ALGOLS AS LIMITS ON BINARY EVOLUTION SCENARIOS

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ABSTRACT. Evolutionary scenarios must account for Algol binaries surviving their first phase of mass transfer. The outcome of this phase is dependent upon the rapidity of the initial mass transfer, which can be estimated by calculating the radial reponse of potential progenitors to mass loss. Limits on the donor's evolutionary state, and its companion mass, can be placed on systems which would transfer mass on a thermal or dynamical timescale. Slower mass transfer rates are necessary for the successful transition to an Algol. Considering 1.5 and 5.0 $M_\odot$ models, the former succeed in case A and Br systems, while the latter can do so only in case A systems. To evolve into an Algol binary, all systems seem to require initial mass ratios near one.

1. INTRODUCTION

The formation of Algol binaries has been a classic problem for stellar evolution. Consisting of a lower mass giant and a higher mass main-sequence star, the reversed evolutionary state has been explained by the transferral of mass from the evolved giant to the main-sequence star (cf. Paczynski 1971). However, numerical investigations, conducted with the most realistic assumptions, have failed to produce a bona fide Algol. Three difficulties have been encountered in evolutionary calculations: the very large range of initial masses and periods to cover; the response of the mass-gaining star; and the role of non-conservative mass transfer. The first can be addressed with simplifying assumptions which generalize the use of single star models. This approach ignores the second difficulty, but it does provide an estimate of the timescale of mass transfer, which is relevant to the gainer's response. At present, the third difficulty can only be addressed through free parameters.

The mass transfer rate in a binary system depends on the difference between the donor star's photospheric radius and its Roche lobe radius (cf. Webbink 1985). Once R_* equals R_L, the "stability" of continued mass transfer depends on the changes in these radii, as characterized by the radius-mass exponent: $\zeta \equiv d\ln R/d\ln M$. If $\zeta_* < \zeta_L$,

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$R_* - R_L$ increases as more mass is removed, causing the mass transfer to accelerate. There are two time-independent methods of estimating ζ_*. If mass loss is very rapid, internal heat flow is negligible and the donor's radial response will be adiabatic ($\zeta_* = \zeta_{ad}$). If mass loss is somewhat slower, the response will be different as the donor adjusts to its new mass by regaining its previous state of thermal equilibrium ($\zeta_* = \zeta_{th}$).

With the values of ζ_{ad} and ζ_{th} for stars just filling their Roche lobes, the future evolution of the binary can be projected. If $\zeta_{ad} < \zeta_L$, dynamical timescale mass transfer will commence. Such rapid mass transfer is thought to result in the formation of a common envelope (Paczynski 1976; see Livio 1988) from which an Algol could not emerge. If $\zeta_{th} < \zeta_L < \zeta_{ad}$, thermal timescale mass transfer will commence. This not-quite-so-rapid mass transfer could result in a swelling accretor and a contact configuration (Benson 1970, and many others) from which it is unlikely that an Algol could emerge. Evidently, Algol binaries originate from systems in which both ζ_{ad} and ζ_{th} are greater than ζ_L.

These results can be used to direct simultaneous-evolution calculations towards the initial masses and periods most likely to follow diverging paths of evolution. In Section 2, the radial response calculations are discussed. In Section 3, the calculations are related to binaries which could not become Algols, creating boundaries for Algol progenitors. The results are also compared with the properties of observed Algols. The implications of the results for evolutionary scenarios are discussed in Section 4. The conclusions are summarized in Section 5.

2. RADIAL RESPONSE OF DETAILED STELLAR MODELS

The radius-mass relations being calculated are special cases of a star's response to mass loss. Previous estimates of ζ_{ad} have been made with polytropic models (Hjellming and Webbink 1987, and references therein). To estimate ζ_{th}, stellar models in complete equilibrium have been used for main-sequence and giant donors (Plavec, Kriz, and Horn 1969; Refsdal and Weigert 1970). The methods used for the calculations presented here are improvements on both approaches and are described below.

The adiabatic response of a model is driven by the preservation of hydrostatic equilibrium. When mass is removed from the surface, each remaining mass shell feels a decrease in pressure and expands somewhat. The adiabatic assumption, of entropy kept fixed in mass, limits how the density and temperature can vary to provide the pressure decrease. The behavior of the surface radius depends upon the expansion allowed by the entropy profile and the original position of the new surface layer. Models with radiative envelopes are more likely to contract: They have lower interior entropies and have further to expand to reach the old surface radius than models with convective envelopes.

The thermal response of a model is determined by the replacement of the energy losses caused by adiabatic expansion. During thermal

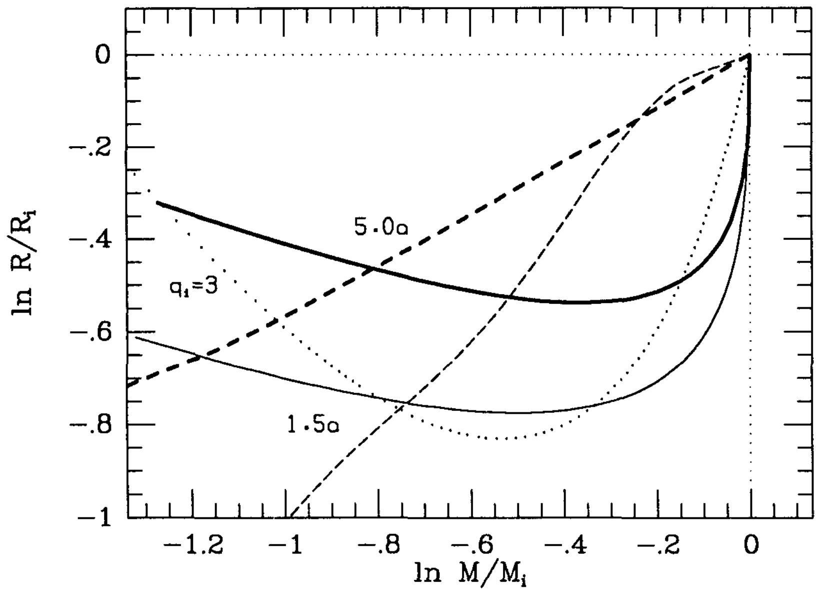

Figure 1. ZAMS response curves (solid=adiabatic, dashed=thermal) for two different masses. A q_i=3 Roche lobe curve (heavy dotted line) is included to illustrate that both models, in such a binary, will begin mass transfer on a thermal timescale, until $R_L < R_{ad}$ when a delayed transition to dynamical timescale mass transfer occurs.

mass	age	log R	log L	log T	m_{core}	m_{env}	$\zeta_{ad,0}$	$\zeta_{th,0}$
1.5a	0.0000	0.1321	0.7716	3.8901	0.1481	0.0000	> 40	0.40
1.5b	1.6075	0.3478	0.8979	3.8139	0.0801	0.0000	> 40	0.47
1.5c	1.2932	0.5118	0.9074	3.7343	0.0000	0.1344	0.92	1.18
1.5d	1.9646	0.5677	0.9209	3.7096	0.0000	0.7152	0.00	0.25
5.0a	0.0000	0.4199	2.7567	4.2425	1.0749	0.0000	> 80	0.60
5.0b	7.1767	0.6806	2.9850	4.1692	0.4262	0.0000	> 80	−0.20
5.0c	7.5799	0.7790	3.1166	4.1529	0.0000	0.0000	> 80	−1.00
5.0d	7.7068	1.5554	2.8146	3.6892	0.0000	0.1329	0.40	−0.05
5.0e	7.7108	1.6493	2.8981	3.6632	0.0000	1.4006	0.15	0.00

Table 1. Model data for response curves (X=0.70, Z=0.02). The values are in solar units; the ages are in 10^9 and 10^7 years for the 1.5 and 5.0 $M_\odot$ respectively; columns 6 and 7 are the masses of the convective regions; columns 8 and 9 are the initial slopes of the adiabatic and thermal response curves.

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relaxation, heat flow corrects the luminosity deficit created by the expansion. The energy added to the outer layers, provided by internal restructuring, causes further pressure changes and radial adjustments. The ultimate result of the adjustments can be estimated by limiting the relaxation to the initial thermal energy generation rate profile. Further relaxation to complete thermal equilibrium is not appropriate because the donor's nuclear evolution keeps the star out of equilibrium regardless of mass loss.

To illustrate points of particular interest to the evolution of Algols, the adiabatic and thermal responses of 1.5 and 5.0 $M_\odot$ stars, at various points in their evolution, are presented here. The structural differences of these stars help to pinpoint the causes of differing responses. Parameters for all the initial models, used in Figures 1-3, are contained in Table 1.

Figure 1 contains the response curves of the zero-age models. Plotted are the changing radii as a function of the decreasing mass. The values of ζ_{ad} and ζ_{th} are merely the slopes of the curves. The initial contraction of the adiabatic curves is due to the radiative envelopes with positive entropy gradients. The eventual re-expansion is caused by the exposure of the convective cores which are isentropic. The expansion occurs earlier for the 5.0 $M_\odot$ model because of its larger convective core mass. The thermal curves for these uniform-composition models are identical to the main-sequence mass-radius relation.

The adiabatic responses of the evolved models change greatly from those of the zero-age models, as shown by the solid lines in Figures 2 and 3. In the Hertszprung gap, nuclear burning creates a positive entropy gradient outside the core, inducing rapid contraction when the majority of the envelope has been removed. At the base of the giant branch, a growing convective envelope reduces the entropy gradient in the envelope to zero, allowing the surface to expand. The change in the initial adiabatic response is primarily dependent on the fraction of the total mass contained in the convective envelope (see Figure 4). A significant decrease in $\zeta_{ad,0}$ occurs when $m_{ce}/M_i \sim 0.05\text{-}0.10$, but note that it does not reach the conventional value of $-1/3$, due to the low entropy helium core.

The thermal responses of the evolved models show marked differences from each other, as shown by the dashed lines in Figures 2 and 3. The 5.0 $M_\odot$ models tend to expand before the end of the main sequence, with the maximum expansion ($\zeta_{th} < -1$) occuring in models positioned in the Hertzsprung gap. While a model's core mass is less than the Schönberg-Chandrasekhar mass of its now smaller mass, ζ_{th} remains approximately equal to its zero-age main-sequence value. When this is not the case, the model is forced to expand, $\zeta_{th} < 0$, as if it were crossing the Hertzsprung gap. The higher mass models undergo more expansion due to the greater distance between their terminal-age main-sequence and giant branch locations in the Hertzsprung-Russell diagram. At the giant branch, ζ_{th} returns to zero as the model's radius becomes dependent on its core mass, not its total mass (Refsdal and Weigert 1970).

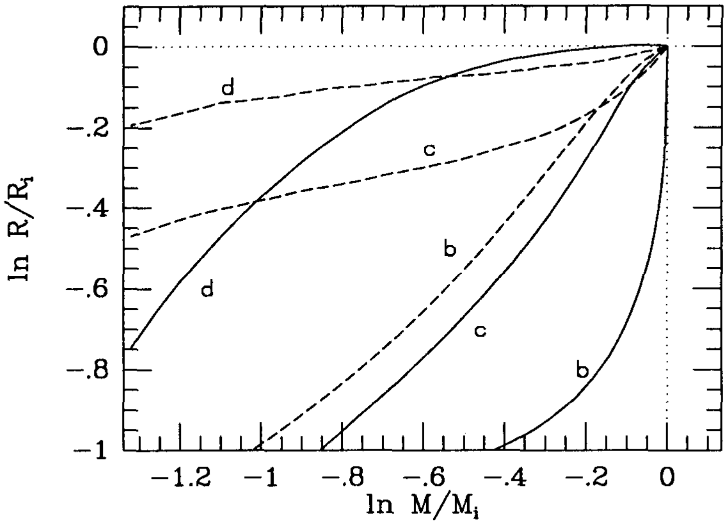

Figure 2. Three evolved 1.5 $M_\odot$ response curves (solid=adiabatic, dashed=thermal). The initial thermal responses are similar, while the adiabatic responses change with the growth of a convective envelope. See Table 1 for the particular model information.

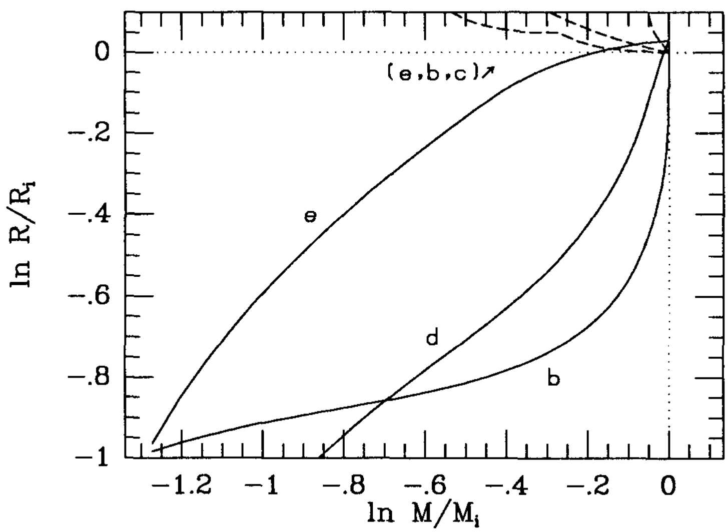

Figure 3. Three evolved 5.0 $M_\odot$ response curves (solid=adiabatic, dashed=thermal). The thermal responses are quite different from the 1.5 $M_\odot$ models, indicating more extreme thermal timescale mass transfer. Note the greater possibility for a delayed dynamical instability in the TAMS model (b).

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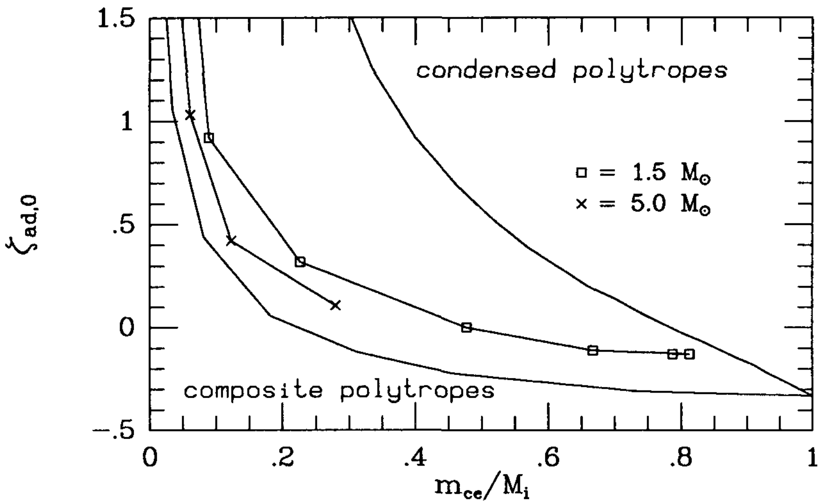

Figure 4. The transition of the initial adiabatic response from contraction ($\zeta_{ad} > 0$) to expansion. Polytropic models (Hjellming and Webbink 1987), approximating ZAMS and giant stars, are shown for comparison. Note the similarity between the responses of the two masses.

3. CRITICAL MASS RATIOS AND OBSERVED ALGOLS

To find potentially interesting behavior in binaries containing either of these masses, the adiabatic and thermal curves may be compared with Roche lobe curves. The presumption is that the star under consideration has just filled its Roche lobe and is beginning mass transfer. Under conservative assumptions, ζ_L is only a function of the initial mass ratio, $q_i \equiv$ donor mass/gainer mass. Critical mass ratios, q_c, are those q_i for which the Roche lobe curve has a tangent point with either response curve. So a binary with $q_i > q_c$ will, at some point, overfill its Roche lobe and undergo unstable mass transfer on the appropriate timescale. Non-conservative q_c can be found with an appropriate Roche lobe formula. Since angular momentum losses probably dominate, critical mass ratios, in such cases, are generally smaller.

A conservative Roche lobe curve, for a binary with q_i=3, has been included in Figure 1 to illustrate the criteria for unstable mass transfer. Both zero-age models have $\zeta_{th} < \zeta_L < \zeta_{ad}$, so mass transfer begins on a thermal timescale. Only for $q_i \sim 1$ is mass transferred from a zero-age donor on a longer-than-thermal timescale. Actual thermal relaxation, which causes the Roche lobe to remain filled as mass is transferred, occurs mostly in the envelope of the donor and not in the core. The interior responds adiabatically as mass transfer continues, producing a delayed transition to dynamical timescale mass transfer when $R_L < R_{ad}$. A delayed dynamical instability may lead to common envelope evolution, but unlike that associated with cataclysmic variables. The non-degenerate nature of the core does not allow rapid shrinking below the Roche lobe, so the donor is likely to be completely disrupted.

More evolved main-sequence donors are able to contract as their cores are exposed, so higher initial mass ratios are needed for the delayed instability to occur. The 5.0 $M_\odot$ models have larger, higher-entropy cores than the 1.5 $M_\odot$ models, so critical mass ratios for the former are smaller throughout the main-sequence. For both masses, the likelihood of a delayed instability decreases in the Hertzsprung gap as the entropy difference, between the core and the surface, increases. In any case, the possibility of its occurrence sets an upper limit on the initial mass ratio of main-sequence Algol progenitors.

As noted in Section 1, the initial phase of thermal timescale mass transfer itself may prevent the formation of Algols. The changes, from nuclear evolution, cause ζ_{th} to decrease from its zero-age value, exacerbating the problem. Since $q_{c(th)}$ becomes less than one, larger mass transfer rates may be expected from more evolved donors even if $q_i=1$. The greater expansion of the 5.0 $M_\odot$ thermal curves causes $R_{th} - R_L$, for a given q_i, to be larger than for a comparably evolved 1.5 $M_\odot$ donor. Thus, independent of the shorter relaxation time, a higher mass donor tends to have higher mass transfer rates. Higher mass donors, therefore, have a smaller range of initial periods from which Algols could evolve.

When the donor reaches the base of the giant branch, the criterion for initial dynamical stability becomes relevant, as ζ_{ad} changes rapidly with the growing convective envelope. The decrease of $q_{c(ad)}$ below one implies that any binary with a lobe-filling giant and $q_i \geq 1$ will form a common envelope. These systems do not become Algols either.

Does the distribution of current Algols reflect any of these results concerning their progenitors? Systems with spectroscopic mass ratios, taken from Giuricin, Mardirossian, and Mezzetti (1983), are plotted in Figure 5, although several were excluded for not being classical Algols. The periods and masses have been extrapolated back to q=1, assuming conservation of total mass and orbital angular momentum. Also shown, as solid lines, are the periods of lobe-filling components at the beginning and end of the main-sequence, as well as at the base of the giant branch. The latter serves as the boundary for dynamically unstable mass transfer, where $\zeta_{ad} = \zeta_L(q_i=1)$. The dashed line is the boundary for thermally unstable mass transfer, where $\zeta_{th} = \zeta_L(q_i=1)$.

A few remarks can be made about the positions of the systems in this diagram. At high masses ($M_1+M_2 \geq 4\ M_\odot$), none are near the dynamical stability boundary. The spread of systems above the thermal stability boundary can be explained by recalling that the thermal stability criterion is a lower limit, allowing relaxation in the core not just the envelope. At low masses ($M_1+M_2 < 4\ M_\odot$), the systems are bounded above by the dynamical stability boundary. The relative paucity of systems within the low-mass main sequence could be explained by their absence or rarity among initial binaries, as suggested by

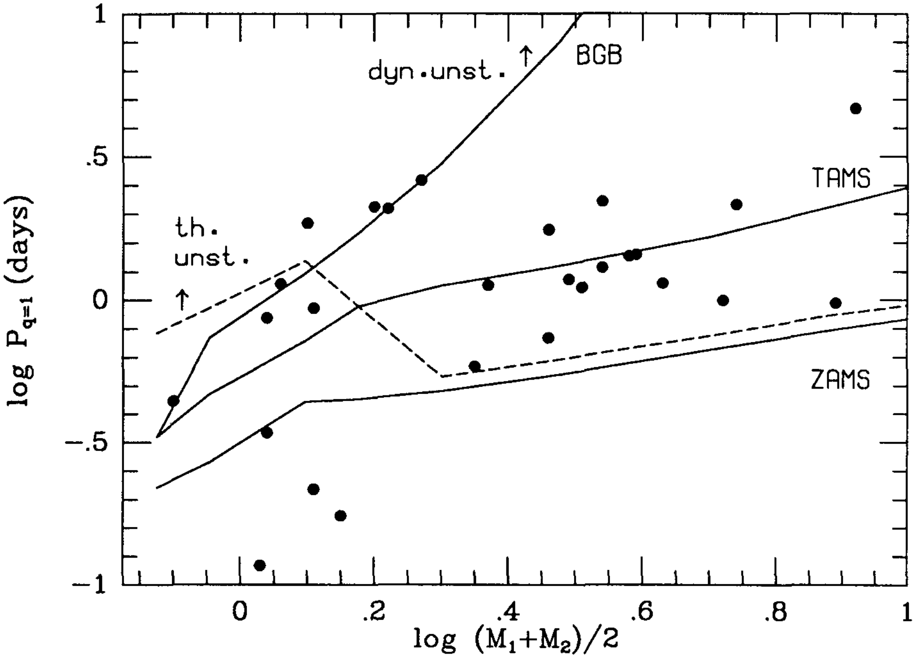

Figure 5. The distribution of Algol binaries returned to q=1 while conserving total mass and angular momentum. The solid lines mark the periods of lobe-filling models at three points in their evolution. The dashed line comes from thermal response calculations. The period ranges for unstable mass transfer are indicated.

Kraitcheva, et.al. (1978a,b). Several of the systems fall below the period for zero-age main-sequence contact systems; angular momentum losses appear to be the probable cause (Ziolkowski 1969; Refsdal, Roth, and Weigert 1974; Iben and Tutukov 1984).

4. DISCUSSION

Why should the initial mass ratios be near one? The lack of high-mass systems above the TAMS boundary can be explained by large differences between ζ_{th} and ζ_L, leading to mass transfer rates of 10^{-5} $M_\odot$/yr and contact configurations (Benson 1970). Near the TAMS boundary for these systems, ζ_{th} decreases below zero, which increases the difference with ζ_L for any initial mass ratio. The same effect is accomplished with higher mass ratios: $\zeta_L(q_i=2) = 2.6$, while $\zeta_L(q_i=1) = 0.46$. Smaller $\zeta_L - \zeta_{th}$ would allow more stable mass transfer and increase the probability of avoiding contact. Thus, a high-mass Algol progenitor must begin mass transfer before crossing very far into the Hertzsprung gap, and its mass rato must be close to one. In addition, de Greve

(1988) has pointed out that, in systems of nearly equal masses filling their Roche lobes near the zero-age main sequence, the gainer develops a larger convective core and evolves faster. The gainer fills its Roche lobe due to nuclear evolution, not thermal effects, and again, a contact configuration develops. This further limits the initial periods of massive Algol progenitors.

For low-mass progenitors, the thermal restrictions are not so severe. Larger values of ζ_{th} would allow stable mass transfer before the base of the giant branch. At the BGB boundary, ζ_{ad} decreases dramatically, and dynamical timescale mass transfer ensues for any system with $q_i>1$. Tout and Eggleton (1988) envision a scenario where the mass ratio can be decreased, by an enhanced stellar wind, to avoid this circumstance. This would increase the range of initial periods or the possible initial mass ratios which could produce Algols.

What will happen to the current Algols? Their current mass ratios doom the second mass transfer episode to a common envelope phase, since the majority of Algols have periods long enough for the main-sequence star to evolve to a giant before filling its Roche lobe. For those with periods not as long, continued mass transfer increases the mass difference, also causing the period to lengthen. If circumstances do not initially drive dynamical timescale mass transfer, the mass ratio will be so large as to force unstable thermal timescale mass transfer, possibly leading to delayed dynamical timescale mass transfer. The result will ultimately be a pair of white dwarfs (Webbink, 1979, 1984; Yungelson, Tutukov, and Fedorova 1988).

5. CONCLUSIONS

The results presented here are a small portion of the detailed stellar model calculations performed for my thesis. They have confirmed the initial dynamical stability of donor stars evolving across the Hertzsprung gap. A consequence of the thermal stability limit is that higher mass systems ($M_{d,i} > 1.5\ M_{\odot}$), with $q_i>1$ or periods long enough for overflow after the main-sequence, are unlikely to evolve into Algols. Lower mass systems ($M_{d,i} < 1.5\ M_{\odot}$) appear to be less susceptible to thermal timescale mass transfer. Instead, the dynamical stability limit, requiring Roche lobe overflow before the donor reaches the giant branch, restricts their initial periods and mass ratios. Neither suggestion is new, but these calculations provide a better framework for evaluating scenarios creating the whole variety of binary systems. More details of individual responses for more initial masses will be published in the future.

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DISCUSSION

Rucinski cited work by B. Paczynski and R. Sienkiewicz (Acta Astr. **22**, 73, 1972) which was based on a formalism similar to Hjellming's and asked how the results compared. Hjellming replied that their paper involved "condensed polytropes" which provided the upper line in his Figure 7. His detailed models tended to confirm the results of Paczynski and Sienkiewicz but a direct comparison is difficult because of the very large initial increase in radius caused by the superadiabatic region in giant stars.