COMMON ENVELOPE EVOLUTION OF BINARY STARS

Mario Livio
Dept. of Physiscs, Technion, Haifa
and
Dept. of Astronomy, University of Illinois, Urbana

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ABSTRACT. We discuss the common envelope phase in the evolution of binary systems. The problem of the efficiency of energy deposition into envelope ejection is treated in some detail. We describe the implications of common envelope evolution for the shaping of planetary nebulae with close binary nuclei and for double white dwarf systems, considered to be the progenitors of Type I supernovae.

1. INTRODUCTION

Common envelope (CE) evolution has by now been widely recognized as an essential phase in the evolution leading to the formation of cataclysmic variables (CVs) and of double white dwarf (WD) systems, which are the possible progenitors of Type I supernovae (SNe) (e.g. Ostriker 1975, Paczynski 1976, Webbink 1984, Iben and Tutukov 1984). It very probably plays an important role also in some x-ray binaries (e.g. Bailyn and Grindlay 1987, Eggleton and Verbunt 1986) and certainly in such systems as binary pulsars.

In the CE phase, the binary components (or their cores) move inside a typically non-corotating (and not necessarily hydrostatic) extended envelope. The main effect of this phase is <u>to reduce the separation between the components</u> and to cause in some cases the <u>ejection of the common envelope</u>. In most of the cases of interest to us here, the formation of a CE is the consequence of a dynamical mass transfer event (another possible cause is tidal instability). Dynamical mass transfer is associated typically with mass being transferred from <u>the more massive component</u>, in a stage in which it possesses <u>a deep convective envelope</u> (e.g. in the AGB phase). Under such conditions, the star is unable to contract as rapidly as its Roche lobe (in fact it expands), thus an unstable mass transfer process ensues (Paczynski and Sienkiewicz 1972). As a consequence of the high accretion rate, the secondary star, driven out of thermal equilibrium, starts expanding (especially if the accretion rate exceeds the Eddington limit) and fills its own Roche lobe. The resulting mass flow leads to the formation of a CE configuration (e.g. Yungelson 1973, Webbink

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1977, Prialnik and Livio 1985).

Algols manage to avoid the fate of a CE, very probably by the following two things happening: (i) mass transfer is initiated (by the primary filling its Roche lobe) before the primary becomes a giant, (ii) the secondary star enhances mass loss from the primary, thus reducing the mass ratio. These two facts result in the primary escaping dynamical mass transfer. The distribution in the mass-period diagram of the lobe filling secondaries of 101 semi-detached systems (Giuricin, Mardirossian, and Mezzetti 1983), is consistent with this conclusion (Webbink 1988). In addition, calculations with tidally enhanced mass loss, manage to produce systems in which the primary fills its Roche lobe after the mass ratio has been reduced to $q < 0.7$, which ensures a peaceful mass transfer event (Tout and Eggleton 1988).

Attempts to follow the CE evolution in detail have been impeded mainly by the fact that: (a) it involves a large number of hydrodynamic and thermodynamic processes spanning a wide range in both length scales and timescales and (b) it is intrinsically a three-dimensional problem. Nevertheless, several calculations were performed (e.g. Alexander, Chau, and Henriksen 1976, Taam, Bodenheimer, and Ostriker 1978, Meyer and Meyer-Hofmeister 1979, Livio, Salzman, and Shaviv 1979, Delgado 1980, Livio and Soker 1984a,b). These calculations demonstrated the importance of establishing the efficiency of deposition of orbital energy into envelope ejection. Two-dimensional calculations were carried out by Bodenheimer and Taam (1984) and Taam and Bodenheimer (1988) and recently, Livio and Soker (1988) performed a three-dimensional calculation. The most important new result of the multi-dimensional calculations (besides demonstrating that a large fraction of the envelope can indeed be ejected) has been in the realization that mass ejection takes place preferentially in the orbital plane.

In what follows, we shall describe in some detail the problem of the efficiency of energy deposition (Section 2). We shall then discuss the implications of CE evolution for planetary nebulae (PNe) with binary nuclei and for double WD systems.

2. EJECTION OF THE COMMON ENVELOPE

The main effect of CE evolution is to produce a reduction in the separation of the binary. The most direct evidence for the reality of the CE phase is provided by PNe with binary nuclei. In this case it is quite clear that a spiralling-in process of the binary components has taken place, leading to a significant decrease in the binary separation, accompanied by envelope ejection.

An important physical quantity in determining the final configuration emerging from the CE phase, is therefore, the efficiency with which orbital energy can be deposited into envelope ejection. It is useful to define a parameter α_{CE} by the relation (Tutukov and Yungelson 1979, Livio and Soker 1988)

$$\alpha_{CE} = \frac{\Delta E_{bind}}{\Delta E_{orb}} \quad . \tag{1}$$

Here, ΔE_{orb} is the change in the orbital energy of the binary between the beginning and the end of the spiralling-in process and ΔE_{bind} is the binding energy (namely, gravitational minus thermal) of the ejected material. In the case that the entire envelope is ejected, α_{CE} is given approximately (for a large decrease in the separation) by $a_f/a_f{}^0$, where a_f is the actual final separation and $a_f{}^0$ is the separation that would have been obtained at 100% efficiency of energy deposition.

Before discussing the physical processes that can affect the value of α_{CE}, we would like to clarify some ambiguity that exists in the literature concerning its definition. In a series of works, Iben and Tutukov (1984, 1985, 1988) use approximate expressions for ΔE_{bind} and ΔE_{orb}. In their formulation, α_{CE} is defined by the relation

$$\frac{GM_1^2}{a_i} = \alpha_{CE} \frac{GM_{1R}M_2}{a_f} , \tag{2}$$

where M_1 and M_2 are the masses of the primary and secondary (respectively), M_{1R} is the mass of the primary's core and a_i, a_f denote the initial and final separations, respectively. Two things should be remarked about this definition: (i) Even at 100% efficiency of energy deposition, α_{CE} as defined by eq. 2 assumes a value of order 1 for $M_1 \gg M_2$ and a value of order 1/4 for $M_1 \approx M_2$. This point has already been noted by Iben and Tutukov (1988). (ii) The expression used for the binding energy may underestimate the actual binding energy of the common envelope by as much as 50% in some cases (although it should be noted that for AGB stars, the expression $\Delta E_{bind} = GM_{star}M_{envelope}/R_{star}$ generally approximates the binding energy of the envelope to within 10%).

In view of points (i) and (ii) above, we feel that it is advisable to use exact values for ΔE_{bind}, ΔE_{orb} (eq. 1) when a value of the efficiency parameter α_{CE} is to be used. This is particularly important, since as we shall see in the next sections, differences in α_{CE} can be crucial for determining the outcome of the CE phase.

We shall now consider the physical processes which determine the value of α_{CE}. The two major factors which can act to reduce the efficiency of orbital energy deposition into envelope ejection are: (a) efficient energy transport and (b) non-spherical effects.

If the timescale for energy transport in the CE is short compared to the orbital decay timescale, then energy generated by the gravitational drag can be transported efficiently to the surface, without causing dynamical mass motions. This situation was found under some circumstances in the calculations of Taam, Bodenheimer, and Ostriker (1978), of Meyer and Meyer-Hofmeister (1979) and of Livio and Soker (1984a) and Soker, Harpaz, and Livio (1984). It should be noted, however, that all of these calculations assumed spherical symmetry, thereby depositing the frictional energy into an entire spherical shell (of a relatively large mass), rather than locally or in a torus (in the case that the orbital period is much shorter than the orbital decay timescale). This assumption obviously tends to suppress the development of mass motions. Nevertheless, it remains very probably true, that in the outer layers of evolved AGB star configurations, where the rate of energy deposition is not very high, we do not expect a large expansion to occur (the energy being transported efficiently and radiated away). This is also the case if the mass of the secondary star is very low (in particular brown dwarf secondaries, e.g. Soker, Harpaz, and Livio 1984), so that the rate at which energy is generated by the spiralling-in process represents only a small perturbation to the AGB star's luminosity. On the other hand, in certain stages of the CE phase leading to the formation of double WD systems (to be discussed in Section 4), the drag luminosity can reach $L_{drag} \sim 10^{41}$ erg s^{-1} in the inner layers of the CE. It is clear that in this case dynamical mass motion will ensue and energy transport will have virtually no effect on α_{CE} (the process is essentially adiabatic).

The importance of non-spherical effects ((b) above) has been demonstrated by Bodenheimer and Taam (1984, 1988) and Livio and Soker (1988). It was found that <u>mass ejection takes place in a narrow region (half angle of order 10°) around the equatorial plane</u> (this has been predicted by Livio, Salzman, and Shaviv 1979 and Livio 1982). Material in the plane is accelerated (down the density gradient) to velocities <u>exceeding the escape velocity</u>. This has the effect of reducing α_{CE}, since the energy deposition process is inefficient in the sense that only a fraction of the envelope mass is imparted with more energy than it needs to escape. Typical values for α_{CE} implied by the calculations of Taam and Bodenheimer (1988) and Livio and Soker (1988) were in the range $\alpha_{CE} \sim 0.3 - 0.6$.

The question that now arises is, are there also processes capable of increasing the efficiency of envelope ejection? Four such processes exist (in principle at least) and they involve the triggering of <u>additional</u> energy sources. These are: (i) the recombination energy in the ionization zones, (ii) mass ejection by the AGB star itself (as in PNe resulting from single star evolution), (iii) enhanced nuclear energy production due to the injection of new fuel into the burning shells and (iv) nuclear burning on the surface of the secondary star, in the case that it is a white dwarf.

We shall now discuss briefly each of these ((i)-(iv)) possibilities. (i) If the recombination energy of the hydrogen and helium ionization zones can be deposited into mass motion, it can certainly facilitate mass ejection, since with the inclusion of this energy, a significant fraction of the envelope has a positive total energy (as originally, pointed out by Paczynski 1967). This can also make the mass ejection process somewhat less concentrated to the orbital plane.

(ii) Livio and Soker (1988) have defined a parameter γ_{CE} characterizing the spin-up of the CE. It is given by $\gamma_{CE} \equiv \tau_{spin\text{-}up}/\tau_{decay}$, where $\tau_{spin\text{-}up}$ is the timescale it takes the spiralling-in binary to spin-up the interior common envelope, and τ_{decay} is the orbital decay timescale. For low values of γ_{CE} ($\gamma_{CE} \lesssim 1$), considerable spin-up of the CE can occur. Consequently, orbital decay is significantly slowed down, because the drag force depends on the relative velocity between the binary and the CE. Livio and Soker have shown that γ_{CE} assumes smaller values in highly evolved AGB stars and for more massive secondaries. If spin-up of the CE to corotation can indeed occur (which is highly uncertain, because it depends among other things on the poorly known viscosity), orbital decay may be essentially arrested. In such a case, the AGB star may eventually eject the CE as a planetary nebula by itself (like a single star).

(iii) Two-dimensional calculations (Taam and Bodenheimer 1988) reveal the development of a circulation pattern. As material in the orbital plane moves outwards (to be ejected), material from above and below the plane flows in to replace it. In principle at least, this induced circulation could inject hydrogen rich material into the helium burning shell, or heavy elements (from the ashes of helium burning) into the hydrogen burning shell. If this happens, nuclear energy generation could be greatly enhanced, inducing a much higher mass loss. On the other hand, it is possible that as a result of mass outflow from above the burning shell and the concomitant reduction in pressure, nuclear burning will be essentially extinguished.

(iv) Nuclear burning on the WD surface is unlikely to contribute much to envelope ejection. Rather, such burning may help in keeping the puffed-up configuration of the CE.

It should be noted that all of the processes described in (i)-(iv) (if operative) involve additional energy sources (to orbital energy) and therefore, strictly speaking should not be related to the definition of α_{CE} (eq. 1). If we nevertheless continue to define α_{CE} formally by eq. 1, then the inclusion of these (potential) additional energy sources in the spiralling-in process, can result in an increase in the value of α_{CE}.

We shall now discuss the implications of the CE phase for PNe with binary nuclei and for the formation of double WD systems.

3. PLANETARY NEBULAE WITH BINARY NUCLEI

An updated list of PNe with binary nuclei (see Bond and Livio 1988) is given in Table 1. In addition, A14, H3-75, He 2-58, He 2-36, and Sh 2-71 probably contain binary nuclei, since the central star is of too late a type to ionize the nebula (J. Kaler, private communication). Attempts to identify a fully consistent evolutionary scheme for each object are extremely important, in that, they can provide (among other things) an observational determination of α_{CE}. However, such attempts are often impeded by uncertainties both in the observations and in the evolutionary models (e.g. Iben and Tutukov 1988). Here we would like to discuss the morphology expected for PNe which result from CE evolution.

One of the main conclusions of the calculations of the CE phase is that mass ejection is quite strongly concentrated towards the orbital plane. Consequently, a "density contrast" is expected between the equatorial (orbital plane) and polar directions, in the ejected envelope material. The question is now, what are the implications of this density contrast for the "interacting winds" model (Kwok 1982, Kahn 1983), which has had considerable success in explaining the shaping of PNe (of single stars). In this model, about 2000 years after the cessation of the slow wind (the ejected envelope of the AGB star), a

TABLE 1

Planetary Nebulae with Observed or Suspected Binary Central Stars

Planetary Nebula	Central Star	Spectra	Orbital Period (days)
NGC 2346	V651 Mon	? + A0-A5V	15.991
K1-2	VW Pyx		0.6707
HFG1			0.582
A 46	V477 Lyr		0.4717294
A 63	UU Sge	sd0 + K-MV	0.46506918
DS1	LSS 2018	sd0 + ?	0.357113
A 41	MT Ser	sd0 + MV	0.1132269
LT-5	HD 112313	sd0 + G5 III-V	1.200?
		+ G ?	1.994?
A35	BD -22°346F	? + G8 III-IV	a few hours? 0.766? 0.433?
IRAS Source 1912 + 172P09		? + B9	
NGC 1360		sd0 + ?	8.2 ?
NGC 1514		sd0 + AO III	
NGC 6826	HD 186924	Of 6p	0.23768?
IC 418	HD 35914		0.16157?
NGC 6543	HD 164963	07 + WR	0.06038?

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fast (V_{fast} ~ 1000 km s^{-1}) wind starts emanating from the hot remnant core. The fast wind runs into the slow wind (which moves at V_{slow} ~ 20 km s^{-1}), shocks it and generates a "snow plow" effect. It has been recently suggested by Balick (1987) and Balick, Preston, and Icke (1987), that different degrees of density contrast between the equatorial and polar directions, are responsible for the different morphologies of PNe. In this scenario, the fast wind (and material accelerated by it) can penetrate deeper into the lower density material in the polar direction. For a relatively mild density contrast, this will tend to produce elliptical PNe (in the projected image). In the case of a high contrast, after the fast wind breaks through the slow wind in the polar direction, a "butterfly" morphology will be obtained.

In an attempt to follow the shaping of PNe (with binary central stars) by the interacting winds model (following a CE phase), Soker and Livio (1988) have performed a two-dimensional hydrodynamical calculation of the process. They have demonstrated that for the type of density contrast expected to result from CE evolution, the density structure of the flow that is obtained, is consistent with the morphology of PNe with binary nuclei (Bond and Livio 1988). In particular, structures which in projection produce two arcs in the equatorial direction (like in A41 and A63, Bond and Livio 1988, Grauer and Bond 1983) and expanding "bubbles" with high density knots (ansae) in the polar direction (like in NGC 6826), were produced. Thus, the incorporation of the results of CE evolution, into the interacting winds model seems to provide a promising scenario for the formation and shaping of PNe with close binary nuclei. These systems can later evolve to become cataclysmic variables. <u>A better determination of the orbital parameters and in particular of the masses of the binary components, can (in principle at least) lead to an observational determination of α_{CE}</u>, and thus, can provide us with valuable observational constraints on CE theory.

4. DOUBLE WHITE DWARF SYSTEMS AND TYPE I SUPERNOVAE

One of the presently favored models for Type I SNe involves the merger of two white dwarfs with a total mass exceeding the Chandrasekhar limit (e.g. Webbink 1984, Iben and Tutukov 1984).

A typical scenario starts with either (a) two stars of comparable masses (in the range 3.7-6 $M_\odot$) at separations 10-100 $R_\odot$ or with (b) two stars with rather disparate masses (in the range 5-9 $M_\odot$) at separations 70-1500 $R_\odot$. In the first case ((a) above), the primary undergoes an early case B Roche lobe overflow event, the mass transfer is assumed to be conservative and only the second mass transfer episode (when the original secondary fills its Roche lobe) involves a CE phase (Webbink 1984). In the second case ((b) above), the primary undergoes a case C (or late case B) mass transfer event and at least two CE phases are expected to occur (e.g. Iben and Tutukov 1984, IT). The two routes are supposed to lead to the formation of double WD systems, a fraction of which at least, are at sufficiently small separations ($a \lesssim 3.5\ R_\odot$) and with a total mass exceeding the Chandrasekhar mass, so that they can be

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expected to merge (being brought together by the emission of gravitational radiation) within less than a Hubble time.

Some (of the many) problems remaining with this model are related directly to CE evolution. One of the predictions the scenario has, is that there should exist a population of close double WD binaries.

In a recent work, Robinson and Shafter (1987) reported null results from a radial velocity search intended to detect pairs with orbital periods between 30 sec and 3 hr, in a sample of 44 WDs. They concluded that the space density of short-period binary WDs brighter than $M_v = 12.75$, is less than 3.0×10^{-5} pc^{-3} with a probability of 90% and less than 1.6×10^{-5} pc^{-3} with a probability of 70%. This finding in itself is conflicting (although only marginally) with expectations from the IT and Webbink scenarios regarding the period distribution of binary WDs, when a value of $\alpha_{CE} = 1$ (100% efficiency of energy deposition) is assumed. Robinson and Shafter's result is consistent with the expectations from CE evolution, if a value of $\alpha_{CE} \simeq 0.4$ is used (Livio and Soker 1988), since in this case double WD systems are produced with shorter orbital periods (and the probability of their detection becomes lower).

The smaller value of α_{CE}, however, introduces a difficulty associated with the occurrence of Type I SNe in elliptical galaxies. The problem there, is whether the proposed scenarios are capable of delaying the explosions by more than 10^{10} years after the major phase of star formation has ceased. It has been suggested (by IT) that the "clock" delay mechanism is provided by the fact that some WD binaries are formed (when $\alpha_{CE} = 1$ is assumed) with orbital periods exceeding $\sim$ 12 hours. In this case, the timescale for the reduction of the separation (by gravitational radiation) is of the order of 10^{10} years. The problem with smaller values of α_{CE} is that if the systems indeed undergo (at least) two CE phases, then the binary WD separations that are obtained are too small to provide the necessary delay. In fact, type I SNe in ellipticals cannot be explained in this way if $\alpha_{CE} < 0.8$ (Tornambe et al. 1988).

Two possible solutions to this problem are: (i) type I SNe in ellipticals result <u>only</u> from the scenario ((a) above) which involves only one CE phase (and thus, a sufficiently large separation can still be obtained, even for $\alpha \sim 0.4$). (ii) The two CE phases involve very different values of α_{CE}, one of which needs in fact to be formally larger than one (e.g. via spin-up of the CE, as outlined in Section 2). In this case, however, the Robinson and Shafter (1987) observations remain (at least) intriguing. An increase of their sample is essential to resolve this issue.

Three recent works have demonstrated that the merging WDs scenario is at least promising. On the observational side, Saffer, Liebert, and Olszewski (1988) have discovered that the cool white dwarf L870-2 (EG 11, WD0135-052) is a double line spectroscopic binary consisting of a detached pair of DA WDs, with an estimated orbital period of P = 1.55578 days. While this particular system cannot produce a type I SN, because the sum of the masses is very probably below the Chandrasekhar limit and also the relatively large separation implies a lifetime (before merger) of many Hubble times, its discovery is important in establishing that a population of detached double WD systems (with moderate separations) does exist. This discovery also implies that the space density found by Robinson and Shafter for relatively short period WDs, may underestimate the space density of longer period systems.

An evolutionary scenario leading to the formation of L870-2 can (potentially) provide information on the value of α_{CE}. Two such scenarios are possible (in principle at least). In one, the system had to undergo two CE phases (in a similar way to the IT picture, although clearly with smaller initial masses). Because of the relatively large final separation (of the two WDs), such a scenario would require the product of the two α_{CE} involved, to be larger than one (Iben and Webbink 1988). This can perhaps be achieved, if the first CE occurs in a very evolved configuration (e.g. case C mass transfer), thus allowing either spin-up of the CE or the usage of the recombination energy (see Section 2). A second possibility (in principle) is that the initial separation was sufficiently large, so that the transformation of the primary into a WD did not involve a Roche lobe overflow, but sufficiently small ($a \sim 2\text{-}3\ R_{AGB}$) so that tidal interaction between the two components (assuming that the primary was not completely synchronized) could lead to a decrease in the separation. In this case, only one CE phase took place (when the original secondary filled its Roche lobe) and thus the final separation can be quite large even if $\alpha_{CE} \sim 0.4$.

On the theoretical front, two recent works have demonstrated that a potential difficulty of the merger scenario, pointed out by Hachisu, Eriguchi, and Nomoto (1986), can in fact be overcome. Hachisu et al. claimed (on the basis of energy conservation arguments) that configurations consisting of a massive WD surrounded by a massive thick disk (which forms from the material of the dissipated lighter WD), cannot be constructed. Such configurations were assumed to be the consequence of mass transfer from the lighter WD onto the heavier one, once the less massive WD fills its Roche lobe prior to merger (Tutukov and Yungelson 1979). However, Mochkovitch and Livio (1988) have recently shown, that the difficulty in generating such configurations resulted from the assumption made by Hachisu et al. (1986), of no pressure support between the heavy disk and the central WD. Mochkovitch and Livio have demonstrated that once this assumption is relaxed, such configurations can be constructed. Furthermore, in a three-dimensional numerical simulation, Benz et al. (1988) have shown that once the lighter WD is allowed to overfill its Roche lobe, a catastrophic mass transfer event ensues. This results in a complete disruption of the secondary in less than 3 orbital periods and its transformation into a disk around the primary (with pressure support).

Thus, while many problems still remain, in particular with the later phases (the transport of angular momentum, the possibility of carbon ignition in the disk etc.), the merger of two WDs, following a series of CE phases, remains an attractive model for Type I SNe.

5. CONCLUSIONS

We have shown that the evolution of interacting binaries can host a

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rich variety of phenomena associated with common envelope phases.

The physics of the CE and its final outcome involve still many open questions, however, significant progress has been achieved recently. In particular, the following points have been established.
(1) The value of the parameter describing the efficiency of energy deposition, α_{CE}, is of the order of 0.4 when no additional energy sources (to orbital energy) are included.
(2) Spin-up of the CE and the recombination energy in the ionization zones may play an important role in CE evolution.
(3) Common envelope evolution and the interacting winds model provide a promising scenario for the shaping of planetary nebulae with binary nuclei.
(4) The merger of binary white dwarfs remains a viable model for type I supernovae.
(5) Observations of close binary nuclei of planetary nebulae, of binary WD systems and of systems similar to pre-cataclysmic variables (e.g. Feige 24, 39 Ceti, BE UMa, HD 128200) can provide invaluable information for CE evolution theory.
(6) Algols are extremely important in the fact that they delineate observationally the boundary between conservative and CE evolutions.

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REFERENCES

Alexander, M. E., Chau, W. Y., and Henriksen, R. N. 1976, Ap. J., **204**, 879.
Bailyn, C. D. and Grindlay, J. E. 1987, Ap. J. Lett., **316**, L25.
Balick, B. 1987, Astron. J., **94**, 671.
Balick, B., Preston, H. L., and Icke, V. 1987, Astron. J., **94**, 1641.
Benz, W., Bowers, R. L., Cameron, A. G. W., and Press, W. H. 1988, preprint.
Bodenheimer, P. and Taam, R. E. 1984, Ap. J., **280**, 771.
Bond, H. E. and Livio, M. 1988, in preparation.
Delgado, A. J. 1980, Astron. Ap., **87**, 343.
Eggleton, P. P. and Verbunt, F. 1986, M.N.R.A.S., **220**, 12P.
Giuricin, G., Mardirossian, F., and Mezzetti, M. 1983, Ap. J. Suppl., **52**, 35.
Grauer, A. D. and Bond, H. E. 1983, Ap. J., **271**, 259.
Hachisu, I., Eriguchi, Y., and Nomoto, K. 1986, Ap. J., **308**, 161.
Iben, I. Jr. and Tutukov, A. V. 1984, Ap. J. Suppl., **54**, 335.
Iben, I. Jr. and Tutukov, A. V. 1985, Ap. J. Suppl., **58**, 661.
Iben, I. Jr. and Tutukov, A. V. 1988, in IAU Symp. 131, Planetary Nebulae, in press.
Iben, I. Jr. and Webbink, R. F. 1988, in preparation.
Kahn, F. D. 1983, in Planetary Nebulae, IAU Symp. 103, ed. D. R. Flower (Dordrecht: Reidel), p. 305.
Kwok, S. 1982, Ap. J., **258**, 280.

Livio, M. 1982, Astron. Ap., 109, 37.
Livio, M., Salzman, J., and Shaviv, G. 1979, M.N.R.A.S., 188, 1.
Livio, M. and Soker, N. 1984a, M.N.R.A.S., 208, 763.
Livio, M. and Soker, N. 1984b, M.N.R.A.S., 208, 783.
Livio, M. and Soker, N. 1988, Ap. J., 329, 764.
Meyer, F. and Meyer-Hofmeister, E. 1979, Astron. Ap., 78, 167.
Mockovitch, R. and Livio, M. 1988, Astron. Ap., in press.
Ostriker, J. P. 1975, paper presented at IAU Symp. 73, Cambridge, England.
Paczynski, B. 1967, paper presented at IAU General Assembly, Commission 35.
Paczynski, B. 1976, in IAU Symp. 73, Structure and Evolution of Close Binary Stars, eds. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht: Reidel), p. 75.
Paczynski, B. and Sienkiewicz, R. 1972, Acta Astr., 22, 73.
Prialnik, D. and Livio, M. 1985, M.N.R.A.S., 216, 37.
Robinson, E. L. and Shafter, A. W. 1987, Ap. J., 322, 296.
Saffer, R. A., Liebert, J., and Olszewski, E. W. 1988, Ap. J., in press.
Soker, N., Harpaz, A., and Livio, M. 1984, M.N.R.A.S., 210, 189.
Taam, R. E. and Bodenheimer, P. 1988, Ap. J., in press.
Taam, R. E., Bodenheimer, P., and Ostriker, J. P. 1978, Ap. J., 222, 269.
Tornambe, A., Matteucci, F., Iben, I. Jr., and Nomoto, K. 1988, in Lecture Notes in Physics, Vol. 287, Nuclear Astrophysics, eds. W. Hillebrandt, R. Kuhfuss, E. Muller, and J. W. Truran (Berlin: Springer), p. 284.
Tout, C. A. and Eggleton, P. P. 1988, M.N.R.A.S., 231, 823.
Tutukov, A. V. and Yungelson, L. R. 1979, Acta Astr., 23, 665.
Webbink, R. F. 1977, Ap. J., 211, 486.
Webbink, R. F. 1984, Ap. J., 277, 555.
Webbink, R. F. 1988, in Critical Observations vs. Physical Models for Close Binary Systems, ed. K.-C. Leung (New York: Gordon and Breach), p. 403.
Yungelson, L. R. 1973, Nauch. Informatsii, 27, 93.

DISCUSSION

Eaton asked about the time-scale of common-envelope evolution. He thought it might be the dynamic time-scale, whereas he understood that planetary-nebula formation took about 10^4 years. Livio replied that planetary nebulae with binary nuclei were probably formed by spiralling within an AGB envelope, which did indeed take 10^4 years. The common-envelope phase would be appreciably shorter in duration only inside less evolved giant configurations. Then it would produce what A. Renzini has called a "lazy" planetary nebula which cannot be observed because its core does not get hot enough. Eaton also raised questions about 5 Cet, a system containing a K3 giant, having an orbital period of 56^d, in which mass appears to be transferred from the giant to the less massive star at a rate of about $5 \times 10^{-7} m_\odot \ yr^{-1}$. Can this be reconciled with

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common-envelope theory? Livio did not claim to have the complete answer. There are indeed cataclysmic variables that appear to have unstable mass-ratios. The instability does not grow very quickly, however; its rate of growth is proportional to $(P^2\tau)^{1/3}$, where P is the orbital period and τ the time-scale of mass-transfer itself.

Leung asked what a system in the common-envelope phase would look like. In particular would there be light changes and what would be the period? Livio doubted that there would be observable light changes; the orbital period should be of the order of a year. He thought it would be difficult to detect such a system because the two stars are embedded in an AGB envelope and may be indistinguishable from a normal AGB star (it would be most unlikely that an orbital eccentricity, which could introduce some asymmetry, would survive into that stage). Since mass-loss from the object would be confined to the orbital plane, the discovery of an AGB star losing mass only in one plane might lead to identification of a common-envelope object. Hrivnak suggested that one could look for radial-velocity variations of the cool supergiant, especially in a system suspected of being in the second common-envelope phase, in which a white dwarf of mass comparable to that of the supergiant core was in orbit about the latter within the envelope.

Kondo asked what percentage of mass could be lost from a system in mass-transfer without the process deviating from the predictions of the conservative case. Livio thought the fraction could be as high as 10 per cent, but he and De Greve insisted that the fraction of angular momentum lost was more important in changing the evolution of a system. Livio suggested that the lost 10 per cent should not have a specific angular momentum in excess of 1.7.

Martin asked how the envelope was coupled to the binary system; were magnetic fields included in the calculation of the coefficient α_{CE}? Livio replied that the calculation was, unfortunately, complicated enough, even without including magnetic fields. The coupling is a form of gravitational drag; material in the envelope is shocked by the motion of the secondary. Plavec asked if there were cataclysmic variables in which the loser is a dwarf of spectral type earlier than K. Livio replied that the mass-losing component of GK Per is a G-type dwarf. Eggleton suggested that losers of earlier types would not be observed since the mass-ratios would be too extreme and the mass-transfer too rapid for a cataclysmic variable with such a companion to form.