THE ASTROPHYSICAL JOURNAL, 374:623–630, 1991 June 20

THE COMMON ENVELOPE PHASE IN CLASSICAL NOVAE: ONE-DIMENSIONAL MODELS

ANURAG SHANKAR,[1] MARIO LIVIO,[2] AND JAMES W. TRURAN
Department of Astronomy, University of Illinois, 1002 West Green Street, Urbana, IL 61801
Received 1990 August 27; accepted 1990 December 13

ABSTRACT

The effects of energy deposition due to the motion of the secondary in an expanding nova envelope are explored for 1 $M_{\odot}$ white dwarfs. Results of one-dimensional hydrodynamic calculations show that a common envelope phase can significantly accelerate mass loss from the system, thereby altering the outburst character. Such a rapid mass loss is necessary in order to explain the early appearance of a nebular spectrum and of X-ray emission, in a number of observed systems.

Subject headings: stars: binaries — stars: mass loss — stars: novae — stars: white dwarfs

1. INTRODUCTION

Attention has recently been drawn to some circumstantial evidence for a common envelope (CE) phase in classical novae (CNs) (Truran, Shankar, & Livio 1991). This evidence includes the observed rapid hardening of the radiation field following the light maximum, and the morphology of the ejecta. A significant amount of envelope matter has to be lost at sufficient high mass-loss rates to explain the rapid emergence ($t \approx 100$ days) of the nebular spectrum and of X-rays observed in a number of CN systems (e.g., Williams 1990, Ögelmann, Krautter, & Beurmann 1987). Since hydrodynamic models of outbursts of CNs (e.g., Starrfield, Sparks, & Truran 1974; Starrfield, Truran, & Sparks 1978; Prialnik, Shara, & Shaviv 1978) do not typically predict the rapid (burst) ejection of all of the accreted mass on a CO white dwarf (although more mass is ejected when some mechanism for the enrichment of the envelope by heavier elements is assumed to operate), and since the wind mass loss time scales are longer than 100 days (at least for envelopes of solar composition, e.g., Kato 1983a, b), and additional, efficient mass-loss mechanism is required to explain these observations. The CE mechanism presents itself as a natural source of energy in the nova envelope, with the ability to tap directly the orbital energy and angular momentum. The importance of CE evolution in the context of other types of binaries (e.g., the formation of binary planetary nebula nuclei, the formation of cataclysmic variables, etc.) has been demonstrated by a number of authors (Paczyński 1976; Taam, Bodenheimer, & Ostriker 1978, Meyer & Meyer-Hofmeister 1979; Bodenheimer & Taam 1984; Iben & Tutukov 1984; Webbink 1988; Livio & Soker 1988; Taam & Bodenheimer 1989, 1990).

The relevance of the CE mechanism in the context of CNs was first pointed out by MacDonald (1980). He investigated in some detail the consequences of energy deposition in an expanding nova envelope due to the drag experienced by the secondary as it moved inside the CE. Using one-dimensional hydrodynamics, he found that the CE mechanism could only reproduce the characteristics of slow novae. MacDonald, Fujimoto, & Truran (1985), and MacDonald (1986) addressed again the potential significance of the CE phase in CNs. More recently, Livio et al. (1990) have carried out a two-dimensional study of the CE phase in very slow novae. Although the results clearly indicate the possibility of mass loss due to the CE mechanism and provide clues to the geometry of the flow, their method of calculation and the assumptions on which they are based reflect the fact that theirs is a very preliminary attempt to model a very complex problem. For example, these authors used as their initial model and extended envelope in hydrostatic equilibrium, and assumed the evolution to be adiabatic. The assumption of hydrostatic equilibrium for a very slow nova envelope at visual maximum is not entirely unreasonable, as shown by the numerical models. However, it is clearly inadequate in the more general case, since the effects of expansion can be quite important (as we shall see later), and must be included in any calculation of the CE phase in CNs.

In view of the above, we have carried out one-dimensional hydrodynamic calculations of the CE phase in CNs, which include a fast nova development, a full equation of state, and a treatment of radiative transfer of energy in the diffusion approximation. In particular, we address at some level each of the following three questions in this paper: (1) What is the time scale of the CE phase?, (2) What is the magnitude of the energy input to the nova envelope during the CE phase?, and (3) What are the implications of the energy input to the loss of the envelope matter? In § 2 we describe the relevant physical input. The method of calculation and the results are presented in § 3, followed by a discussion and conclusions.

2. THE COMMON ENVELOPE PHASE

2.1. *The Direct Observational Evidence*

The occurrence of a CE phase in the evolution of CNs in outburst is a forced consequence of the runaway induced expansion of the nova envelope in a short-period (hours) binary system. Observationally, a variety of CNs display spectra at visual maximum resembling those of A or F supergiants, implying photospheric radii of 10^{12}–10^{13} cm. Alternatively, the expansion velocities (as inferred from the principal spectra) lie in the range 500–3000 km s^{-1} for fast novae and 150–300 km s^{-1} for slow novae (Payne-Gaposchkin 1957). Assuming the rise time to be as short as a day for all novae (slow or fast), we obtain envelope radii at visual maximum which are of the same order (10^{12}–10^{13} cm). For parameters typical of cataclysmic binaries, the orbital separation is only of the order of a few $\times\ 10^{11}$ cm. The secondary, therefore, is located deep within the nova envelope at visual maximum. The

[1] Current address: Steward Observatory, University of Arizona, Tucson, AZ 85721.

[2] Permanent address: Department of Physics, Technion, Haifa 3200, Israel.

conclusion that *all CNs undergo a CE phase* thus seems inescapable. The symbiotic novae are the only likely exceptions, since the large binary separations in their case preclude a CE phase.

Typical CNs systems find themselves in a CE phase rather hastily. It takes a typical fast nova a few minutes to enter the CE phase, whereas it can take several hours for slower novae. As a result, the effects of drag energy deposition can take several hours for slower novae. As a result, the effects of drag energy deposition can be important early in the evolution of the outburst, namely on the rise to visual maximum (e.g., MacDonald 1980).

2.2. *The Duration*

While the time scale is difficult to ascertain accurately, it is clear that the CE phase can last for a few months, as demonstrated by the novae DQ Her, HR Del, and others, which stayed at visual maximum for a prolonged period. The rapid emergence of the nebular spectrum (Williams 1990) or of X-rays (Ögelmann et al. 1987) on time scales as short as 100–200 days, on the other hand, points to a very efficient, though not necessarily short-lived, CE phase, since continued ejection due to CE mechanism can occur even after the nebular stage (see, e.g., Truran et al. 1991). The efficiency of the CE mechanism depends on a number of factors, to be discussed later in this paper. However, it is safe to assume that the CE phase lasts at least until the transition to a nebular stage occurs for slow novae. For faster CNs, the initial burst ejection is very likely sufficient to compel the system to evolve more rapidly into a nebular stage.

A crude estimate of the duration of the CE phase can be obtained from a consideration of the energetics. If we assume that the duration $t_{\rm CE}$ is approximately equal to the time it takes for the drag energy to match the binding energy of the envelope, we can write

$$L_d t_{\rm CE} = E_{\rm bind} = \frac{GM_1}{a} \Delta M_1 , \qquad (1)$$

where L_d is the drag luminosity; M_1 and ΔM_1 are the white dwarf and the accreted envelope masses, respectively; and a is the binary separation. Assuming $M_1 = 1.0\ M_\odot$, $a = 10^{11}$ cm, $\Delta M_1 = 10^{-4}\ M_\odot$, and an average value for $L_d = 8000\ L_\odot$ (see § 3.3), we obtain $t_{\rm CE} \simeq 90$ days, which agrees well with observations described earlier.

2.3. *Physical Conditions in the Common Envelope*

The motion of the secondary in the CE is typically found to be supersonic. Figure 1 displays the orbital velocity of the secondary and a function of the white dwarf mass, the second mass, and the binary orbital period. The characteristic range of sound velocity at the orbital separation in the CE is represented by the arrow. Mach numbers of 1–2.5 are expected for typical orbital periods of nova binaries in the range 1.5–5 hr. In the case of subsonic motion, a correction to the drag energy deposition has to be included (see eq. [2] below).

For slow novae, the expanding envelope is primarily radiation dominated when it reaches the secondary. Figure 2 shows that the boundary between the convective/radiative region lies well inside $r = a$, for a representative slow nova envelope. The luminosity incident at the location of the secondary is roughly equal to the Eddington luminosity (with respect to electron scattering) for the underlying white dwarf.

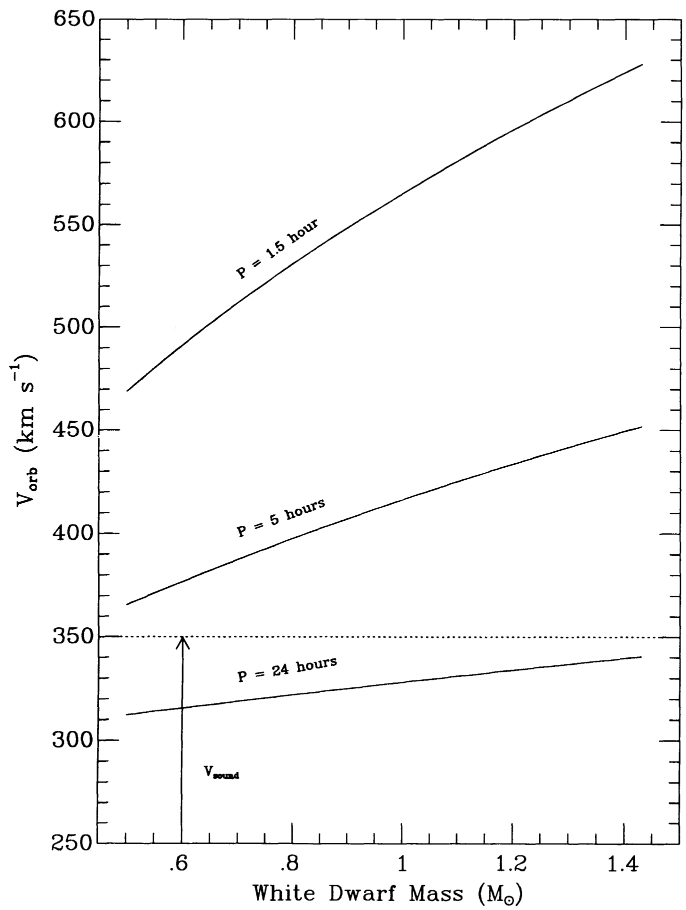

FIG. 1.—The secondary orbital velocity as a function of the primary mass, secondary mass, and the binary orbital period. The curves represent secondary masses of 1.0, 0.9, 0.7, and 0.5 $M_\odot$. The arrow indicates the range of typical sound velocities in a nova envelope at the binary separation, implying supersonic motion of the secondary through the CE for P = 1–5 hr.

Clearly, the questions of irradiation of the outer layers of the secondary its associated effects become important at this stage. However, this problem is beyond the scope of the present work.

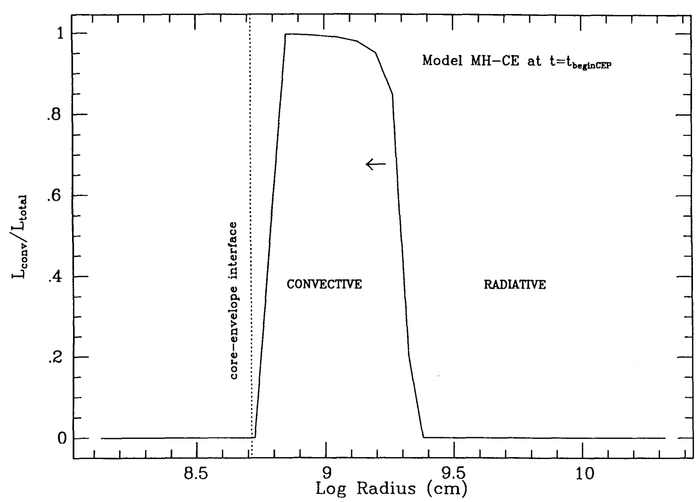

FIG. 2.—The ratio of convective to total luminosity in a representative fast novae envelope at the onset of the CE phase. Note the envelope is primarily radiative.

Numerical studies of gas flow past gravitating objects (e.g., Tamm & Fryxell 1988; Shima et al. 1985) have shown that most of the energy dissipation occurs within an interaction region centered at the secondary. Neglecting the density gradients over the secondary accretion radius, the location of energy deposition is therefore assumed to be (i) along the bow shock, which forms ahead of the secondary, and (ii) in the wake of the secondary. Note that both (i) and (ii) are contained within a single secondary's accretion radius. The effect of density gradients over the accretion radius can potentially change the characteristics of the above picture, as suggested by Fryxell & Taam (1988). While this can introduce an inaccuracy by a factor of a few in the calculated drag luminosity, we feel that in the present, exploratory one-dimensional calculation, larger uncertainties associated within nonspherical effects make the inclusion of such a factor unnecessary.

Two- and three-dimensional calculations of supersonic flows past gravitating objects have shown that the dissipation rate is adequately described by the standard Bondi-Hoyle formalism (e.g., Shima et al. 1985; Livio et al. 1986). The drag luminosity is given by

$$L_d = \eta \xi(\mathscr{M}) \pi R_{\rm acc}^2 \rho v_{\rm rel}^3 , \quad (2)$$

where R_A is the secondary's accretion radius, and ρ is the density in the interaction zone. $v_{\rm rel}$ is the relative velocity of the secondary in the CE, given by

$$v_{\rm rel} = \sqrt{(v_{\rm out}^2 + v_{\rm orb}^2)} . \quad (3)$$

where $v_{\rm out}$ and $v_{\rm orb}$ represent the outflow and the orbital velocities respectively. η in equation (2) is an efficiency factor and $\xi(\mathscr{M})$ is a Mach number–dependent drag coefficient (Shima et al. 1985). The accretion radius can be written as

$$R_A = \frac{2GM_2}{v_{\rm rel}^2 + c_s^2} , \quad (4)$$

where M_2 is the mass of the secondary and c_s is the sound velocity in the envelope in the vicinity of the secondary. This expression describes adequately the numerical results of Mach numbers larger than or of the order of unity (Shima et al. 1985).

The efficiency factor η in equation (2) is introduced to simulate the effects of rotation (which cannot be treated in our one-dimensional calculations), which decreases the relative velocity $v_{\rm rel}$, and thus L_d.

Figures 3 and 4 illustrate the density and the expansion velocity profiles in a representative fast nova ($M_1 = 1.0\ M_\odot$, $M_2 = 0.5\ M_\odot$, $Z_{\rm env} = 0.30$, $\dot{M} = 10^{-9}\ M_\odot\ {\rm yr}^{-1}$) envelope at the onset of the CE phase. It should be noted that the expansion velocity is substantially lower in the interaction region than that for the early, high-velocity ejecta. The dependence of the drag luminosity on envelope parameters is shown in Figure 5 (assuming $\eta = 1$, see discussion of a lower value of η in § 3.3). For a typical nova binary system ($M_1 = 1.0\ M_\odot$, $M_2 = 0.5\ M_\odot$, $v_{\rm orb} \approx 400$ km s^{-1}, $P = 5$ hr) it shows L_d (calculated using equation [2]) as a function of the density in the interaction region and the outflow velocity. It is clear that the density in the vicinity of the secondary plays an important role in determining the magnitude of the rate of drag energy deposition. In order to obtain the density in the interaction region and the structure of the envelope following the nova explosion, it is necessary to perform a full hydrodynamic calculation.

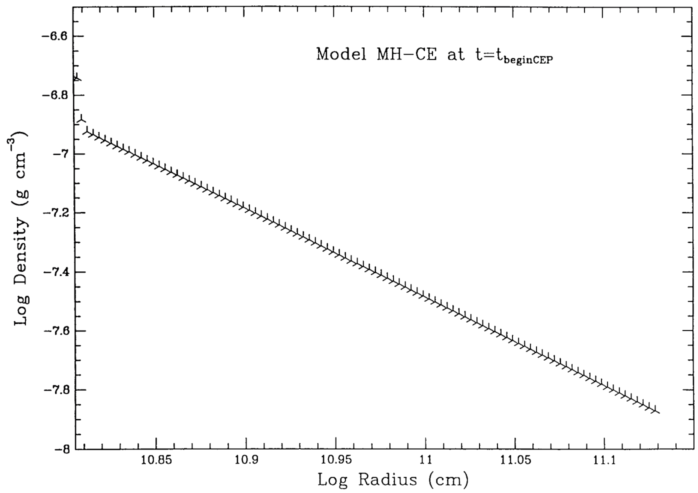

FIG. 3.—The density profile of the CE in the vicinity of the interaction region in a representative fast nova envelope at the onset of the CE phase.

2.4. *Evolution of the Binary Separation*

There are three factors which conspire together to determine the orbital evolution of a nova binary: (1) systematic loss of orbital angular momentum via the action of magnetic braking and/or gravitational radiation; (2) a separation increase which occurs due to mass loss during nova outbursts (assuming that the mass carries the specific angular momentum of the white dwarf); and (3) a separation decrease which is due to frictional angular momentum loss during the CE phase. In a recent work, Livio, Govarie, & Ritter (1991) have demonstrated that as a result of factors (2) and (3) the orbital period of short period systems decreases, while it increases for systems with $P \gtrsim 8$ hr. In general, the period change due to nova outbursts (factors [2] and [3] combined) was found to be a significant fraction of that obtained from the secular evolution ([1] above). The calculations of Livio et al. (1991) demonstrate the importance of understanding the details of the interaction of

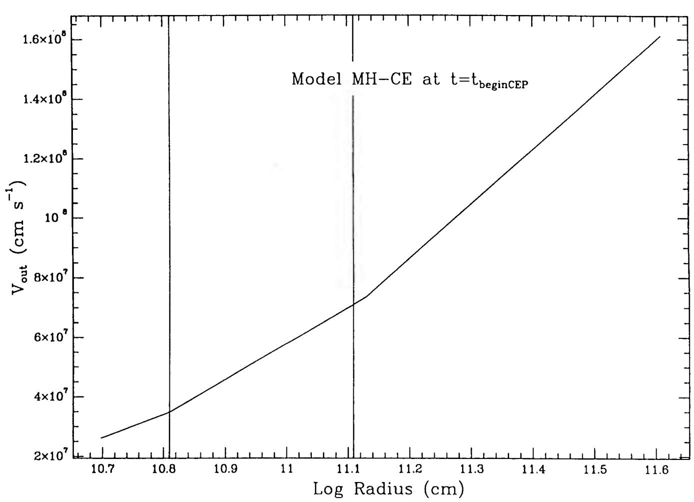

FIG. 4.—The outflow velocity profile in a representative fast nova envelope at the onset of the CE phase. The interaction region is bounded by the two vertical lines. Note that the average outflow velocity over the interaction region is much lower than that for the shell ejected by the early, burst mass loss.

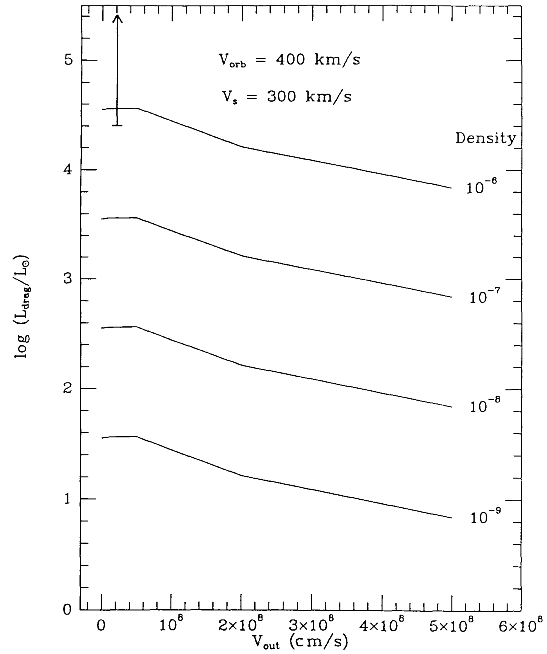

FIG. 5.—The drag luminosity (given by eq. [2]) as a function of the outflow velocity and the density in the interaction region for a typical nova binary ($M_1 = 1.0\ M_{\odot}$, $M_2 = 0.5\ M_{\odot}$, $P = 3.5$ hr). The arrow represents the range of typical plateau bolometric luminosities for CNs.

the secondary with the CE gas. This provides further motivation for the calculations presented in the present work.

3. THE NUMERICAL MODELS

3.1. *Method and Assumptions*

All of the calculations reported here were performed using the one-dimensional, Lagrangian hydrodynamic stellar evolution code described by Kutter & Sparks (1972), supplemented by the treatment of accretion as described by Starrfield, Sparks & Truran (1985). The code was modified to include drag energy deposition in the manner described by equation (2). The drag luminosity was calculated self-consistently at every time step and added spherically symmetrically to the energy sources in the zones included in the interaction region. The assumption of spherical symmetry represents certainly a limitation in light of the two-dimensional calculations by Livio et al. (1990), which show that local nonspherical effects are important. The deposition of the same amount of drag energy over a much larger volume in a spherically symmetric manner is expected to produce a weaker effect on the envelope hydrodynamics. We therefore consider the results of the one-dimensional calculations as representing a *lower limit* to the violence of mass motions caused by the CE mechanism.

In order both to ensure smoothness of the physical variables over the interaction region and to increase the accuracy, we calculated a very finely zoned envelope (5000 zones) model. Drag energy was then deposited in the manner described above and the model was evolved until prohibitively large computer time usage and small time steps caused us to terminate this calculation at the end of approximately 1 day of time evolution. Since the drag energy for this model was found to stay virtually constant in time (see Fig. 8), we continued the calculation at a lower resolution (95 zones) by simply adding the constant drag luminosity to the interaction zone (we ensured that the drag luminosity stays roughly constant over the envelope ejection time scale by performing another low resolution calculation). This procedure allowed us to avoid the numerical discontinuities associated with drag energy deposition in a crudely zoned model and to continue the calculation until essentially the entire envelope was lost. In addition, it made it possible for us to distinguish easily between the mass-loss characteristics of the models which were calculated with and without the CE effects.

3.2. *The Input Models*

We choose a 1.0 $M_{\odot}$ white dwarf accreting material rich in heavy elements ($Z_{CNO} = 0.25$) at a rate of $10^{-9}\ M_{\odot}\ yr^{-1}$ as the initial model for our study. The justification for this choice is provided by (1) the observational evidence for CNO enhancements in a number of nova systems (see Truran & Livo 1986) and (2) the fact that it represents a judicious compromise between the typically suggested white dwarf masses for nova systems due to observational selection effects (Politano et al. 1990), and the mean field white dwarf mass.

3.3. *Results*

Parameters of the models and the results for five model calculations are presented in Table 1. Of the five, three include the drag energy deposition (models MH-CE, ML1-CE, and ML0.3-CE). The letter following the "M" indicates a high (H) or a low (L) resolution model, depending on whether it is a 5000 zone or a 95 zone model, respectively. The low resolution model sequences ML1-CE and ML0.3-CE represent calculations assuming deposition efficiences (η in eq. [1]) of 1 and 0.3, respectively. Models MH-NCE and ML-NCE are calculations which do not include CE effects. They were computed for comparison with models that include the drag energy deposition. The main results of the model calculations can be described as follows:

1. The deposition of drag energy accelerates and enhances mass loss. One can already see this trend in Figure 6, which shows the results for the high-resolution model MH-CE at the end of $t = 1$ day. Counting the drag energy deposition causes the mass loss to be accelerated, resulting in rapid mass ejection

TABLE 1

CHARACTERISTICS OF ONE-DIMENSIONAL MODELS

Model	Z(CNO)	$t_{evolution}$ (days)	$M_{env}/M_{\odot}$	$M_{ej}/M_{\odot}$	v_{ej}^{max}	M_{ej}/M_{env}
MH-CE	0.25	~1	2.1×10^{-5}	8.8×10^{-7}	1600	0.042
MH-NCE	0.25	~1	2.1×10^{-5}	8.2×10^{-7}	1600	0.039
ML1-CE	0.25	~20	2.1×10^{-5}	2.0×10^{-5}	1600	0.952
ML0.3-CE	0.25	~20	2.1×10^{-5}	1.8×10^{-5}	1600	0.857
ML-NCE	0.25	~70	2.1×10^{-5}	1.2×10^{-5}	1600	0.571

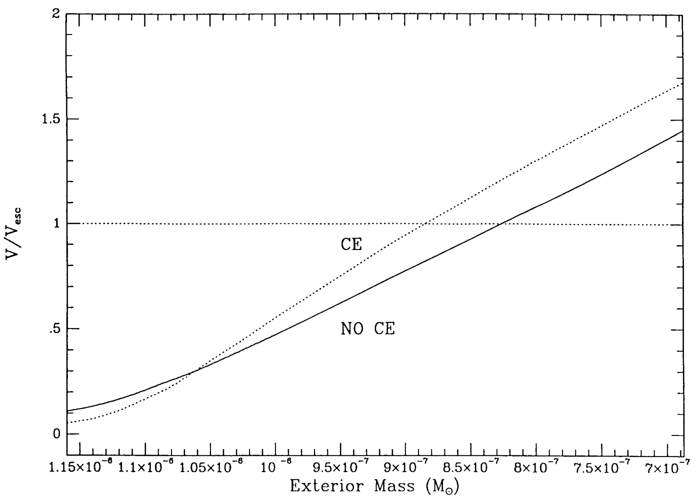

FIG. 6.—The velocity profiles obtained from models MH-CE and MH-NCE at the end of $t = 1$ day. The ejected mass, which is given by the intersection of the curves with the dotted line representing $V/V_{esc} = 1$, is larger for the model with drag energy deposition.

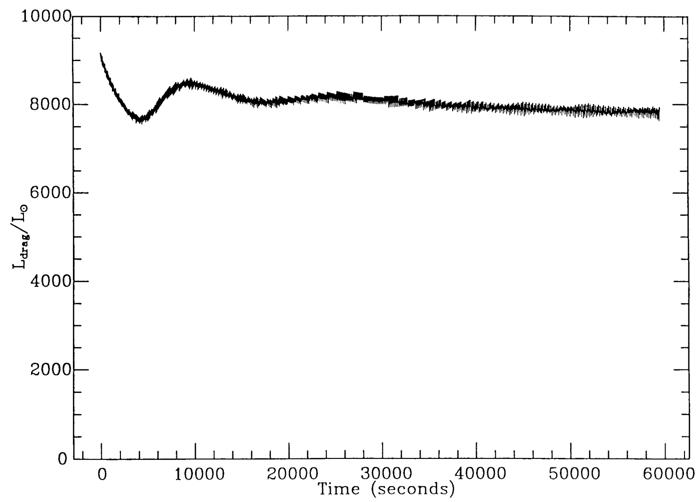

FIG. 8.—The time evolution of drag luminosity obtained from the high-resolution model MH-CE.

from the envelope in roughly 20 days (see Fig. 7). This time scale is in agreement with estimates by MacDonald (1980), who obtained an ejection time scale of roughly 30 days. Note that at the end of the calculation ($t = 20$ days), the model with drag energy deposition (ML1-CE) ejected 1.8×10^{-6} $M_\odot$, whereas the model without it (ML-NCE) ejected a *total* of roughly 1.2×10^{-6} $M_\odot$. The deposition of drag energy caused the ejection of essentially the entire envelope in 20 days. The implied CE phase induced average mass loss rate in model ML1-CE is 3.65×10^{-4} $M_\odot$ yr^{-1}.

2. The drag luminosity attains a nearly constant value of 8000 $L_\odot$ during the first day of evolution (Fig. 8) and is confirmed to stay near this value over the envelope ejection time scale (20 days). Note that MacDonald (1980) also found the drag luminosity to attain a nearly constant value in his models. The density in the interaction zone modulates the drag luminosity as can be seen from Figures 8 and 9. This is due to the fact that both the relative velocity and the secondary's accretion radius approach nearly constant values (see Figs. 10 and 11). Detailed nova calculations show that for models which produce relatively slow novae (when no enhancement of heavy elements is assumed), the density in the vicinity of the secondary stays roughly constant for at least 10^6 s (see Livio et al. 1990, 1991), after which it starts to decline. The reason for the decline is that matter in the interaction region is lost more rapidly due to drag energy deposition than it can be replenished by the slow outflow in regions with $r < a$. For models that produce fast novae (such as the ones presented here), the density at the orbital separation achieves a constant value since a strong outflow continues to supply matter to the interaction region. It is clear, therefore, that the outcome of a CE phase depends strongly on the speed class of the nova.

It should be noted that the Mach number stays constant at a value of approximately 2 (Fig. 12). In addition, the magnitude of the drag luminosity is found to be dependent on the nova speed class. L_{drag} achieves higher values for faster novae as a consequence of larger density in the interaction region (see eq. [2]). A stronger outflow can replenish the matter which is lost

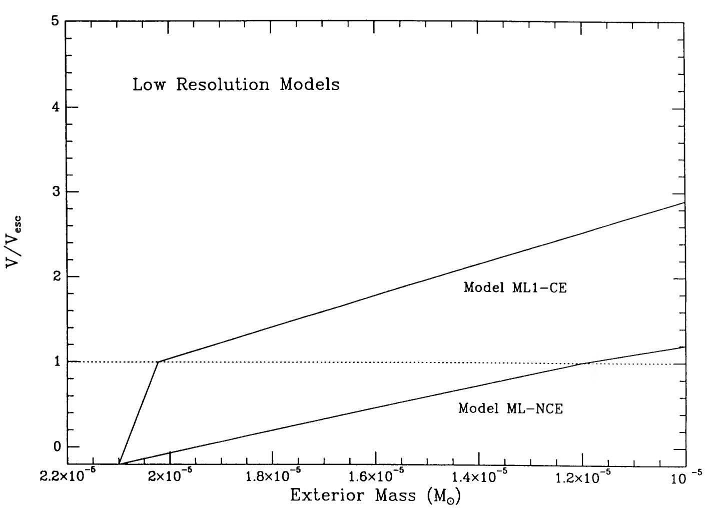

FIG. 7.—The velocity profiles obtained from models ML1-CE at $t \approx 20$ days and ML-NCE at $t \approx 70$ days. Model ML1-CE has ejected nearly all its envelope mass (2.1×10^{-5} $M_\odot$), whereas model ML-NCE ejects a total of 1.2×10^{-5} $M_\odot$.

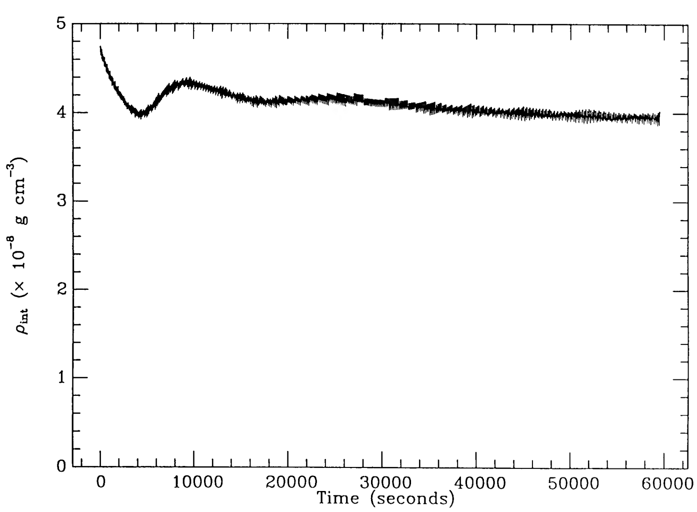

FIG. 9.—The time evolution of the average density in the interaction zone for the high-resolution model MH-CE.

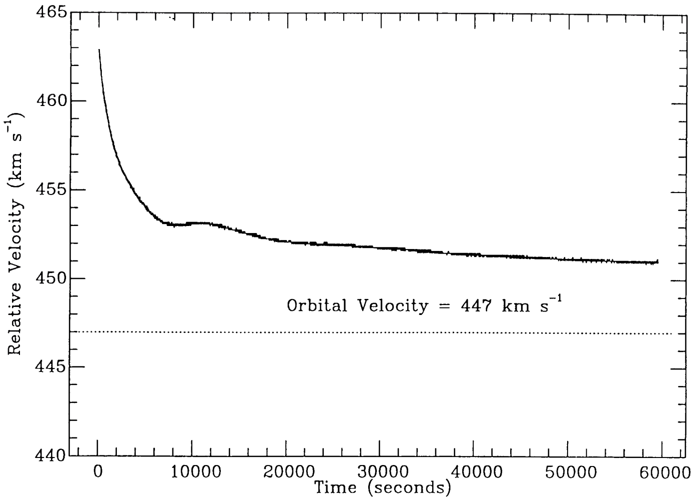

FIG. 10.—The time evolution of the relative velocity of the secondary with respect to the CE for the high-resolution model MH-CE.

from the interaction region more efficiently, thereby preventing the density from dropping to values it assumes for a weaker outflow in the case of slow/very slow novae. This behavior was confirmed both by one-dimensional test calculations for slow novae and by two-dimensional calculations of the CE phase for a very slow nova (Livio et al. 1990).

3. The maximum velocity of ejection for models with and without the drag energy deposition is nearly the same (1600 km s^{-1}). This is due to the fact that it represents the velocity of the shell ejected by energy deposition in the envelope by the positron decays, which is the same in the two models. Ejection continues at lower velocities as a result of the drag energy deposition following this initial burst ejection. The velocity profile for models ML1-CE and ML-NCE are shown in Figure 7. Recall that the present calculation is one-dimensional. The two-dimensional calculations of Livio et al. (1990) have shown that material is ejected preferentially in the orbital plane. The deposition of the drag energy in a much smaller amount of mass could result in higher ejection velocities than the ones described in the spherically symmetric case. Indeed a

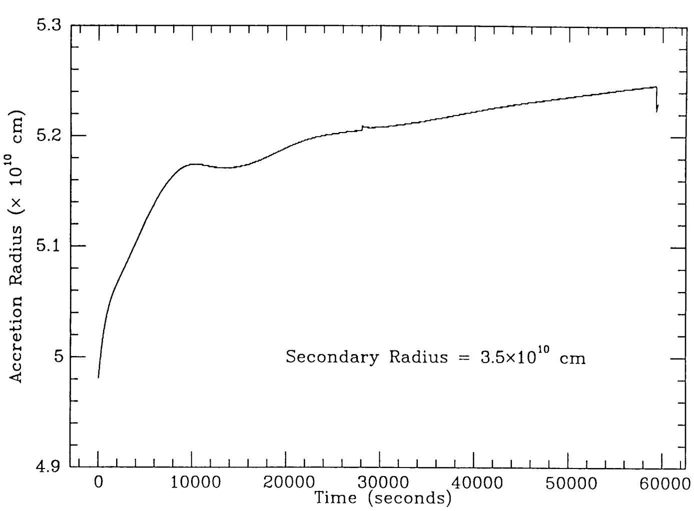

FIG. 11.—The time evolution of the secondary's accretion radius for the high-resolution model MH-CE.

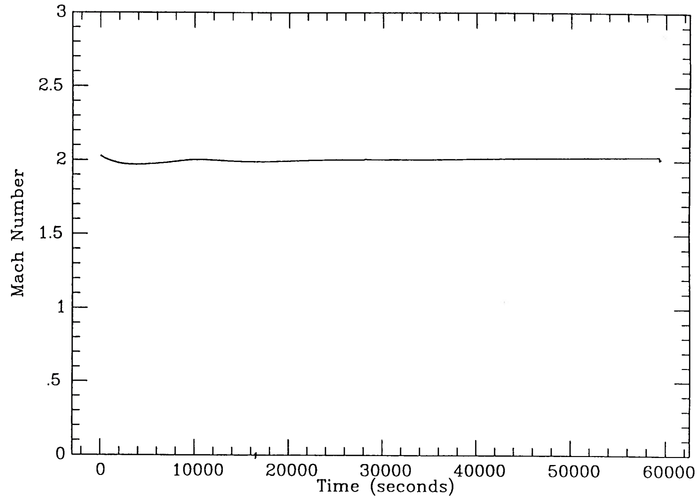

FIG. 12.—The time evolution of the Mach number of the secondary's motion through the CE for the high resolution model MH-CE.

maximum velocity of 1976 km s^{-1} was obtained in the calculation of Livio (1990), for an envelope which was assumed to be initially at rest.

4. The results for model ML0.3-CE indicate that even at reduced deposition efficiencies (that can be expected from rapid rotation of the envelope in the vicinity of the secondary), the CE mechanism can accelerate mass loss considerably.

The main result described in (1) above does not agree with that of MacDonald (1980). It is, however, difficult to compare the two studies directly, since the work by MacDonald investigates the effect of a CE phase on an initially weak thermonuclear runaway (TNR) which would otherwise result in a slow nova, whereas we have attempted to simulate the effects of a CE phase on an initially strong TNR (and therefore a fast nova). The dependence of the results on the nova speed class can be quite significant, a point to which we allude to in (2) above.

4. DISCUSSION

The three studied mechanisms capable of inducing mass loss during a nova outburst are (1) burst ejection associated with the early and extremely dynamic evolution in response to the TNR; (2) radiatively driven winds; and (3) an efficient CE phase. Among these, burst ejection is generally recognized as being responsible for expelling up to perhaps one-half the envelope mass, for fast novae. The energetics of the hot CNO cycle (see Truran 1982) shows clearly that enhanced envelope CNO abundances can liberate enough energy to match the envelope binding. However, such early mass ejection alone cannot explain the rapid evolution for a system such as DQ Her, which shows significant CNO enhancements but is clearly a slow novae, perhaps due to its low white dwarf mass (Ritter 1990) and/or the presence of a magnetic field (see Livio, Shankar, & Truran 1988). Table 2 lists the time scale for the loss of the accreted envelope by nuclear burning and by radiatively driven winds for a number of white dwarf masses. The wind mass-loss time scale estimates are based on the implicit assumption that the stellar wind formulation by Abbott (1982) for early-type stars adequately represents the situation in the case of novae. It appears at first sight that radiation driven winds may indeed be capable of ejecting the remnant envelope

TABLE 2

ENVELOPE DEPLETION TIME SCALES

$M_{WD}/M_{\odot}$	τ_{nuc}(yr)	τ_{wind}(yr)
0.8..........	1800	410
1.0..........	330	30
1.2..........	50	1.7
1.35.........	5.6	0.1

mass on a time scale of ~ 100 days (for massive white dwarfs). The applicability of the Abbott formula to the nova case is, however, questionable. In particular, comprehensive calculations by Kudritzki (1990) seem to indicate that the actual wind mass-loss rates may be a factor of 10 lower for novae, implying mass-loss time scales which are 10 times longer than those presented in Table 2 (see, however, also Kato 1983a, b). This would leave the CE interaction as the only studied mechanism which is potentially capable of inducing rapid mass loss for white dwarfs of mass below $\sim 1.2\ M_{\odot}$. The numerical calculations presented in the previous section seem clearly to substantiate this claim.

An efficient CE phase points to the possiblilty of obtaining high ejection velocities (as shown by the two-dimensional calculations by Livio et al. 1990) even in systems with no envelope CNO enhancement. While the composition of the envelope does affect somewhat the densities (and thus the drag energy deposition), in the envelope, the deposition of a large amount of energy into a relatively small mass (due to nonspherical effects) results almost inevitably in relatively high escape velocities. Note that the standard picture of CN evolution demands CNO enhancements in the envelope prior to the TNR in order to produce a violent outburst resulting in a fast nova (Starrfield et al. 1974). Unfortunately, mass and/or abundance determinations are available for only a handful of CN systems, which makes it difficult to identify potential candidates for a CE phase driven mass loss. Only one observed system, namely DK Lac, shows a low CNO enhancement ($Z = 0.06$; Collin-Souffrin 1977) but is identified as a fast nova due to its high ejection velocities (~ 1000 km s^{-1}) and rate of decline. DK Lac also shows a high He/H ratio (Collin-Souffrin 1977; Ferland 1979); however, this is not expected to increase the violence of the TNR. The CE phase can in principle provide a natural explanation for such seemingly anomalous systems.

The conventional picture of spectral evolution of CNs suggests that the photosphere first moves outward in radius, achieving its largest radius at visual maximum. This is followed by a retreat of the photosphere to essentially the white dwarf dimensions as outer envelope layers become increasingly tenuous in response to rapid expansion. Photoionization by the resulting blackbody, with temperatures $\sim 10^5$ K, is thought to explain the nebular phase. However, a number of studies (Ferland, Lambert, & Woodman 1986, 1977; Shields & Ferland 1978), which used the data on V1500 Cyg (Nova Cygni 1975) to investigate the possible origin of the coronal line region (characterized by gas at $T \sim 10^6$ K), suggest that the usual 10^5 K blackbody is unable to explain both the continuum observations and the existence of ions such as [Fe x]. These studies also indicate that the origin of a hot gas may lie in the regions of the ejecta shocked by random supersonic motions within the ejecta. Extensive or coronal lines in the case of very slow nova HR Del 1967 (Andrillat & Hauziaux 1971) 3 yr after the outburst imply that the shocking mechanism may be independent of speed class. We speculate that these features make the interaction between the secondary and the CE an attractive mechanism to explain the origin of the hot coronal region in novae. It is natural to expect multiple shock structures in the interaction region due to the complex interaction between the outflow and the secondary's motion through it. Clearly, such a possibility deserves attention and further study.

5. CONCLUSIONS

The following conclusions can be drawn, based on the work presented in this paper:

1. All classical novae undergo a common envelope phase following the thermonuclear runaway.
2. The drag experienced by the secondary, as it moves through the common envelope, deposits energy in the expanding nova envelope at a rapid enough rate to induce significant hydrodynamic mass motions. The energy deposition can (at least in the case of a relatively dense envelope) eject the bulk of the envelope on a time scale of less than 100 days. This agrees well with both X-ray observations and emergence of a nebular phase for a number of classical nova systems.
3. Mass loss rates as high as $10^{-4}\ M_{\odot}$ yr^{-1} can be obtained as a result of additional energy deposition by the common envelope interaction.
4. The common envelope phase lasts at least through to the transition to nebular phase (which can be as short as 100 days for some novae).
5. An efficient common envelope phase may explain observed high ejection velocities in classical nova systems which show little or no CNO enhancement.

The authors would like to thank Larry Smarr and the National Center for Supercomputing Applications at the University of Illinois, where all of the numerical calculations were performed. A. S. would like to express his gratitude to Lisa Ensman, Dimitri Mihalas, and Andi Burkert for many fruitful discussions. This work has been supported in part by the NSF grant AST 86-11500 and AST 89-17442 at the University of Illinois and by the Foundation for the Promotion of Research at the Technion.

REFERENCES

Abbott, D. C. 1982, ApJ, 259, 282
Andrillat, Y., & Hauziaux, L. 1971, Ap&SS, 13, 100
Bodenheimer, P., & Taam, R. E. 1984, ApJ, 280, 771
Collin-Souffrin, S. 1977, in Novae and Related Stars, ed. M. Friedjung (Dordrecht: Reidel), p. 123
Ferland, G. J. 1979, ApJ, 231, 781
Ferland, G. J., Lambert, D. L., & Woodman, J. H. 1977, ApJ, 213, 132
———. 1986, ApJS, 60, 375
Fryxell, B. A., & Taam, R. E. 1988, ApJ, 335, 862
Iben, I., & Tutukov, A. V. 1984, ApJS, 54, 335
Kato, M. 1983a, PASJ, 35, 33
———. 1983b, PASJ, 35, 507
Kudritzki, R. 1990, private communication
Kutter, G. S., & Sparks, W. M. 1972, ApJ, 175, 407
Livio, M., Govarie, A., & Ritter, H. 1991, A&A, in press
Livio, M., Shankar, A., Burkert, A., & Truran, J. W. 1990, ApJ, 356, 250
Livio, M., Shankar, A., & Truran, J. W. 1988, ApJ, 330, 264
Livio, M., & Soker, N. 1988, ApJ, 329, 764
Livio, M., Soker, N., deKool, M., & Savonje, G. J. 1986, MNRAS, 222, 235
MacDonald, J. 1980, MNRAS, 191, 933
———. 1986, ApJ, 305, 281
MacDonald, J., Fujimoto, M. Y., & Truran, J. W. 1985, ApJ, 294, 263
Marsh, T. R., Wade, R. A., & Oke, J. B. 1983, MNRAS, 208, 33P
Meyer, F., & Meyer-Hofmeister, E. 1979, ApJ, 78, 167

Ögelmann, H., Krautter, J., & Beurmann, K. 1987, A&A, 177, 110
Paczyński, B. 1976, in IAU Symposium 73, Structure and Evolution of Close Binary Systems, ed. P. P. Eggleton, S. Mitton, & J. Whelan (Dordrecht: Reidel), p. 75
Payne-Gaposchkin, C. 1957, The Galactic Novae (Amsterdam: North-Holland)
Politano, M., Livio, M., Truran, J. W., & Webbink, R. F. 1990, in IAU Colloquium 122, The Physics of Classical Novae, ed. A. Cassatella (Berlin: Springer), in press
Prialnik, D., Shara, M. M., & Shaviv, G. 1978, A&A, 62, 339
Ritter, H. 1984, A&AS, 57, 385
Shields, G., & Ferland, G. J. 1978, ApJ, 225, 950
Shima, E., Matsuda, T., Takeda, H., & Dawada, K. 1985, MNRAS, 217, 367
Starrfield, S., Sparks, W. M., & Truran, J. W. 1974, ApJS, 28, 247
———. 1985, ApJ, 291, 136
Starrfield, S., Truran, J. W., & Sparks, W. M. 1978, ApJ, 226, 186
Taam, R. E., & Bodenheimer, P. 1989, ApJ, 337, 849
———. 1991, ApJ, 373, 246
Taam, R. E., Bodenheimer, P., & Ostriker, J. P. 1978, ApJ, 222, 269
Taam, R. E., & Fryxell, B. A. 1988, ApJ, 327, L73
Truran, J. W. 1982, in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Clayton, & D. N. Schramm (Cambridge: Cambridge University Press), p. 467
Truran, J. W., & Livio, M. 1986, ApJ, 308, 721
Truran, J. W., Shankar, A., & Livio, M. 1991, in preparation
Webbink, R. F. 1988, in Critical Observations versus Physics Models for Close Binary Systems, ed. K.-C. Leung (New York: Gordon & Breach), p. 403
Williams, R. E. 1990, in IAU Colloquium 122, The Physics of Classical Novae, ed. A. Cassatella (Berlin: Springer), in press