of mass and angular momentum in the system. After certain observational experience, I think that the conservative mode will be more appropriately applied to the late stages of mass transfer, when the mass transfer rate has already declined perceptibly. For the rapid stages, the picture appears to be different, because of the reaction of the gainer to the mass influx. Unfortunately, this reaction is very poorly understood, and we are still only guessing how much mass is lost from the system. More powerful arguments in favor of a large-scale mass loss from binary systems at certain evolutionary phases came from other considerations.

2. MASS LOSS FROM BINARY SYSTEMS: WHY IS IT POSTULATED?

The most convincing argument is probably the existence of the cataclysmic variables. Novae and dwarf novae are interacting binary systems, usually (but not always) of a very small size, where an accreting white dwarf occasionally reacts violently to a fairly gentle influx of hydrogen-rich material from its mate. The loser is typically a red dwarf of about the same mass as the white dwarf, and the whole system could in some cases be completely located inside the Sun. Orbital periods are usually a few hours. When not in a nova or nova-like outburst, these systems are quite inconspicous. Even much more inconspicuous are similar dwarf pairs which do not interact since the red dwarf does not fill the critical Roche lobe, as in V 471 Tauri. They are hard to discover, but must be quite abundant in the vicinity of the Sun.

White dwarfs are very old stars: so what was the earlier history of these dwarf pairs? We know of only one other type of binary systems that have similar properties (small masses, small orbital angular momenta, large spatial density). These are the contact systems of the W UMa type. This is why Kraft originally suggested a genetic relation. Today we believe that a very different story is more correct: namely, that the dwarf pairs are descendants of giant binaries with periods of several hundred days. The white dwarfs in cataclysmic binaries are fairly massive: usually above 0.7 $M_\odot$, up to the Chandrasekhar limit. Such a massive white dwarf can hardly be grown elsewhere than inside a red supergiant, on the second giant branch, when the supergiant's radius can easily be about 500 $R_\odot$ or more. But such a huge star needs an even bigger binary system, otherwise its expansion would be arrested by mass transfer via Roche lobe overflow long before any significant ascent on the giant branches. If the system initially was very large, we must postulate a tremendous reduction of its orbital angular momentum to achieve the transformation into a dwarf pair; and, naturally, mass must be flowing out to carry away the momentum. This is, in principle, the evolutionary scheme for cataclysmic variables as advanced by Ritter (1976), Paczynski (1976), Webbink (1976) and others, and almost generally accepted nowadays. I know of only one serious dissenting voice. Shu, Lubow, and Anderson (1979) express grave doubts that such a long-period binary could be "whittled down so skillfully as to always leave a star the size of a main-sequence star which just fills its Roche lobe." (Let me remark that this is not always the result: probably many more non-interacting pairs are formed, such as V 471 Tau). Shu et al. still prefer Kraft's idea of a genetic relation between the W UMa stars and the cataclysmic variables. Independently of this argument, their paper is important for the topic I am discussing, since theirs is the only existing treatment of the outflow of matter from a contact system through the L_2 point.

In the cataclysmic variables, we have a class of binary stars that (if we accept the majority view) apparently would not exist at all without a previous large-scale mass and angular momentum loss from the system (in fact, Kraft's concept implies some losses, too). In contrast, the following two important classes of binaries, also products of mass transfer, can in principle be modelled in the conservative mode,

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but when one compares either individual systems or statistical properties of the whole group with theoretical predictions, one concludes that theoretical models and observed systems do not match. Agreement is obtained only if we postulate non-conservative evolution, with substantial mass and angular momentum outflow from the systems.

The two types of objects are the Wolf-Rayet stars and the Algols. Observations tell us that good many Wolf-Rayet stars are binaries, with an OB companion. Already at the beginning of the fruitful period of mass-transfer studies, Paczynski (1967) suggested that the WR stars are products of mass transfer of case B in massive binary systems. Detailed calculations were performed by de Loore and de Grève (1975) and de Loore et al. (1975), using the conservative scheme. One can obtain a WR remnant of the loser in this way, but rather implausible restrictions must be placed on the initial mass ratios, and it is not possible to reproduce the short periods (of a few days) observed in many WR systems. New calculations, combining mass transfer via the Roche lobe overflow with a strong mass and angular momentum loss through a stellar wind, correct these shortcomings and match the observed systems much better (Vanbeveren and Packet, 1979; Vanbeveren et al., 1979). The fraction of mass lost from the systems seems to vary from one star to another, but in general more material leaves the system than is accreted; also the angular momentum loss is heavy.

In the case of the semi-detached binaries of the Algol type, the conservative models appeared to describe the observed systems beautifully, but attempts to fit observations quantitatively failed (Plavec, 1973). In some cases one could argue that, by the very nature of the objects, their parameters established observationally were as inaccurate as the models. Yet even the first well-determined system AS Eri (Popper, 1973) could hardly be interpreted without angular momentum loss (Refsdal, Roth, and Weigert, 1974), and other cases are worse. Moreover, Kopal (1971) pointed out that some low-mass Algols could not have reached their present state in the lifetime of the Galaxy by mass transfer only, and that mass loss must have occurred. As more observational data and computed models accumulated, broader statistical discussions became possible, such as the recent one by De Grève and Vanbeveren (1980). Their observational sample consists of 100 unevolved binaries and 40 evolved ones. Using several different evolutionary scenarios, they modelled the evolution of the unevolved sample, and then compared the statistical distributions of masses, mass ratios, and periods with the actually observed evolved systems. The conservative mode appears to be definitely ruled out. They find statistical evidence for a substantial mass loss from the system: perhaps 80% of all the mass leaving the loser actually escapes from the system, and only 20% is captured by the gainer. As I already remarked at the Toronto Symposium (Plavec, 1980a), the game played by interacting binaries seems to be of the Las Vegas kind: many losers lose a lot, but on the average, gainers gain only a little. Accompanying mass outflow from the system is a considerable loss of angular momentum of the orbital motion. In the conservative scheme, the increasing disparity of masses towards the end of the mass exchange process leads to a substantial lengthening of the orbital period. With considerable angular momentum loss, the final periods remain of the same order of magnitude as the initial ones.

We see that the arguments in favor of mass loss from interacting binary systems presented so far are convincing but leave the process very indeterminate. In fact, one could argue that, naturally, with a sufficient number of initial arbitrary parameters one can work miracles in comparing models with observations. Thus the above statistical results should only make us more persistently inquisitive about the physical processes leading to mass loss.

3. MASS LOSS: WHEN AND HOW

3.1 Case A of Mass Transfer

Two main-sequence stars in a short-period orbit have little room for expansion. When the more massive one fills its critical lobe and tidal overflow starts, a very modest swelling of the gainer -- and for large initial disparity in masses simply the shrinkage of the orbit -- will make that star fill its ciritical lobe, too, and we have a contact binary. In addition to this theoretical prediction, we do observe a large number of systems where the two stars are in contact already near the zero-age main sequence: the W UMa systems. One must be cautious, however, and not throw into the same bag all contact systems. One important parameter is the degree of physical contact, measured in terms of the distance of the actual common envelope from the outermost possible common closed envelope (the one passing through the L_2 point). If the physical common envelope has expanded so far that the system nearly fills all the available closed volume, we speak of a deep contact.

Let us assume that such a deep contact does indeed develop, for example in a W UMa system the more massive component expands as it exhausts hydrogen in its core. This is the case envisaged and studied by Shu, Lubow, and Anderson (1979). Mass outflow can then occur in the vicinity of L_2 , which is the neutral point located on the axis of the system behind the less massive component (provided the binary can be approximated by a Roche model). Shu, Lubow, and Anderson studied the case when L_2 has a real dynamical meaning, that is when the outer envelope is corotating with the whole system, and the Roche model is therefore applicable. There are better chances for this assumption to be true in a slowly evolving, low-mass W UMa system. Near L_2 gravity is weak, being balanced by the centrifugal force, and gas pressure can overcome it. An outflowing stream forms. Very soon the stream will make the sonic transition to a supersonically moving mass loss stream. It begins to lag behind the rapidly spinning binary system, and a gravitational torque acts upon each element of the stream. If this torque is strong enough, it will fling the fluid elements to infinity, and we have a real mass loss, accompanied by a severe angular momentum loss, since the material at L_2, being very far from the center of gravity of the system, carries with it a substantial amount of specific orbital angular momentum. Shu and collaborators show that this must happen as long as the mass ratio of the component stars lies between 0.064

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and 0.78. For nearly equally massive components, gravity in the vicinity of L_2 remains too strong; for extremely small mass ratios, the system acts nearly as a single star, and the torque is weak. In these two cases, the stream develops but cannot escape. Rather, it strikes itself, closes, and forms an outer ring encircling the whole system. Its future fate depends to a large degree on its viscosity. If viscosity is large, the ring will spread, some material will fall back to the stars, while a fraction of it escapes into infinity with an excess angular momentum. Because of this analogy with the inner accretion disks, Webbink (1976) coined for it the logical but awful term excretion disk. If viscosity is small, Shu and collaborators speculate that the mass of the ring can grow so much that it may eventually fragment self-gravitationally and produce a number of planet-like bodies encircling the binary.

An alternative case of deep contact was studied by Meyer and Meyer-Hofmeister (1980). They assume that the matter in the envelope is not corotating, so that the Roche model with the L_2 point is not applicable. This model is probably more appropriate for cases when the deep contact develops quickly, as in the rapid phase of case A mass transfer. The common envelope is now less restricted in expansion, and the tidal interaction between it and the inner binary core generates so much frictional heat that the expansion is driven all the way to the formation of a huge giant star with a double core. By the same process, the inner binary system shrinks more and more. When a rotationally symmetric configuration is eventually established in the interior, frictional heat will no longer be available, and the supergiant envelope will collapse. However, since it contains most of the angular momentum, an accretion disk will form, and a fraction of the mass (though presumably small) will escape from the system even during this shrinkage. When the disk collapses, a "rejuvenated" main-sequence star will be seen, with a mass not much smaller than the combined mass of the original two components. An observer too absorbed in observing galactic clusters to read the paper by Meyer and Meyer-Hoffmeister will be puzzled by noticing a blue straggler.

If we go for a while back to the W UMa systems, we notice that one of the hard-fought problems is just whether the deep contact will actually develop or not. Many investigators (e.g., Webbink (1976) and references herein) argue that zero-age contact systems suffer cyclic, thermally unstable mass transfer episodes, and that this relaxation on a dynamical time scale prevents the growth of deep contact. The subsequent evolutionary scenario was examined by Webbink (1976). In the course of many cycles, the more massive star will inexorably grow more massive. As it leaves the main sequence, thermal instability will aggravate to such a degree that the less massive star will be completely swallowed. Webbink predicts that the remnant will look like a rapidly rotating single star above the main sequence. For our discussion today it is essential that he predicts shedding of about three quarters of the initial orbital angular momentum. Associated with this dissipation of angular momentum is mass loss, probably via an external, "excretion" disk. Webbink maintains that the final outcome of the evolution of a W UMa system is a single red giant evolving ultimately into a single white dwarf, just as in the case of an ordinary single star of small mass.

3.2 Tidal Outflow from Convective Envelopes: Cases Bc and Cc

Deep convective envelopes of giant and supergiant stars, both on the first giant branch or on the asymptotic branch of their evolutionary track through the Hertzsprung-Russell diagram, are strongly unstable against mass loss via tidal overflow. When such a star fills its critical volume, its critical surface will shrink because of decreasing mass ratio. However, the convective envelope will continue to expand, thereby increasing the instability and accelerating the mass outflow (Paczynski, 1965; Paczynski, Ziolkowski, and Zytkow, 1969; Lauterborn and Weigert, 1972). As a consequence, the rate of mass outflow builds up extremely quickly. In our calculations (Plavec, Ulrich, and Polidan, 1973), we encountered rates as high as 0.1 $M_\odot$ per year. Now for a gainer with radius R (in solar radii), the Eddington luminosity is reached when the transfer rate is $\dot{M} = 10^{-3}$ R ($M_\odot$/year), so for practically any gainer, peak mass transfer from a convective envelope implies supercritical accretion. At the onset of mass transfer, a disk will usually be formed, but with the advent of supercritical accretion, the radiation pressure will build a powerful stellar wind as a shield against excessive accretion. Here is another mode of an extensive mass and angular momentum loss from the system. The supercritical phase is short, on the order of years or decades, but the system will be thoroughly devastated, and eventually will shrink considerably. No matter how valid may be the objections against the formation of the cataclysmic variables from very long-period systems, substantial shrinkage of the giant systems is hardly questionable. Further evolution was studied by Webbink (1978). Expansion of the gainer makes its potential well shallower, eventually reduces accretion to subcritical, and soon afterwards leads to the formation of a common envelope. As the gainer penetrates the envelope of the giant, another phase of mass outflow from the system ensues, this time due to aerodynamic drag. The giant sheds mass and angular momentum from its enormous envelope, while inside the two stellar cores keep approaching each other. Most of the envelope will be dissipated on a time scale of 10^3 years. We have the same phase as already described in the calculations by Meyer and Meyer-Hoffmeister (Sect. 3.1). The final stabilization of the close dwarf pair seems to require yet another phase of supercritical accretion, i. e. a powerful stellar wind again.

3.3 Tidal Outflow from Radiative Envelopes: Case Br, Cr

Suppose now that the more massive star fills its critical lobe before it ascends the giant branch, i. e. at a stage when its envelope is wholly or predominantly radiative. Then the maximum rate of tidal mass outflow from it is dictated by its thermal time scale and is (Paczynski, 1971):

$$\dot{M} = 3.2 \times 10^{-8}\ R\ L\ /\ M \qquad (M_\odot/\text{year})$$

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where all the quantities pertain to the loser, and must be evaluated for its state at the beginning of mass transfer. This formula leads to moderately high mass transfer rates, on the order of 10^{-4} $M_{\odot}$/year, which should be subcritical for main-sequence gainers. For short-period systems, like U Cephei, accretion should occur directly on the gainer. For longer periods, above 6 days or so, accretion should occur via an accretion disk. Viscosity in such a disk enables the material ultimately to be actually accreted, but at the price of shedding a fraction of it from the outskirts of the disk, as angular momentum must be transported outward. The problem has been studied most recently by Papaloizou and Pringle (1977). In the absence of tidal torques, 30 to 50 % of the disk material has to be lost from the Roche lobe in order to allow the remaining matter to accrete. The effect of a tidal torque is to reduce this fraction, and Papaloizou and Pringle estimate that in the cataclysmic variables, only a few per cent of the material is actually dissipated. Thus a modest mass loss from the system is indicated in case of disk accretion, but there seems to be some latitude for variations from system to system.

So far nothing indicates that in Algols, which are typically fairly short-period systems, any substantial mass loss should occur. However, we have so far ignored the reaction of the gainer to accretion. Unless the two stars are nearly of the same mass, the initially less massive gainer will have a considerably longer thermal time scale, which sets an upper limit to the amount of mass per unit time the star will be able to accomodate. This critical value is given by an equation analogous to the one used above, but this time we plug in the appropriate values for the gainer and get, of course, lower values: The gainer typically cannot accomodate the inflowing material and remain in thermal equilibrium. The problem was first studied in any greater detail by Flannery and Ulrich (1977), although Benson called attention to it already in 1970. What happens is that material of higher than equilibrium entropy is buried adiabatically beneath the surface, liberating large amounts of thermal energy. The gainer swells exponentially until it fills its own critical Roche lobe. We then have another case of a contact binary, and if we again assume corotation in the common envelope, mass outflow through L_2 should ensue, with further shrinkage of the system, aggravating the problem and leading to an extremely close binary, or complete coalescence. This result is acutely embarrassing, since it is hard to imagine how any interacting binary of this type can ever survive and transform into an Algol system -- yet we observe good many Algols! Nature obviously solves or evades this dilemma and we must find out how. From statistical considerations mentioned in Sect. 2 we know that some mass and angular momentum losses do occur in most or all systems, therefore also a phase of shallow contact appears to be acceptable. Large scale mass outflow and the accompanying very drastic shrinkage will probably not occur if we avoid massive outflow from L_2. Indeed, the corotation implied in Flannery and Ulrich's calculations (and properly labeled by them as an uncertain assumption) is unlikely to materialize in rapidly evolving systems. But it is also possible that the rapid swelling of the gainer does not occur. We know that the spherically symmetrical accretion assumed in the calculations is unlikely to occur. Either a fairly narrow stream impinges on the gainer in the orbital plane, or accretion occurs in an equatorial belt from a disk. The problem of redistribution of matter and energy beneath the surface of the gainer is also obscure, but, in the first place, as Ulrich recognized recently (1980), "perhaps the matter can cool radiatively to the stellar surface temperature before it expands, and thus achieve a lower state of entropy. The Benson expansion might then not occur at all because of the heat sink this overcompressed matter represents." Let me remark here that the IUE observations of strongly interacting Algol-like binaries made by me and R. H. Koch (Section 4.2) may indicate a way in which the star escapes the swelling and growing into contact. Another, or related, escape route was suggested by Wilson and Twigg (1980): Accretion tends to accelerate the gainer's rotation. When the maximum velocity of rotation is reached, the star cannot accomodate any more material with high angular momentum. I think this idea is worth exploring, and possibly the phenomenon of strong stellar wind from the gainer we observed with IUE is related to the Wilson-Twigg mechanism. In the discussion following the paper by Wilson and Twigg, Pringle objected that an accretion disk is very efficient in disposing of with the excess of angular momentum. However, a fully developed disk may not always be available to shield the star, or the shielding is not perfect. If it were, why would the gainers in U Cep, AW Peg, RZ Sct, etc. rotate so much faster than the synchronous speed prescribes?

3.4 The Wolf-Rayet Binaries: Case B for Massive Stars

Tidal mass outflow of type B from radiative envelopes of massive stars transforms these into Wolf-Rayet stars. This type of evolution is probably typical for stars more massive than about 15 $M_\odot$. A strong stellar wind is present at all phases. This is a phenomenon not specific to binary stars, and it would not be necessary to discuss it here were it not for the fact that model calculations can match the observed systems only if we assume that the wind is anomalously strong. It has become customary to parameterize the mass outflow rate due to stellar wind by the formula $\dot{M} = - N L / c^2$, thereby indicating that the decisive stellar parameter is the luminosity, but leaving the proportionality factor N open to *ad hoc* adjustments. According to De Loore (1980), for luminous stars, if single, N is about 50 to 150, while for the OB components of massive binaries, one has to use values between 300 to 500, i.e. about four times as high. It is naturally possible to argue qualitatively that components of binary stars may be more prone to a strong stellar wind-type outflow, since over certain surface regions the effective gravity is considerably weakened if the star is anywhere near the critical Roche lobe. Moreover, hot companions, and in particular strong X-ray emitters, provide heating (Basko *et al.*, 1977). In the future, these crude arguments will have to be replaced by a solid analysis, otherwise the binary people will be accused of arbitrarily juggling the parameters.

When an effort is made to represent all the properties of the WR stars including the chemical composition of their atmospheres, one

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has to assume stellar wind mass loss rates about ten times higher than for normal stars, i.e. N can be as high as 3000 for the phases when, after the end of the Roche lobe overflow, the WR star has already formed (Vanbeveren and Packet, 1979). This is in agreement with the observations by Conti (1979) and others. We deal here with a phenomenon specific to WR stars and therefore properly belonging to another session of this Colloquium.

3.5 Second Phase of Mass Transfer

The first phase of mass transfer ends when the loser either ignites helium, or, if its mass is too low for it, its hydrogen-rich envelope is almost completely lost and the remant collapses on the white dwarf inside. But, as a matter of cosmic justice, the original gainer is in due time bound to exhaust its core hydrogen, expand, and eventually reach its critical surface, to start a new phase of mass transfer. We can again distinguish cases A, B, C as before, since they refer to the evolutionary stage of the loser in question. Since as a rule the mass transfer in the first phase tends to increase the periods and orbital separations (although not so much as it would in the conservative mode), cases appropriate for longer periods will occur even more frequently in the second mass transfer phase. In particular, many of the losers will now be giants with deep convective envelopes, prone to catastrophic mass loss.

However, the reaction of the gainer will now be different, since it is either a degenerate or collapsed star, or, possibly, a helium-burning subdwarf. This latter possibility may be rather academic. It is true that stars with initial masses above about 2.7 $M_\odot$ ignite helium in their cores, contract and therefore terminate their mass loss in case B, and then contract rapidly to come to equilibrium near the helium main sequence. However, their subsequent evolution is fast (Paczynski, 1971), and as a rule they are converted into something else before the other component reaches its Roche lobe. Only the helium stars within a narrow range of masses, about 1 - 2 $M_\odot$, expand again and temporarily become red giants again; therefore a second stage of mass transfer from the same star may occur (Plavec, 1973), probably associated with a powerful stellar wind and possibly catastrophic mass transfer if the Roche lobe is actually filled.

As a matter of fact, the remnants of the first mass transfer are not yet pure helium stars; there is always a thin envelope which is reasonably hydrogen-rich ($N(H) \sim N(He)$) (De Grève et al., 1978; Vanbeveren and De Grève, 1979). The evolution of these remnants is particularly interesting if they are sufficiently massive to behave like WR stars. In the calculations by Vanbeveren and Packet (1979), great emphasis has again been put on a very strong stellar wind, which represents a powerful sink of mass and angular momentum.

Massive helium-burning remnants eventually explode as supernovas. The neutron stars (or possibly black holes) formed by the explosion then become X-ray emitters as soon as the other companion approaches its critical Roche lobe and develops either a strong stellar wind and/or tidal lobe overflow. Low-mass helium stars (below about

$0.9 M_\odot$) never ignite carbon; rather, they cool off and become carbon-oxygen white dwarfs.

If the system containing a white dwarf was formed by convective tidal overflow, which dissipated most of the system's orbital angular momentum, the residual system is a close dwarf pair, and the second mass transfer stage leads to a variety of eruptive phenomena generally termed a cataclysmic variable. Very low rates of mass transfer ($10^{-7} M_\odot$/year is probably an upper limit) suffice to stimulate the eruptive activity. Each eruption means a certain loss of mass from the system; in novae, the rate may be of the order of $10^{-5} M_\odot$ per outburst, in dwarf novae and related objects (symbiotic stars) perhaps $10^{-7} M_\odot$ per year.

Descendants of the first mass transfer in case B with outflow from radiative envelopes are generally fairly wide systems. Thus the tidal outflow from the non-degenerate components will not come until they reach the giant branch, and often not until they are on the asymptotic branch. Before that happens, they develop substantial stellar wind, say $10^{-6} M_\odot$/year, and the fraction of it captured by the former mass-loss remnant (10^{-2} to 10^{-4} of the total outflow) may be sufficient to stir new life in the remnant. This is probably the basic model for the symbiotic variables. Paczynski and Rudak (1980) distinguish two types of the symbiotics, depending sensitively on the rate of mass inflow onto the accreting dwarf star. If the dwarf star reacts violently, we have mass loss with each flare-up. In any case, the powerful stellar wind dissipates mass and angular momentum, and the symbiotics justly fall into the scope of this review.

4. OBSERVATIONAL EVIDENCE OF MASS LOSS FROM BINARY SYSTEMS

We will now review observational evidence and see if it can be reconciled with theoretical predictions. This is a difficult task, for two basic reasons. One is that the pronounced mass loss phases tend to be short. The supercritical accretion discussed in Section 3.2 lasts of the order of decades; the common envelope stages when a binary resembles a huge supergiant may last perhaps on the order of 10^3 years. These time intervals are extremely short compared to the quiet quasi-equilibrium phases of stellar evolution; thus the number of systems caught at phases of extensive mass loss is bound to be small. To be sure, these phases will be spectroscopically conspicuous. This fact probably has some bearing on the fact that despite the odds, we do observe quite a number of peculiar and puzzling objects which we are unable to understand or even classify and categorize. And, indeed, our chances of even recognizing the binary nature of such a "crazy stellar object" are quite small. The two stars are surrounded by a huge inhomogeneous cloud of gas, extending far out and obscuring the two components, as well as displaying spectral lines with quite confusing radial velocities. This is the second basic reason why our confrontation of theory and observations is bound to be difficult.

Equipped thus with the knowledge that we hardly can know anything for sure, let us set out to explore the observational evidence (?)

for mass loss (?) from interacting binary (?) objects.

5.1 β Lyrae

The famous binary system β Lyrae has several unusual properties, which I will enumerate here without going into the observational or theoretical evidence. The component stars have masses approximately 6 $M_\odot$ and 16 $M_\odot$. The smaller mass belongs to a reasonably normal B8 II giant, which probably fills its critical Roche lobe and transfers mass to its mate. Although the B8 star is the less massive component, all the stellar spectral absorption lines are formed in its photosphere. Extensive search for spectral lines of the more massive component, recently extended into the far ultraviolet, has not been succesful, although there have been occasional claims to the contrary. The shape of the light curves shows quite convincingly that the secondary star cannot be spherical. A very detailed treatment of the V and B light curves led Wilson (1974) to the conclusion that the more massive object has the shape of a very flattened disk. If it is an ellipsoid of rotation, the ratio of the axes is 3:1, and the equatorial radius extends as far out as the Roche geometry permits. Since this star is the gainer in the mass-transfer process, one can anticipate that it may be surrounded by an accretion disk. Such a disk, however, appears to be different from the usually modelled "alpha disks" currently in use for cataclysmic variables. If we scale up such an alpha-disk to match the β Lyrae system, we get a flat object geometrically quite thin near the central (accreting) star, and fanning out gradually as the z-component of the star's gravity decreases with distance. Even at the distance of the critical Roche lobe, i.e. about 30 $R_\odot$ from the center of the gainer, and for a very high rate of mass transfer ($\dot{M} = 5 \times 10^{-4}$ $M_\odot$/year), its semi-thickness should be only about 1.5 $R_\odot$. If the gainer itself is a slightly evolved star of about 12 - 16 $M_\odot$, its radius may indeed agree with Wilson's polar value of 10 $R_\odot$. We observe the system nearly edge-on (Wilson found, for the mass ratio of 3 now deemed best, $i = 89^\circ$). Therefore the polar regions of the star should be visible above and below the edge of the disk, and since they radiate much more intensely, their eclipse would be noticeable on the light curve, but it is not. Thus the Wilson model, however uncanonical, appears the best one we have. Perhaps it is more directly related to the models of differentially rotating stars developed by Bodenheimer and Ostriker, for which the first known counterpart was probably found in the Trapezium eclipsing binary BM Orionis (Popper and Plavec, 1976). Or the accretion rate is so high that the disk is "bloated" in the vicinity of the accreting star. This is my preferred explanation: that the accretion disks around non-degenerate stars are not simply the scaled-up alpha disks, but are geometrically much thicker, at least near the star.

The orbital period of the system is 12.93 days and increases very rapidly. Over the interval 1950-1966, it lengthened by 0.004 days (Herczeg, 1973). This is explained by rapid mass transfer. If the process conserved mass of the system and its orbital angular momentum, the rate of mass transfer would be about 10^{-5} $M_\odot$/year. But we know that the mass transfer is non-conservative.

Ziolkowski (1976) was able to reproduce, to a good degree, the present masses of the components, as well as the period and its change, by means of a conservative mass-transfer scenario of type B, starting with a period of 1/4 of its present length. In this picture, β Lyrae is actually an ordinary Algol system. The peculiar shape of the gainer is far from typical for Algols, however, but one can argue that the rate of mass transfer in β Lyrae is several orders of magnitude higher than in typical Algols. This is no doubt true, but we know now very definitely that the process is not conservative. A strong evidence for mass loss from the system comes from modern observations in the ultraviolet.

Observations with the Copernicus satellite, started in 1973, revealed a rich emission-line spectrum of rather highly ionized plasma (Hack et al., 1975, 1976, 1977). More recent IUE observations (Hack. Flora, and Santin, 1980; Plavec, 1980b; Plavec and Dobias, 1979; Kondo et al., 1980; Plavec, Dobias, and Weiland, 1981) extend the observed spectral range to a complete coverage longward of λ 100 nm. Emission lines are strong and numerous in the far UV, shortward of about 220 nm, and include these ions: C II, C III, C IV, N II, N V, Mg II, Si II, Si III, Si IV, Al III, Fe III, and Ni II. The only intercombination line present in significant strength is Si III] 189.2 nm. Thus it is possible to derive a good estimate of the electron density in the line emitting region: log N_e = 12.5, which is a fairly high density, corresponding to the transition region between the solar chromosphere and photosphere. However, the emission line strengths are on the whole not seriously diminished in either eclipse, so that the emitting volume must be considerably larger than the size of the components. Apparently without exception, the emission lines display P Cygni profiles with fairly strong absorption components; thus the optical thickness of the line-forming region is not negligibly small. The average outflow velocity is about -150 km/s. As a rule the lines do not show marked variations of radial velocity with orbital phase. So far, only a component of C III 117.5 nm has been found to move in phase with the gainer. It appears that the whole system is embedded in a rotating and expanding plasma, centered on the mass-accreting component. The large size of the emitting volume combined with its fairly high density imply that the rate of mass outflow from the system is fairly large, and may equal the above-mentioned conservative mass transfer rate of 10^{-5} $M_\odot$/year. It is, of course, now clear that the actual rate of mass outflow from the loser may be much higher.

What is the source of the energy of the outflowing wind? The emission lines are collisionally excited, since most of them are transitions to the lowest energy level of the particular ion. Recombination plays a negligible role since the He II lines λλ 108.5 and 164 nm are absent. The source of ionization is not clear, but there is little doubt that the energy is ultimately supplied by accretion. The wind may be driven by radiation pressure generated at places where the process may be locally supercritical. The source of ionization may be x rays generated at the same location, or turbulence associated with the accretion process. Radio (Jameson and King, 1978) and infrared observations (Phillips et al., 1980) show that the system is surrounded

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by a gas cloud emitting also an optically thin free-free continuum. This cloud is also unlikely to be permanently bound to the system.

4.2 The Serpentids

For a long time it was thought that β Lyrae is a unique system, since the Copernicus satellite did not find another spectrum similar to that of β Lyrae. This was, however, due to the limited magnitude range of the satellite. In August 1978, observing with R. H. Koch, we discovered, in the course of only two or three IUE shifts, at least five binaries with the same kind of ultraviolet emission spectrum. They are RX Cas, SX Cas, W Cru, V 367 Cyg, W Ser, and possibly AR Pav (the latter is usually classified as a symbiotic star). I will call them the W Serpentis stars, or briefly the Serpentids, since W Ser appears to be the prototype of the group. Although the absolute and relative strengths of the emission lines differ from system to system, the spectra are rather remarkably similar. All these stars are unfortunately too faint to be observed at high dispersion, and the low dispersion spectra smooth out the line profiles so much that their P Cygni character is not obvious. The same appearance have the profiles in β Lyrae, if we compare the low dispersion (Fig. 1) and high-dispersion (Fig. 2) spectra.

SX Cassiopeae has an orbital inclination so close to 90° that total eclipses occur of the smaller, accreting star, and one was observed by us in February 1979 (Fig. 3). In the optical region, the normally observed A6 III spectrum of the gainer disappears completely, and so does a strong ultraviolet continuum which must be related to accretion (I believe it comes from the innermost parts of an accretion disk). The emission lines, however, persist without much change, and therefore become much more conspicuous in eclipse than they are out of eclipse. As already stated in the case of β Lyrae, this lack of a pronounced eclipse effect suggests that the emitting volume must be considerably larger than the eclipsed volume. The eclipsed component of SX Cas has a radius about 6 $R_{\odot}$, the eclipsing star 17 $R_{\odot}$, and their separation is about 80 $R_{\odot}$. Actually, the lack of substantial weakening of the emission lines at the primary eclipse of SX Cas can have yet another explanation, namely that the emitting material is associated with the eclipsing component. Several arguments make this interpretation attractive. The secondary component (seen in front at primary eclipse) is a G8 III giant, rather similar to the cooler component of Capella, and as such should dispaly the same chromospheric UV emissions. The overall similarity of the observed emission spectra is indeed striking; we can certainly say that the emission lines discovered in the Serpentids are formed in a quasi-chromospheric environment. However, the relative strengths of the individual lines are different, in particular N V is as a rule more pronounced relative to C IV and Si IV. Again, the absolute strength , i.e. the actual power emitted in these lines, is quite considerably higher in the Serpentids than in Capella and similar ordinary single G giants. Perhaps most important are the arguments based on the high-dispersion observations of β Lyrae described in the preceding section: The pronounced P Cygni profiles which are not seen in quiet chromospheres, and the concentration of the C III emitters around the accreting component. Moreover, in β Lyrae we do not have a late-type giant that could be responsible for the emissions, and the same is probably true about V 367 Cygni. The remaining Serpentids do have late-type giant or supergiant components, but they also display clear symptoms of a large-scale interaction (mass transfer and/or loss), such as strong optical emission lines, shell absorption lines, large light fluctuations, distorted radial-velocity curves, variable periods, etc. In most Serpentids, these phenomena are actually more prominent than in β Lyrae. Certainly one of the reasons is that in β Lyrae the loser is unusually hot and luminous, and dominates the spectrum at almost all the accessible wavelengths. The losers in general appear to be fairly normal and well behaving; emission lines, shell absorptions, and large light fluctuations appear to be associated with the accretion process going on at or around the gainer. The complex structure of the gainer is best seen in eclipsing systems where the loser is so faint as to act as a mere dark screen, and this situation seems to be best realized in W Serpentis.

While the eclipses help considerably in revealing the structure of the interacting components, they at the same time signal that we should expect all possible complications. This is because the eclipsing systems are those seen edge-on, and the disk-forming material then obscures our view of the component stars themselves. Therefore I searched for additional Serpentids among spectroscopic but non-eclipsing binaries. It is hard to establish criteria in the optical region for this purpose; I looked at peculiar Be stars and shell stars. So far, three objects have been identified as very likely being of the W Ser type: KX And (HD 218393), HD 51480, and HD 72754. CX Draconis is another possible candidate. KX And is bright enough to be observed at high dispersion, and sure enough, the emission lines discernible at low dispersion all have P Cygni type profiles when observed at high dispersion. The emission lines tend to be weaker and fewer in the non-eclipsing objects. Probably the accretion process happens to be weaker, but on top of that, the relatively stronger continuous radiation makes the emission lines less conspicuous (Plavec, 1980b).

Although it appears fairly convincingly established that accretion is the source both of the energy that makes the material radiate in emission lines and that drives it away from the system, the possible contribution should be investigated of an extensive chromospheric/coronal complex surrounding the loser. In SX Cas, there exists a certain dilemma concerning the mode of mass loss from the G8 III giant. If we assume that this star fills its critical Roche lobe, then its mass will be only 0.4 $M_\odot$, and the gainer will be 8 times as massive. This disparity in masses is unusual. Theoretically it may occur, but only at the very end of the mass-transfer process, when the mass transfer rate should already be very low. If we, on the other hand, assume that the loser is smaller than its critical lobe, the most likely mass ratio will be more normal (about 3) and the masses will be also more acceptable (although the G star will still have only 1.6 $M_\odot$), but it will be even harder to explain the presumably high rate of mass outflow from the loser. The G8 III giant has too low luminosity ($\sim$ 130

$L_\odot$) to lose mass significantly through an ordinary stellar wind typical for cool giants and supergiants.

What if the stellar wind is considerably enhanced in these binary star components? Even if the G8 III does not completely fill its critical lobe, it will be sufficiently distorted to have regions of low surface gravity. Moreover, the part of its surface facing the gainer may be heated to generate an enhanced stellar wind. It is also worth noticing that a whole class of G - K components in binary stars exists, with very active chromospheres and coronas. These are the RS C Vn systems, and there is no reason why some kind of similar activity could not exist in SX Cas and related objects. Huge coronal loops of the type envisaged by Rosner, Tucker, and Vaiana (1978) may exist in RX Cas, SX Cas, etc., as they exist in the RS CVn stars (Simon and Linsky, 1980). All these factors may combine to enhance considerably the mass loss from the losers in at least some of the Serpentids, and there may exist emission line components associated with the losers. However, they probably play a subordinate role in the observed spectra. There exist Algols with similar G - K type losers, yet no emission lines have been found in the far ultraviolet; yet the sole difference between them and the Serpentids seems to be in the rate of mass transfer.

To summarize: I suggest that β Lyrae and the other five eclipsing and 3-4 non-eclipsing Serpentids lose mass from the system because of a strong stellar wind generated by accretion. The energy of accretion is most likely also the ultimate source of ionization and excitation of the energy lines observed in the far ultraviolet.All the Serpentids are fairly large systems, as their periods range between 13 days (β Lyrae) and 200 days (W Crucis). They are undergoing mass transfer in case B, and theory predicts that accretion should occur via a disk. What the theory did not predict is the mass outflow, indicating that the process is strongly non-conservative and that not much of the material is really accreted after all. (Plavec, 1980b).

4.3 The Algols

Typical semi-detached systems of the Algol type are observed in a stage where the mass transfer rate is already very low. No wonder, then, that their spectra appear rather normal in the far ultraviolet. An exception among the short-period Algols is U Cephei, which has shown considerable activity over the past few years, starting with a strong increase in the H_α emission discovered in 1974 (Plavec and Polidan, 1975; Batten et al., 1975). At times, the excess continous radiation narrowed the total phase of the primary eclipse so much as to make it almost partial (Olson, 1980). Olson concludes that this extra radiation was coming from a temporary disk extending radially not far from the B7 gainer (only about 1.5 times its radius), but thicker than the canonical alpha-disk models postulate (semithickness up to 0.6 the B7 star radius). Piirola (1980) from polarimetric observations supports the conclusion that the disk was optically and geometrically thick. Surprisingly, Crawford (1980) argues that the H_α emission line profiles can be understood only in terms of a gas cloud extending beyond the Roche lobe of the gainer, and considerably turbulent. Interestingly, Olson finds that the rate of mass transfer during the period of the disk formation and presence was not higher than normal (on the order of 10^{-6} $M_\odot$/year). Crawford's model implies that part of this material leaves the system.

Ultraviolet IUE observations of U Cephei were obtained when U Cephei was again quiescent, i.e. H_α emission as well as the excess continuum radiation were absent. Nevertheless, Kondo, McCluskey, and Stencel (1980) detected the mass-transferring stream by its absorption effects on mid-ultraviolet resonance lines of Fe II 259.9 nm and Mg II 279.6 and 280.3 nm. The radial velocities measured for the edges of the absorption features are as high as 400 - 500 km/s. From these large values and from the phase dependence of the radial velocities they conclude that only part of the stream will actually impinge on the B star. The rest escapes from the system, although a fraction may be recaptured by the G8 III loser.

Polidan and Peters (1980) studied, with the Copernicus satellite, the Be star HR 2142 which they had showed to be an 81-days binary a few years ago (Peters and Polidan, 1973). Complex changes in absorption line profiles are interpreted as signatures of gaseous streams. From their structure, which is quite complex, they conclude that a substantial fraction of the stream actually avoids the gainer and escapes into space. Moreover, the gainer shows a fairly strong stellar wind in the Si III line at 120.6 nm, not unexpected for a rapidly rotating B1e star. Similar phenomena were observed in yet another Be star, CX Draconis = HR 7084. This star, too, is an interacting binary as shown by Koubsky (1978), but its period is much shorter, 6.7 days. If the interpretation of HR 2142 is confirmed by IUE observations now in progress, it would imply that about 10^{-7} $M_\odot$/year flows from it into space.

An extensive investigation of the circumstellar H_α emission in Algols and related objects was reported by Plavec and Polidan (1976) and by Peters (1980). Emission at H_α tends to be stronger and more permanent in binary systems with periods above 6 days: these are the systems in which one expects accretion via a disk according to Lubow and Shu (1975). Huge circumbinary clouds were found in W Ser, V 367 Cyg, β Lyr, and BM Cas. These are my "W Serpentis" systems except for BM Cas which appears to have the right properties but failed to show any far ultraviolet emissions or continuum. The more ordinary Algols of longer period contain less circumstellar gas, which tends to concentrate in a disk around the gainer. However, Peters finds evidence of mass outflow from such systems from deep, blue-shifted ($v \simeq -30$ km/s) absorption cores seen near the secondary eclipse, as if gas were streaming out from the circumstellar disk roughly along the system axis away from the loser. She estimates that in TT Hydrae (A2e + G5, P = 7 days) a few times 10^{-8} $M_\odot$ escape in this way from the system every year.

4.4 Circumbinary Ca II Disks

In a comprehensive study which is, regretfully, still largely unpublished, Polidan (1979) surveyed more than 150 Be stars and similar objects for the infrared emission triplet of Ca II at $\lambda\lambda$ 849.8, 854.2, and 866.2 nm. Twenty percent of the objects surveyed did show this triplet in emission, and preponderant among them are the interacting binary stars, such as HR 2142, W Ser, V 367 Cyg, KX And, HD 51480, ϕ Per, and the symbiotics AG Peg and CI Cyg. All these systems have relatively long periods, and if accretion takes place, it should form an accretion disk.

It is surprising that all the three lines are seen with equal intensities despite the ratios of the gf values being 1:9:5. Moreover, the infared emission is never accompanied by emission in the near ultraviolet Ca II doublet H and K. This places severe constraints on the location and properties of the emitting region. Polidan argues that the emitting cloud has the shape of a flat annulus located outside the binary systems, at distances between 50 $R_\odot$ and 200 $R_\odot$ from the hotter components. The gas in the cloud should be cool ($T_e \simeq 5000$ K) and fairly dense ($N_e \simeq 10^{10}$ cm^{-3} , $N_H \simeq 10^{11}$ cm^{-3}). Although no P Cygni profiles are seen, such a circumbinary disk must gradually dissipate, and has therefore to be replenished by material flowing out of the system during active phases of mass transfer. This is again a type of mass loss that has not been predicted by any theory.

4.5 The Symbiotic Stars

In the optical region of the spectrum of a symbiotic star, we observe a late-type stellar spectrum (usually gM, sometimes gK or gG) with superposed emission lines of fairly high excitation, like He II, [Ne V] , [Fe VII] . Frequent presence of forbidden lines indicates that low-density plasma must extend far from the exciting star(s). The observed high-excitation lines can best be explained by the presence in the system of a hot component, small enough to be hidden in the light of the cool giant at optical wavelengths. Observations with IUE generally confirm this binary nature. In some systems (AG Pegasi: Keyes and Plavec, 1980; RW Hydrae: Kafatos et al., 1980; BF Cygni: Slovak and Lambert, 1980) the continuum is easily visible and has a slope appropriate for a hot star. In other objects (CI Cygni: Slovak and Lambert, 1980 ; AR Pavonis: Koch et al., 1980) the FUV continuum is surprisingly flat, although the prominent He II recombination line at 164 nm tells us that a hot source must be present. The systems with a flat continuum tend to be eclipsing. Therefore, as Slovak and Lambert pointed out, the best explanation is that the hot component is surrounded by a disk, which in the eclipsing systems is seen edge-on and obscures the central hot object. In a few systems, orbital motion has been detected from observations of optical spectral lines, and suggests long periods, of the order of a year.

Thus the picture emerges of a long-period system with a giant and a compact hot object, i.e. most likely a binary system at or near the second phase of mass transfer. In some systems, the giant may fill its Roche lobe, but this does not seem to be the rule, and we should in fact not expect Roche lobe overflow. Mass outflow via stellar wind probably suffices to stimulate the flare-like activity of the compact object, while Roche lobe overflow would be too overwhelming or outright catastrophic (see Section 3.2). Nomoto, Nariai, and Sugimoto (1980) calculated such a case of a very rapid accretion on a white dwarf. They find that the white dwarf will expand and become a supergiant, so that we again have a large contact binary with ensuing large mass and angular momentum loss. This is certainly different from the behavior of symbiotic stars, although the recurrent nova T CrB, sometimes counted as one of them, may be on the verge of a catastrophic mass transfer. In that star, however, the hotter object is probably too massive to be degenerate (Webbink, 1978).

Symbiotic stars either behave like very slow novae (AG Peg) or, more typically, tend to flare up quasi-periodically like dwarf novae. Therefore their compact components will not be very different from those in cataclysmic variables. Perhaps, on account of the larger size of the binary systems in the symbiotics, and on account of the stellar wind as against the Roche lobe overflow from the red dwarfs in the cataclysmic variables, the accretion disk is less important, if it exists at all. The spasmodic eruptive behavior will depend very sensitively on the structure of the gainer and the rate of mass accreted. Interesting models were developed by Bath (1977), Tutukov and Yungel'-son (1975), and by Paczynski and Rudak (1980).

In our study of AG Pegasi (Keyes and Plavec, 1980) we found that the compact object need not be hotter than about 35,000 K, and resembles the WR nuclei of some planetary nebulae by its mass, probable size, and the WR profiles of those emission lines that are formed close to it.

The nova-like eruptions will of course eject some material and thereby gain access to the Colloquium for the symbiotics. However, more important is the steady outflow caused by stellar wind. Observations of the nebulosities seen in the symbiotics (in the emission lines) show that they extend over regions at least comparable in size to the size of the binary systems, and often considerably larger. A simple argument (Tutukov and Yungelson, 1975) shows that such a nebulosity must dissipate, solely on account of thermal motions, on a time scale of the order of 10^2 to 10^3 years. Thus the circumbinary cloud must be constantly replenished, and the required stellar wind should yield a mass loss rate of 10^{-6} to 10^{-5} $M_{\odot}$/year. We should therefore expect the loser to be a full-size giant or supergiant on the asymptotic branch, and not too far from its Roche lobe. Observational evidence is not yet quite conclusive on this point. For example, in AG Pegasi, one rather sees a wind or stream moving from the hot component to the cool giant (Hutchings, Cowley, and Redman, 1975). This may be a temporary situation, following the nova-like outburst that occurred about 100 years ago, and may in principle agree well with the model by Bath (1977). Nevertheless, the similarity to WR stars, and in particular to WR nuclei of some planetary nebulae should keep reminding us that some hot subdwarfs may themselves be sources of stellar wind (see also Sect. 4.7).

4.6 The BQ [ ] Stars

Ciatti, D'Odorico, and Mammano (1974) called attention to a group of objects rather similar to the symbiotics and to compact planetary nebulae. Like the symbiotic stars, they display high-excitation emission-line spectra, including forbidden lines (hence the symbol []). As in the symbiotic stars, a very late giant or supergiant seems to be present or at least suspected. Unlike the symbiotics, the level of photometric activity is quite low. This may indicate a somehow different nature of the hot object (perhaps a helium star without thin nuclear burning shells), or less active cool stars. Webbink (1978) suggested that the BQ stars may be binaries transferring mass in the convective mode (of type Bc or Cc) just prior the onset of the fully supercritical accretion. Very little is known about these objects, and even their binary nature is yet to be proven. It is clear, though, that their further study may clarify significantly the problem of relations between cataclysmic variables, symbiotic objects, planetary nebulae, and various transition objects.

4.7 Stellar Wind from Helium Subdwarfs?

At the end, I would like to mention two objects that do not seem to fit any above group fully. Although also dissimilar in many respects between themselves, they may be telling us something about the helium remnants of the first mass transfer phase.

V Sagittae is a short-period system (P = 12.6 hours) usually included among the cataclysmic variables. The primary is similar to WR stars, although it must be smaller and much less massive. What distinguishes it from typical cataclysmic variables is also the fact that the mass transfer seems to proceed from the WR compact star to its mate, i.e. the stellar wind blows in the reverse direction (Whyte and Eggleton, 1980).

The other star is the famous puzzle, ϕ Persei. Here, we have a much bigger system (P = 127 days), containing a very peculiar early Be star with a variable shell spectrum. Gas motions in this system are complex, but they seem to be predominantly towards or past this Be star, rather than originating on it. Considerable disagreement exists as to the nature of the secondary star, if it has been seen at all. Recently Poeckert (1979) discovered a weak emission line of He II moving apparently in antiphase to the Be star. If it originates in the vicinity of the companion, then the mass of that star should be about 3.4 $M_\odot$ compared to the 21 $M_\odot$ primary (Be) star. A hot object of 3.4 $M_\odot$ can be a remnant of a star which before mass transfer and/or loss had about 13.4 $M_\odot$. This is just below the lower limiting mass of 15 $M_\odot$ usually adopted for the progenitors of the Wolf-Rayet stars. Therefore the secondary in ϕ Persei may be a weak WR star, in which case a fairly strong wind blowing from it and partly accreted by the Be star is not so surprising.

By mentioning the cases of V Sagittae and ϕ Persei, I would like to point out that the helium stars with masses below the WR limit may play a non-negligible role in certain systems now developing through the evolutionary phases between the first and second mass transfer phases.

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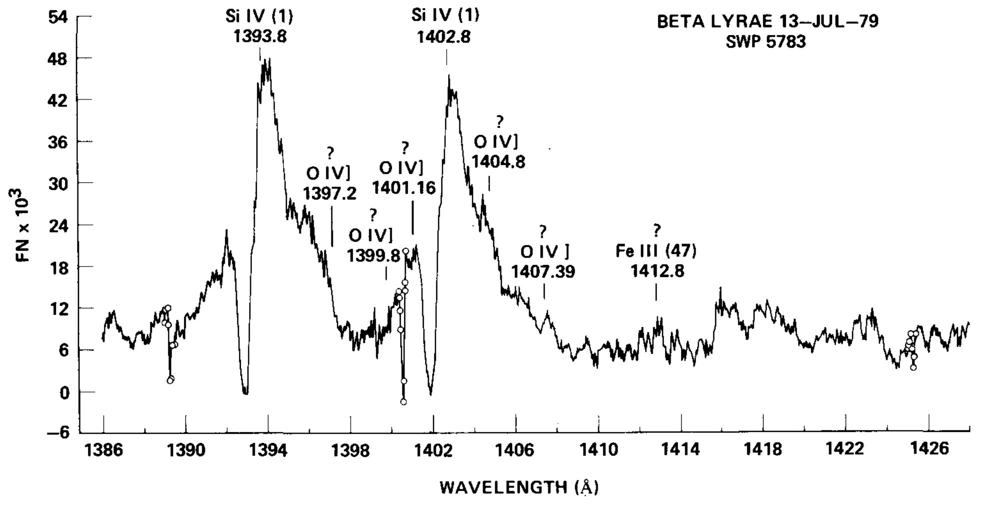

Fig. 1.: High-dispersion spectrum of β Lyrae shows P Cygni emissions.

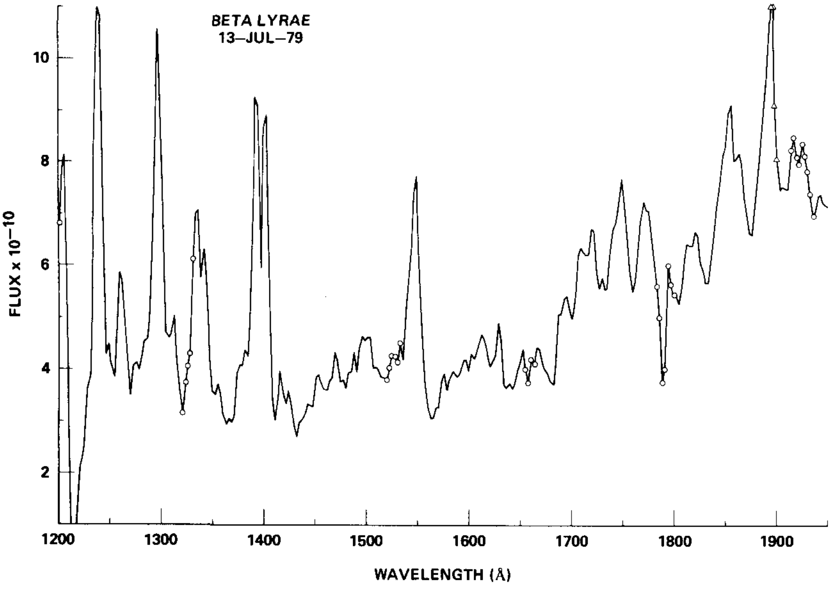

Fig. 2.: Low-dispersion spectrum shows emission lines distinctly, but their P Cygni character is completely obscured.

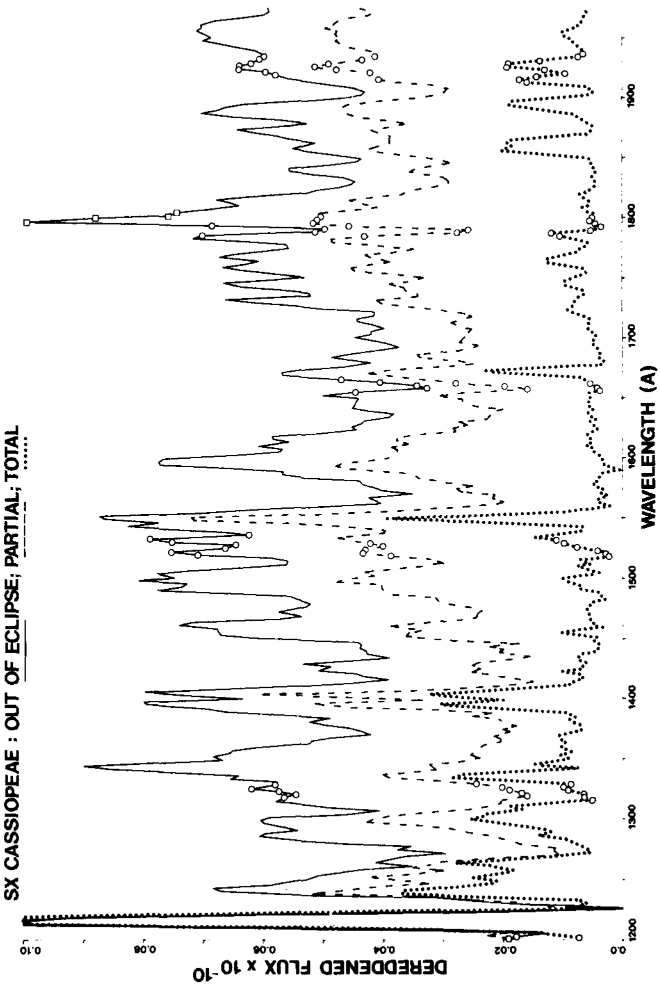

Fig.3.: Far ultraviolet (IUE) spectra of SX Cassiopeae show dramatic changes during primary eclipse.

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DISCUSSION

NUSSBAUMER: We have UV observations of 3 symbiotic stars. It looks as if each one represents something on its own, qualitatively different from the others. H. Schild and I have done detailed work on one of the objects (V 1016 Cyg) which we tried to model on the idea of its being a young planetary nebula, and we have succeeded with that single star model. This however does not prove that V 1016 Cyg is indeed a single star.

VIOTTI: In my opinion symbiotic stars do not exist, at least as a class of stars. I hope that the next conference on these stars we are organizing for 1981 will give a better insight to the physical processes which take place in their envelopes. But I would like to point out to the importance of the IR and radio observations of interacting binary stars and similar objects. For example, from the IR spectrum of β Lyrae we were able to derive the density distribution within the accretion disk. The matter appears to decelerate towards the inner parts of the disk.

ANDRILLAT: Le triplet infrarouge du calcium est egalement observé dans les étoiles Be qui ne sont pas des systèmes binaries. Est-ce que vous proposez le mème modèle dans ce cas?

KEYES: I do not want to state categorically that Ca II triplet emission implies binarity, although Polidan has indications that several Be stars previously thought to be single, show triplet emission and are binary. I'm not sure that the same model would be applicate to single Be stars.

KWOK: There is strong evidence that nebulae of symbiotic system vary greatly in size. For example, I have observed W Ser the VLA (λ=6 cm) and found a upper limit of 1mJy. On the other hand, there are symbiotic systems which emit free-free emission at 6 cm with flux 50mJy.

SAHADE: Why did you need a late type object to explain the presence of a corona in β Lyrae?

KEYES: We do not. Many of the UV emission features seen in β Lyrae are also present in the transition region spectra of late type giants, however, these is clearly no late type giant present in β Lyr. Therefore, we suggested the corona probably surrounds the disk and is powered by accretion.

FRIEDJUNG: I have three comments and a question. Firstly symbiotic stars differ from each other and these studied by Dr. Nussbaumer seem to differ from more "classical" objects like Z And. Secondly, the narrow emission lines are normally seen is symbiotics; probably cannot be formed in a disk. Passing to stars like β Lyrae, supercritical winds can, I think, exist (some people here may disagree), but special conditions are needed not so easily satisfied. Finally I would like to ask whether you tried to fit the UV energy distribution to accretion disk models such as those of Bath et al. in M.N.

KEYES: We are currently trying to fit accretion disk models to ω Ser stars. Narrow lines do not come from a disk, but we think they come from a region photoionized with recombinations. We think that your model for Z And does not apply to AG Peg, but each of these objects is clearly an individual.