THE ASTROPHYSICAL JOURNAL, 212:533–540, 1977 March 1

ON THE ORIGIN OF CENTAURUS X-3 AND RELATED BINARY X-RAY SOURCES

BRIAN P. FLANNERY* AND ROGER K. ULRICH*†
Institute for Advanced Study
Received 1976 April 2; revised 1976 August 26

ABSTRACT

Numerical calculations following the evolution of both components of a possible progenitor system (15 $M_\odot$, 5 $M_\odot$, 8.53 days) for Cen X-3 have been carried into the first phase of rapid mass exchange in case B. The calculations indicate that the secondary quickly expands, forcing the system into contact in the manner first demonstrated by Benson. Shortly after contact, our calculations terminated when the system entered a phase of extremely rapid mass loss through the outer Lagrangian point L_2.

For a variety of initial conditions, restricted three-body calculations show that the ejected gas escapes the system entirely (its terminal velocity is ~ 200 km s^{-1}), and carries off specific angular momentum $\sim 2\omega D^2$ which, initially, is 10 times the average specific angular momentum. The rapid decrease in separation induced by the loss of angular momentum accelerates the mass loss enormously. We are unable to follow this phase numerically, but the result is likely to be an enormous loss of mass and decrease in period, probably terminating when the primary is stripped of all mass above its helium core. A similar evolutionary phase in a lower-mass binary (4 $M_\odot$, 1 $M_\odot$, 2 days) could lead to the production of the short-period cataclysmic variable stars.

Subject headings: stars: binaries — stars: evolution — stars: mass loss — X-rays: sources

I. INTRODUCTION

The evolutionary sequence leading to the occurrence of X-ray binary systems is not yet understood. Earlier studies of binary evolution (as most recently reviewed by Paczynski 1971) generally have assumed that mass and orbital angular momentum are conserved, and they ignore the role of the secondary component. However, retracing the history of many X-ray binary systems—with Cen X-3 as a prime example—such systems certainly suffered a contact phase during which substantial mass loss may have occurred. When an evolving primary encounters its Roche lobe numerous studies show that mass transfer quickly is driven to a rate appropriate to the star's thermal time scale. In an important, but unfortunately still unpublished, study, Benson (1970) modeled the accretion process and clearly demonstrated that the secondary, with a thermal time scale far larger than the primary, is driven strongly out of thermal equilibrium by the mass exchange. In his system, containing a 5 $M_\odot$ and a 2 $M_\odot$ star with an initial period of 1.0 day, case A mass exchange ensued, but only 0.1 $M_\odot$ could be transferred before the rapidly expanding secondary filled its Roche lobe. A similar phase of rapid expansion was found by Ulrich and Burger (1976) for accretion onto a 5 $M_\odot$ model at a rate of 10^{-3} $M_\odot$ yr^{-1}. This nonequilibrium phase for the secondary suggests that many binary systems will be forced into a contact phase during mass exchange.

* Research sponsored by the NSF grant GP-40 768X.

† Work supported in part by the NSF through grants NSF-AST 75-19750 at UCLA and NSF MPS 71-02670 A05 and AST 75-01398 A01 at California Institute of Technology.

In a recent study of the origin of X-ray binaries de Loore and de Gréve (1975) did not find a phase of rapid expansion in the accreting component. The reason for the discrepancy between their results and those which we will report below seems to be their use of an average rate of mass transfer instead of the actual time-dependent transfer rate. The transfer rate during the interval preceding the reversal of the relative masses is much higher than the transfer rate during the final stages of the mass exchange. Ulrich and Burger (1976) have shown that the behavior of the accreting star depends sensitiviely on whether or not the transfer time is short compared to the thermal relaxation time of the accreting star's envelope. The transfer rate chosen by de Loore and de Gréve (1975) appears to have been just below the critical rate for producing rapid expansion in the secondary.

The question of the occurrence or nonoccurrence of a contact phase of evolution during mass transfer is critically important in understanding the origin of X-ray binary systems. We show below in § IV that for a variety of initial mass ratios, mass flow through the L_2 point results in matter being ejected from the system. This mass loss will influence the reconstruction of the initial properties of the system for the purpose of comparing the observed and expected galactic abundance and distribution. Our choice of the initial masses and separation for the system is based on a model proposed by van den Heuvel and Heise (1972) which neglected mass loss from the system. We show that this system comes into contact and loses mass through L_2. Thus conservative models like that of van den Heuvel and Heise (1972) are not self-consistent.

The particular system that we have chosen to study consists of 15 $M_\odot$ and 5 $M_\odot$ stars with an initial period of 8.53 days. This system undergoes case B mass transfer since the primary does not reach its Roche radius until after hydrogen exhaustion in a core of 3 $M_\odot$. We note parenthetically that case B mass exchange is most favorable for the formation of a binary system with a compact component because any hydrogen remaining in the core after case A mass transfer can ignite in a shell source and drive additional mass transfer. This requirement places a minimum value on the initial separation which is uncomfortably close to the presently observed separation. By simultaneously solving for the structure of both components, we have followed the evolution through the contact phase until a stage of very rapid loss of mass and angular momentum through the outer Lagrangian point L_2. Our basic assumptions and computational procedures are presented in § II, the results are described in § III, and discussed in § IV; conclusions follow in § V.

II. ASSUMPTIONS AND COMPUTATIONAL METHOD

Following earlier studies we assume that, if either star expands beyond a critical radius, then the mass outside this radius, which experiences an unbalanced pressure gradient along an equipotential, will flow away on a dynamic time scale. We evaluate the critical radius in the Roche approximation which assumes that (1) the gravitational potential is provided by point masses (2) in circular orbit, and (3) the stellar envelope rotates synchronously with the orbital period. The critical radius L_i of star i is calculated (Paczynsky 1971) as

$$L_i = D\left(0.38 + 0.2 \log \frac{M_i}{M_j}\right) \quad \text{for} \quad M_i/M_j > 0.523\,,$$

$$L_i = 0.46224 D\left(\frac{M_i}{M_i + M_j}\right)^{1/3} \quad \text{for} \quad M_i/M_j \le 0.523\,, \tag{1}$$

where M_i is the mass of star i and D is the binary separation. Given the orbital angular momentum J, the separation is

$$D = \frac{J^2(M_1 + M_2)}{G(M_1 M_2)^2}\,. \tag{2}$$

Throughout the calculation we have neglected the interaction of the rotational angular momenta of the components. At the onset of mass transfer the radii of gyration and ratio of rotational to total orbital angular momentum are (2.53 $R_\odot$, 0.008) and (0.473 $R_\odot$, 0.0008) for the primary and secondary, respectively.

If the system is in a semidetached or a contact phase, then mass transfer is calculated as a function of the radius excess ΔR of the component losing mass according to the following prescription. First the difference of Roche potential between the stellar surface and critical surface is approximated as

$$\Delta\Omega_i = 0 \qquad \text{for } R_i \le L_i$$
$$= -M_i\left(\frac{1}{R_i} - \frac{1}{L_i}\right) \quad \text{for } R_i > L_i\,. \tag{3}$$

Then the radius excess of the star losing mass is derived from the potential difference between the two components. Finally, the mass transfer rate as a function of radius excess is explicitly calculated for each model at the start of a time step according to the formula

$$\frac{dM(\Delta R)}{dt} = -2\pi \int_{R-\Delta R}^{R} r\rho c dr\,, \tag{4}$$

where r is the radius, R the surface radius, ρ the density and $c = \frac{5}{3}(P/\rho)^{1/2}$ is the sound speed. This formula may be in error by a factor of order 2 because the gas does not simply leave the critical surface at the sound speed for even the simplest cases. The mass transfer rate is sufficiently sensitivie to ΔR that the uncertainty in the actual value of the transfer rate is of no importance to our calculations. Figure 1 shows representative cases for the mass transfer function of the primary and secondary. With this prescription the mass transfer is zero when both components are inside their Roche lobes, and is a function of the potential difference between the star and the lobe or the star and its companion for a semidetached or contact system, respectively.

Accretion is treated in the simplest possible approximation. The matter added to the stellar surface has zero velocity and an entropy equal to the surface entropy. In the restricted three-body approximation, at the onset of mass exchange, the radius of the secondary, 0.29D, greatly exceeds the radius 0.06D at which the stream would achieve circular orbit

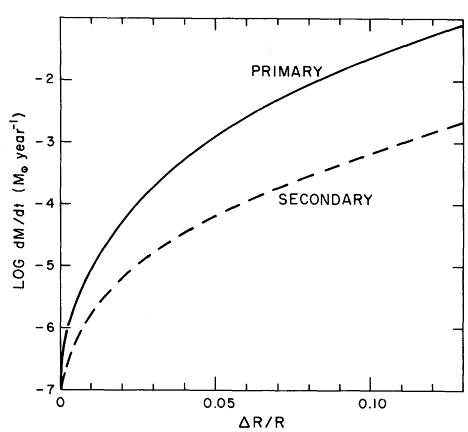

FIG. 1.—The mass transfer rate as a function of radius excess (see eq. [4]). The functions are shown for the primary at epoch C and the secondary at epoch E in Table 1.

(Flannery 1975), so the exchanged material clearly is directly accreted by the secondary. Based on the discussion by Ulrich and Burger (1976) we assume that the large kinetic energy per unit mass of the stream is radiated away in a high-temperature region of area much smaller than the total surface area. Our assumption of corotation at all times bypasses the effects of differential rotation which would exist. However, numerous studies (Faulkner, Roxburgh, and Strittmatter 1968) show that rotation, even at breakup velocity, has little influence on the star's structure unless the differential rotation increases inward, the inverse of the situation here.

With this formulation the normal spherical stellar structure equations for both components are simultaneously solved by a Henyey relaxation technique, but the normal surface boundary condition $M_i(t + \Delta t) = M_i(t)$ is replaced by

$$M_i(t + \Delta t) = M_i(t) + \frac{dM_i}{dt}\Delta t\,, \qquad (5)$$

where the dependence of dM_i on both M_1 and M_2 through L_i acts as a couple between the two stars. The calculations utilized the single-star stellar structure routine of Peter Eggleton as described in Eggleton (1971), Eggleton, Faulkner, and Flannery (1973), and Eggleton (1972). The ratio of mixing length to pressure scale height is taken as 1.5, and the composition is $(X, Z) = (0.70, 0.02)$. The initial model contained zero-age main-sequence stars of 15 $M_\odot$ and 5 $M_\odot$ which neglects the question of pre–main-sequence time scales and the process of close binary formation. Finally, rotational effects are ignored; the stars are treated as single and spherical.

A second set of calculations based on essentially the same assumptions was carried out with the code developed at the University of California at Los Angeles (UCLA) and used by Ulrich and Burger (1976). This code is based on a multisegment fitting procedure, and the time step could not be taken smaller than 50 years because of numerical instabilities. The calculations carried out with the UCLA code agree with the calculations reported here in most important respects up until the point where $\dot{M} > 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. Although the UCLA calculations will not be described in detail, the general agreement between the two sets of results give us confidence that the calculated behavior of the system is not dependent on the precise choice of model parameters, the numerical procedures, or minor variations in the way the mass transfer rate is calculated.

III. RESULTS

In this section we discuss the results of our evolutionary calculations which, for convenience, we separate into four phases: the pre–mass-transfer phase, semidetached phase, contact phase, and (somewhat speculatively) the rapid mass loss phase.

During the pre–mass-transfer phase, which lasts 1.12×10^7 years, the stars evolve independently. Very little happens to the secondary: its core hydrogen content only decreases from 0.700 to 0.672. However, the primary evolves through core hydrogen exhaustion and is undergoing core contraction with the associated rapid increase in radius when the Roche lobe is encountered. At zero age the convective core extends over 5.5 $M_\odot$, and hydrogen is exhausted inside 2.5 $M_\odot$ when mass transfer commences. This phase is in accord with normal post–main-sequence evolution at this mass. The structure parameters for both stars are listed in Table 1 at several epochs, and the trajectories of the components in the H-R diagram are plotted in Figure 2. The rapid increase in radius of the primary is shown in Figure 3. Note that the primary's radius increases by only a factor of ~ 2 before hydrogen exhaustion.

The primary's behavior during the case B mass exchange phase is also in agreement with earlier studies. Prior to the mass transfer the ratio of primary mass to Kelvin-Helmholtz time scale is $2.5 \times 10^{-3}\ M_\odot\ \mathrm{year}^{-1}$. The rate of mass transfer (Fig. 4) shows an exponential increase which levels off at $1.8 \times 10^{-3}\ M_\odot\ \mathrm{year}^{-1}$ before contact is reached. As has been established for stars dominated by radiative envelopes in which entropy decreases with decreasing radius, the mass-losing star both contracts and absorbs thermal energy as material of lower entropy rises to the surface. As the transfer rate approaches the thermal rate, the stellar radius decreases in size following the shrinking critical radius (Fig. 5). In Figure 6 we plot the profile of luminosity versus radius for the primary, showing the integrated effects of the $T ds/dt$ thermal energy term. In the H-R diagram (Fig. 2) the primary is shown to fade and redden during mass exchange in the semidetached phase.

The behavior of the accreting secondary is far more interesting. In contrast to the primary, here material of higher than equilibrium entropy is adiabatically buried beneath the surface, liberating large amounts of thermal energy (Fig. 6). The secondary ascends the main sequence (Fig. 2), reaching a luminosity of log

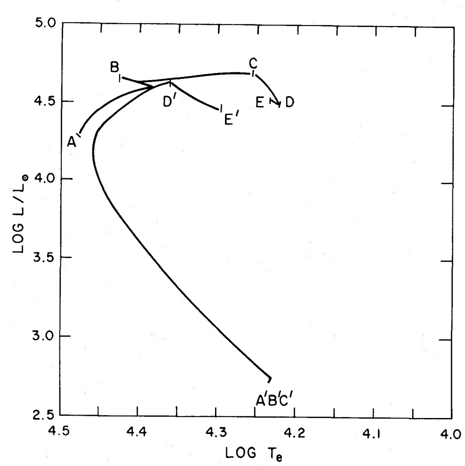

FIG. 2.—Evolution in the Hertzsprung-Russell diagram. Lettered tick marks refer to the epochs listed in Table 1; exchange of mass commences at C, C′, contact at D, D″.

TABLE 1

MODEL PARAMETERS

EPOCH	AGE	PRIMARY $M/M_\odot$	PRIMARY log $(L/L_\odot)$	PRIMARY log T_e	PRIMARY R_{11}†	PRIMARY R/L	SECONDARY $M/M_\odot$	SECONDARY log $(L/L_\odot)$	SECONDARY log T_e	SECONDARY R_{11}†	SECONDARY R/L	LOG (dM_2/dt)	REMARKS
A.......	0	15.000	4.272	4.477	3.56	0.226	5.000	2.728	4.232	1.86	0.192	...	Maximum
B.......	1.1199(7)	15.000	4.653	4.429	6.87	0.435	5.000	2.740	4.320	1.90	0.197	...	primary contraction
C.......	1.1225(7)	15.000	4.679	4.255	15.78	1.000	5.000	2.740	4.230	1.90	0.196	−6.91	Mass exchange
D......	+1103*	14.661	4.492	4.220	14.94	1.048	5.339	4.623	4.362	9.07	1.000	−2.76	Contact
E.......	+1459*	14.366	4.526	4.227	15.10	1.148	5.634	4.466	4.295	10.26	1.188	−3.16	L_2

* Age since start of mass exchange.

† Radius in units of 10^{11} cm.

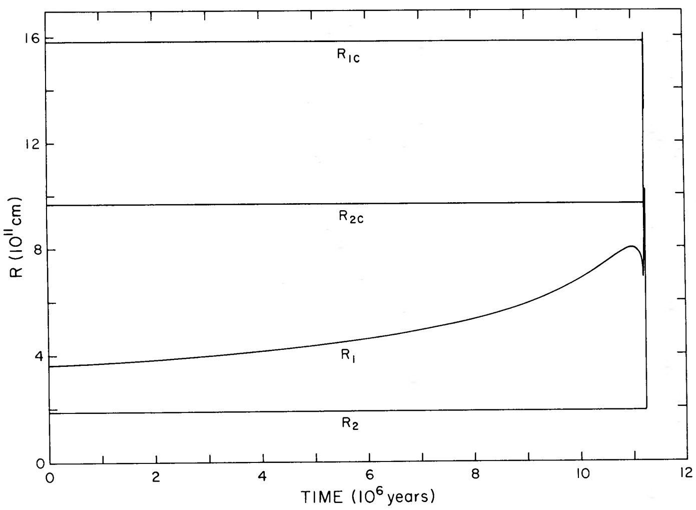

FIG. 3.—Radius versus time. R_1, R_{1c} (R_2, R_{2c}) are the stellar radius and critical radius of the primary (secondary).

$L/L_\odot \sim 4.12$ (i.e., brightens by a factor of 23) after only accepting 0.14 $M_\odot$. At this point the radius begins to increase exponentially (Fig. 5) until the Roche radius is filled after a total accumulation of only 0.34 $M_\odot$. The secondary is overluminous for its mass by a factor of 80 at this point. The phase of mass exchange prior to contact lasts only 1100 years, or 10^{-4} of the previously elapsed evolution.

Once contact is established, we assume that the stars remain physically distinct—unlike the case for the W UMa stars where a large energy exchange exists in the common convective envelope (Lucy 1968)—but the mass transfer now depends on the potential difference between the two stellar surfaces. Both stars are in stages of expansion: the primary as a result of its still contracting core (which hardly reresponds to the mass loss), the secondary as a result of accretion. Although the conical point at L_1 is now filled with gas, free flow onto the secondary continues because the primary simply expands higher into the potential. The expansion of the secondary (Fig. 5) slows the mass transfer rate noticeably (Fig. 4), and allows the primary to brighten (Fig. 2). The secondary continues to accrete, although at a lower rate. The radius expansion is slowed (Fig. 5), and its luminosity decreases (Fig. 2). Nonetheless, both mass exchange and expansion of the secondary persist through the contact phase so that after only an additional 350 years the secondary fills its outer Roche lobe. In the case of corotation, which we have assumed, L_2 is a physically meaningful point for mass loss from the

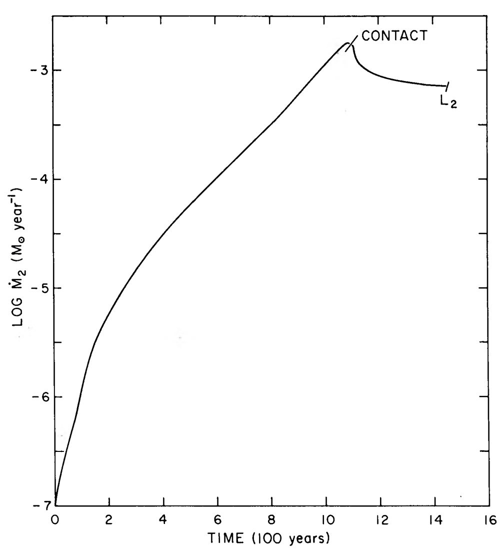

FIG. 4.—The rate of mass exchange onto the secondary versus time. The exchange commened after 11.225 million years.

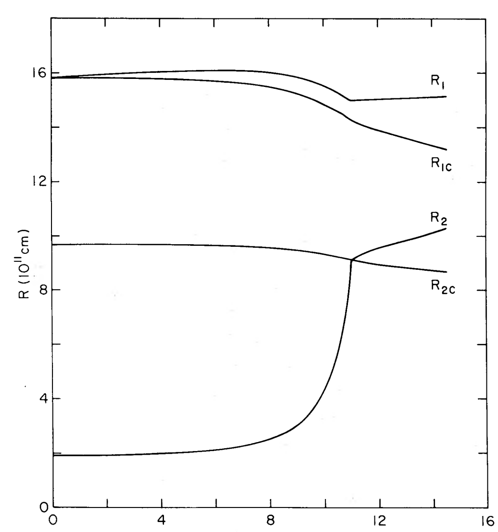

FIG. 5.—Radius versus time after the commencement of mass-exchange. Notation as in Fig. 3.

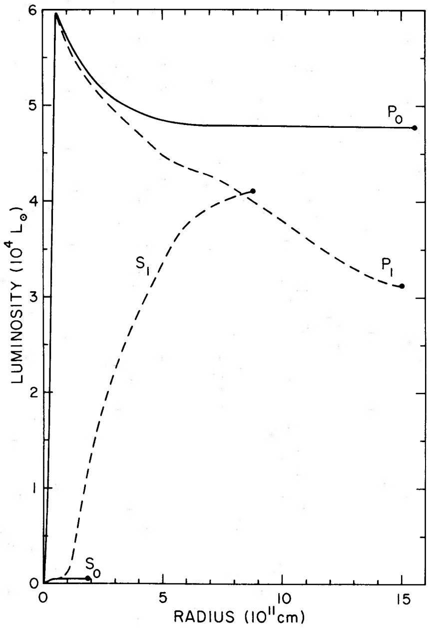

FIG. 6.—Luminosity versus radius. P and S denote the primary and secondary. Subscript zero labels correspond to epoch C of Table 1 (the onset of mass-exchange); subscript 1 labels refer to epoch D (just prior to contact when $\dot{M}_2 = 1.8 \times 10^{-3} M_\odot$ year^{-1}).

system. Corotating gas at L_2 will be driven away by pressure gradients.

An (unsuccessful) attempt was made to follow the evolution beyond the L_2 overflow stage using a simple prescription for the loss of mass and angular momentum, while continuing to assume corotation. Note that without corotation the critical radii and potentials cannot be consistently determined. From the potential difference between the stellar surface and L_2 a radius excess was determined and the mass transfer rate followed analogously with the method described in § II to determine the rate of mass exchange. We assumed that the gas carried away an angular momentum per unit mass of

$$j = \omega L_2^2 , \quad (6)$$

where ω is the circular orbital frequency. Under these assumptions, an instability for mass loss through L_2 exists.

A small amount of mass loss carries away a disproportionate share of angular momentum which forces the separation to decrease according to equation (2). The secondary then exceeds the critical radius by an even greater amount which results in a higher rate of mass loss. We found that after only a few hundred years the time scale for angular momentum loss was reduced to the order of years and was continuing to decrease. At this point numerical problems became overwhelming, but certainly our assumption of corotation could no longer be valid under these conditions. This runaway mass loss arises because the stellar radii cannot shrink rapidly enough to match the rapidly decreasing critical radii. In fact (see below), the angular momentum loss is far greater than was used here, so the difficulty is even more severe.

IV. DISCUSSION

The most important result of our calculations is a confirmation and extension of Benson's (1970) conclusion that close binary systems exchanging mass go through a contact phase of evolution. Our system was wider than the system studied by Benson ($D = 50\ R_\odot$ in our study versus $D = 8\ R_\odot$ in Benson's). In spite of the additional volume for expansion of the secondary, the contact system formed after less than $1\ M_\odot$ had been transferred. It appears that only rather wide systems are likely to avoid the contact phase of mass transfer. The probability of forming a contact system is enhanced for moderate separations because these systems begin mass transfer during a phase of rapid envelope expansion following the end of the main-sequence evolution (Kippenhahn's case B). The envelope expansion is only temporarily slowed by the loss of matter through the inner Lagrangian point. The cause for the envelope expansion, core contraction, is completely unaffected by the envelope mass loss.

The rate of mass loss is set by the thermal time scale for the envelope of the primary. But when the mass exchange begins, the secondary's thermal time scale, 10^5 years, is about 200 times longer than that of the primary. Contact appears unavoidable if our basic assumptions are not violated. In a wide enough system, matter might not be directly accreted; rather the gas might first form a ring which would transform into a disk through the action of viscosity. Even then most disk models suggest that the gas will arrive at the stellar surface in a time short compared to the star's structural response times. While convenient from a computational standpoint, our assumption that the accreted matter arrives with the same entropy as gas already at the surface could be in error. The luminosity distribution in the secondary just prior to contact gives the following luminosity as a function of mass in parentheses: $4.2 \times 10^4 L_\odot$ ($5.34\ M_\odot$), $9 \times 10^3 L_\odot$ ($5.0\ M_\odot$), $5.9 \times 10^2 L_\odot$ ($3.30\ M_\odot$), while the secondary's luminosity prior to mass exchange was $550\ L_\odot$ ($5\ M_\odot$). So the flux of energy through the initial mass of the secondary has increased by a factor of 3.5, but the total flux has increased by a factor 80. The bulk of the energy arises from compression of the accreted gas, and the energy release depends predominantly on the entropy of this accreted gas. A variation in the prescription for specifying the entropy of the accreted gas can be expected to alter the course of the evolution.

Our calculations have shown that the formation of a contact system does not diminish the tendency for the primary to expand. Very shortly after contact, the expansion of the primary drives matter to a point where it can be ejected from the system. According to our assumption of corotation, the matter leaves from the L_2 point. For the system we have studied, the angular momentum per unit mass of this matter, j, is initially 1.58 times the specific orbital angular momentum $j_0 = J/(M_1 + M_2)$. The calculations reported above removed only this amount of angular momentum with the matter lost from the system, and found that the mass loss process grows in an unstable fashion. Using a restricted three-body code provided to us by M. Plavec, we find that the torque exerted on the ejected matter brings j to $1.82\omega D^2$ ($\sim 10 j_0$) for matter leaving from the L_2 point with an initial velocity on the order of the thermal velocity. As long as the initial position of the matter was exterior to L_2 by $0.03D$ or more, the trajectory was independent of variations of the initial velocity comparable to the thermal velocity. The mass loss rate indicated by our calculations requires the radius of the secondary to exceed the second critical radius by at least this amount. Thus angular momentum is lost from the orbital motion at a rate which exceeds that which we used in our calculations, and the mass loss process is more unstable than we found. Furthermore, the terminal velocity of the ejected matter was 180 to 220 km s^{-1} for all trajectories initiated as described above. Consequently, there is no tendency to form a long-lived gaseous envelope around the system.

The assumption that the secondary corotates with the system is unlikely to be valid during a phase of evolution as rapid as we have found. The degree of nonsynchronous rotation, at least near the surface of the secondary, is limited by the fact that the two stars share a common envelope. The primary and secondary have expanded and are probably rotating less rapidly than the system. The velocity difference between the common outer envelope and the core of the primary is unlikely to exceed the sound velocity at the level where the envelope and core are in contact. For our system these considerations suggest that the velocity relative to the corotating coordinates at the surface of the secondary is likely to be less than one-quarter of the orbital velocity.

Restricted three-body calculations were also carried out assuming that the secondary rotates nonsynchronously with rotation periods one-half and twice the orbital period. For the case of more rapid rotation a stream of matter was able to leave the system when the radius of the secondary was less than the critical radius. The value of j for the ejected matter was 1.9 ωD^2. For the case of less rapid rotation, matter could not leave the system until the radius of the secondary exceeded the critical radius by 20%. At this radius a stream from the trailing side of the secondary can be ejected from the system. In this case the value of j for the ejected matter was again $1.9\omega D^2$. Figure 7 shows trajectories for test particles with retrograde initial velocities relative to the rotating coordinates. Particles a and c are bound while particle b escapes. In both these cases as well as the corotating case, the stream of matter has a velocity in excess of the escape velocity when it reaches a large distance. The terminal velocity for the ejected matter is roughly 200 km s^{-1}.

In order to determine if the above restricted three-body results remain valid after some mass has been ejected, additional calculations were carried out for systems with a secondary mass of 5 $M_\odot$ and primary masses of 10 $M_\odot$ and 6 $M_\odot$. On both cases, matter continued to be ejected from the system with a high terminal velocity. The value of j was again in the range 1.8 to 1.95 times ωD^2 for all trajectories except one. The single exception was for the case 6 $M_\odot$ + 5 $M_\odot$ with synchronous rotation. For that trajectory j was $1.7\omega D^2$.

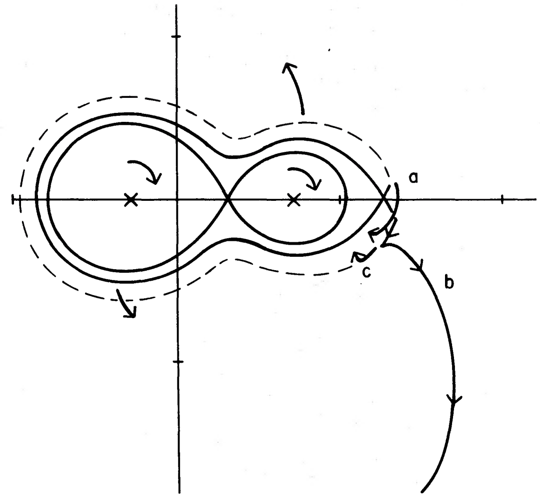

FIG. 7.—Geometry at the time mass loss from the system begins. The inner and outer solid lines show the L_1 and L_2 equipotential surfaces. The direction of rotation of the system is indicated by the arrows which are roughly normal to the L_2 surface. The arrows labeled a, b, and c represent particle trajectories. These trajectories were initiated assuming the secondary was rotating retrograde relative to the rotating coordinate system with an angular velocity equal to 0.25 times the system angular velocity. All particles experience a large torque from the system which tends to bring their velocities toward corotation. Particles a and c remain bound while particle b is ejected. The dashed line represents the approximate location of the system surface with the assumed degree of retrograde rotation.

On the basis of the above trajectory calculations the mass loss instability appears to be sustained. If we assume that most of the mass which is ejected originates from the primary and further assume that the value of j for the ejected matter is $1.9\omega D^2$, the change in D can be found from equation (2). For our system when the primary mass decreases only from 14.4 $M_\odot$ to about 13.5 $M_\odot$, the separation already decreases by a factor of 2.2.

Although no calculations are available, we suspect that this phase of rapid dissipation of the binary's mass and angular momentum would not be likely to be visible. The phase is probably very short lived, of the order of only 10 years. Also the binary will probably fade appreciably as the stellar masses decrease. Ultimately the primary will still be massive enough to ignite helium, so the system will still be bright enough to be seen; but during the rapid mass loss phase the system will be less bright than during the previous mass exchange phase and its lifetime will become two to three orders of magnitude shorter.

V. CONCLUSIONS

The fate of the system after mass loss begins is difficult to predict. It seems clear, however, that once begun, the process of mass loss must continue until some basic change in the structure of the system occurs. Furthermore, the changes take place so rapidly—on the order of hundreds of orbital periods—that no additional mass can be accepted by the secondary. Thus it appears as though relatively close binary systems go through a phase of mass loss instead of mass transfer. The mass loss phase can be terminated either by loss of nearly the entire hydrogen-rich envelope from the primary or by loss of enough mass that the mass ratio is reversed and the critical radius begins to increase. The loss of angular momentum during this phase will bring the two stars very close together.

The interpretation of the origin of the massive X-ray binaries is clouded by our results. The origin for Cen X-3 suggested by van den Heuvel and Heise (1972) is not compatible with our calculations. They proposed an initial configuration much like ours, although closer, but did not include any mass and angular momentum loss during the contact phase. If we assume that a contact phase of evolution did not occur, then the deduction of the initial conditions of the Cen X-3 system presented by van den Heuvel and Heise is valid. Since we then find that contact occurs, we must conclude that Cen X-3 passed through a phase of evolution when angular momentum was lost. Presumably this angular momentum loss occurred during the contact phase discussed here. Similar considerations apply to the related systems Cyg X-1, SMC X-1, and Vela X-1. The problem is then to find initial conditions which permit contact to occur and yield an appropriate final system. We cannot draw any definite conclusions about the appropriate initial conditions without further calculations.

This mechanism should also be applicable in lower mass double stars, say a 4 $M_{\odot}$ star plus a 1 $M_{\odot}$ companion. In the lower mass case the end product would resemble the cataclysmic variable stars containing two solar mass components, one a white dwarf the other a red dwarf. The incubation of the white dwarf would then have occurred in the core of the 4 $M_{\odot}$ star which later has its envelope entirely dissipated and at the same time reduces the orbital period.

This work was performed largely at the Institute for Advanced Study under the support of NSF grant GP-40768X. One of us (R. K. U.) wishes to thank Mr. Steven Drake for his assistance with the calculations at UCLA. The restricted three-body calculations were carried out at the California Institute of Technology.

REFERENCES

Benson, R. S. 1970, Ph.D. thesis, University of California, Berkeley.
de Loore, C., and de Gréve, J. P. 1975, *Ap. Space Sci.*, **35**, 241.
Eggleton, P. P. 1971, *M.N.R.A.S.*, **151**, 351.
———. 1972, *M.N.R.A.S.*, **156**, 361.
Eggleton, P. P., Faulkner, J., and Flannery, B. P. 1973, *Astr. Ap.*, **23**, 325.
Faulkner, J., Roxburgh, I. W., and Strittmatter, P. A. 1968, *Ap. J.*, **151**, 203.
Flannery, B. P. 1975, *M.N.R.A.S.*, **170**, 325.
Lucy, L. B. 1968, *Ap. J.*, **151**, 1123.
Paczynski, B. 1971, *Ann. Rev. Astr. Ap.*, **9**, 183.
Ulrich, R. K., and Burger, H. L. 1976, *Ap. J.*, **206**, 509.
van den Heuvel, E. P. J., and Heise, J. 1972, *Nature Phys. Sci.*, **239**, 67.

Brian P. Flannery: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Roger K. Ulrich: Astronomy Department, University of California, Los Angeles, CA 90024