GRAVITATIONAL RADIATION AND THE EVOLUTION OF LOW MASS BINARIES*

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Abstract. Gravitational radiation of energy and angular momentum can modify and in some cases, control the evolution of a close binary system. The region of interest is briefly delineated. Recent work of the author and colleagues of relevance to this area is discussed, including theoretical studies of accretion, mass loss and mass transfer, and an observational study of a system, HZ 29 where gravitational radiation may dictate its behaviour.

1. Introduction

It is not my intention to give a complete review of the subject under discussion. Several relevant aspects of this topic have appeared in the recently published proceedings of IAU Symposium No. 66. The reader may consult my article there (Faulkner, 1974) for more complete references, particularly in the context of the evolution of novae and nova-like systems. In the present paper I shall concentrate on discussing recent work by myself and a number of colleagues. Much of this work is either being written up or is already in press. The discussion which follows will therefore be in the form of brief summaries of those more complete papers.

The work we have been doing has been largely motivated by a desire to learn whether gravitational radiation can actually be of some definite astrophysical use. In this regard we are far more optimistic than Einstein and Eddington, both of whom studied the question of gravitational radiation losses from a system shortly after the general theory of relativity was published. Eddington, writing a few hundred yards from this room in 1922, noted that Einstein's general formula, when applied to a case he had himself explicitly evaluated, gave a result differing by a factor of two, but gracefully remarked (Eddington, 1923):

The discrepancy is due to a numerical slip in one or other investigation, and is not of much importance.

While subsequently making clear in whose work he felt the error lay, he nevertheless showed that he agreed with Einstein's conclusion that (my translation):

(The losses) are so small that in all conceivable cases, they will have a negligible practical effect.

Had they known that binary stars existed with periods of a few hours, the story might have been very different; for the energy loss rate depends upon the sixth power of the orbital frequency. Dwarf novae increase the importance of the effect relative to the cases Einstein and Eddington considered by factors exceeding 10^{10} – enough to make it interesting, competitive and perhaps even dominant in some situations.

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2. Some Standard Results

We recall some standard results, casting some in a slightly different form for reasons of emphasis.

2.1. KEPLER'S LAW

In conventional binary-star units (AU, $M_\odot$, yr), the separation D, mass M of system and period P satisfy:

$$D^3 = MP^2$$

Thus if $M \sim 1$ and $P \sim 10^{-3}$ (i.e. ~8h), then $D \sim 10^{-2}$ (i.e. $\sim 2R_\odot$). Obviously for system masses within a factor of 2 or so of $1\,M_\odot$, periods significantly less than ~8 h require separations less than $\sim 2\,R_\odot$. Such systems will be very close or even contact binaries.

2.2. GRAVITATIONAL RADIATION LOSSES

2.2.1. *Non-interacting stars*

The standard formula for orbital energy losses via gravitational radiation (e.g. Landau and Lifshitz, 1951) gives us:

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = \frac{-32}{5}\frac{G}{c^5}\left(\frac{M_1 M_2}{M_1 + M_2}\right)^2 D^4 \left(\frac{2\pi}{P}\right)^6 \tag{2}$$

For two non-interacting stars (i.e. stars treated as mass points), the orbital energy ϵ when divided by this expression gives an instantaneous estimate of the time-scale T for a significant change to occur. Earlier experience (Faulkner, 1971) leads us to express T in a manifestly correct dimensional form. However, the reader is warned that, in the analogous context of interacting stars, the particular form of T defined in Equation (4) of Faulkner (1971) contains an error. The quantity $M_\odot$ should be raised to the power -3 rather than the erroneous $+3$. If $M_1 \sim M_2$ we find

$$T = \epsilon / \left(\frac{\mathrm{d}\epsilon}{\mathrm{d}t}\right) \sim 10^{-5} P \left(\frac{Pc}{D}\right)^5 \tag{3}$$

The quantity D/c is the light-crossing time of the system's dimensions. In astronomical units $c \sim 6 \times 10^4$. If we now suppose $M_1 \sim M_2 \sim 1$ in our units and use Kepler again, we find

$$T \sim 3 \times 10^{18}\, P^{8/3} \tag{4}$$

The convenient period $P \sim 10^{-3}$ then yields

$$T \sim 3 \times 10^{10}\ \text{yr}. \tag{5}$$

We have worked throughout the above with T, an instantaneous estimate of the time scale. In fact direct integration in the case of non-interacting mass points (e.g. Landau and Lifshitz, 1951) leads to coalescence after a time of 0.25 T. Thus for periods significantly less than ~8 h, we are dealing with systems in which the gravitational radiation time-scale will be significantly less than 10^{10} yr. Gravitational radiation will then be at least competitive with nuclear timescales and may even become dominant. Furthermore, the inevitable shrinkage of a system of non-interacting stars means that formation of an interacting and therefore potentially different kind of system will occur.

2.2.2. *Interacting stars*

Kraft (1966) suggested that mass transfer would be initiated as a decreasing Roche lobe encroached upon one component (hereafter referred to as the secondary). We now realise that this leads to a qualitatively and significantly different kind of ultimate evolution. The inexorable drain of energy (or, alternatively, of angular momentum) from the system can now be satisfied in part by mass transfer between components rather than by changes in the separation alone. This has been examined in several contexts (e.g. Paczynski, 1967; Faulkner, 1971; Faulkner *et al.*, 1972). The timescale T is still largely appropriate, but the precise behaviour depends upon the slopes of the log R-log M relationships for the secondary star (n) and the Roche lobe as a geometrical entity (a) in addition to the mass fraction ($\mu = M_2/(M_1 + M_2)$) present in the secondary. Even under the restrictive but usually employed assumptions (total mass conserved, no other angular momentum losses, etc.) the separation and period may decrease or increase, depending on $n \gtrless a$; formally, the system's lifetime can be infinite (for example if $n < 7/12$ as $\mu \to 0$). The rate of mass transfer is largely determined by the value of M/R for the secondary. Since the latter expression is approximately constant for the lower main sequence, mass transfer rates have a canonical value of order $\sim 1-2 \times 10^{-10} M_\odot$ yr^{-1}, for low mass main sequence secondaries. For more compact systems, the transfer rates may be greater (e.g. $\sim 10^{-9} M_\odot$ yr^{-1} for HZ 29; Faulkner *et al.*, 1972).

3. Canonical Accretion Rates and Dwarf Nova Outburst Mechanisms

Having produced a canonical rate of mass transfer, and in the expectation that this mass will be accreted by a compact companion, we ask the following questions. Is an accretion rate of $10^{-10} M_\odot \text{yr}^{-1}$ astrophysically useful? Does it do something for us which at least some other rates will not? Taam and I have recently shown (Taam and Faulkner, 1975) that such a rate of accretion will initiate a thermonuclear runaway in the envelope of a $1 M_\odot$ white dwarf. In earlier studies Giannone and Weigert (1967), using rates of 10^{-9} and $10^{-11} M_\odot \text{yr}^{-1}$ on to a $0.5 M_\odot$ white dwarf, found that the former rate initiated a runaway, the latter not. Starrfield (private communication) feels there is really no distinction to be drawn between these cases however, as work he has done with Sparks and Strittmatter shows that ultimately pycnonuclear reactions will initiate similar runaways even for the slowest accretion rates. One cannot therefore really answer the questions posed earlier. Furthermore, even though thermonuclear runaways may develop following accretion at the canonical rate,the timescales for build up are far too long to meet dwarf nova requirements. One expects this would still be true for any ultimate, essentially cyclic, situation if such exists (the above studies being of initial runaways).

These difficulties, coupled with several observational indications that dwarf nova outbursts do indeed originate in the general vicinity of the white dwarf, have led some authors to suggest accretion disk outbursts as an explanation in one form or another, e.g. as a consequence of intrinsic disk instabilities (Osaki, 1974) or of enhanced flow through the disk following an envelope instability in the companion (Bath *et al.*, 1974). Since many of the participants in this symposium are eagerly jumping on this bandwagon, I would like to utter a few words of caution and pessimism.

It seems to me that the analysis of Bath *et al.* (1974), applied consistently to Warner's observations, essentially rules out the very mechanism they claim it supports. Warner's extremely important observations of Z Cha (Warner, 1974) show that the 'hump' characteristic of the hot spot was certainly not enhanced, and possibly even absent during the first two periods he was able to observe (1973, Jan. 8) following outburst (1973, Jan. 2). During the first observed period of 9 January it was present at a substantial enhancement (by a factor ~4.5), while one period ($\sim 1^h 47^m$) later it was more modestly enhanced (by ~3). Bath *et al.* (1974) claimed that the observation of January 9 (by which they meant the first period), with due allowance for changed bolometric corrections, supported their contention of a mass transfer rate enhanced by two orders of magnitude. The same argument, applied to the data of January 8 or the second run of January 9 would show that not only was there no evidence for enhanced mass transfer on January 8, but also that within the space of $1^h 47^m$ on January 9 the rate varied by an order of magnitude. Thus the conclusion that readers were invited to draw (viz. that an uninterruptedly high rate of mass transfer still visible on January 9 caused the earlier outburst of January 2) is by no means inescapable, or even compelling.

During the discussion following Bath's paper in this symposium (Bath, 1976), Pringle remarked that variable obscuration and anisotropy of hot spot radiation could result in apparent and misleading variability in total output where there was none in fact. But let us see where this leads us. It is most unfortunate that observations of Z Cha during its rise to maximum are not available; that is the nature of our subject. However, we do have precisely the kind or observation needed for VW Hyi, a system of very similar period ($P \sim 1^h 47^m$; Warner, 1975). The general mechanism suggested by Bath *et al.* (1974) should also apply there. But as Warner told us this morning (Warner, 1976), in VW Hyi the hump, in intensity units, appears to be unaffected during the rise to maximum, remaining constant as far as he could determine. For example, the hump amplitude remains at ~3300 cts s^{-1} (the average, 'normal-light' value) while the remainder changes from ~15 500 to ~50 000 cts s^{-1} in a 6-h period*. This would be curious behaviour if the general rise is supposed to reflect the processing of an increasing mass transfer rate through the disk. Not only would one expect the spot luminosity to increase absolutely, but also relatively in early stages of the outburst for two reasons: (i) the increasing transfer rate necessarily passes through the spot region first, and (ii) the bolometric correction effect, which Bath *et al.* (1974) emphasise, enhances the ratio of received spot to disk luminosity, the latter being relatively depressed because of its higher characteristic temperature. Pringle informed us, in the discussion following Bath's contribution (Bath, 1976), that there is much confusion about the behaviour of hot spots. When I contemplate the fact that obscuration and radiation anisotropy combine to produce apparent variability when there is none, and constancy when there is real variability, I am reluctantly forced to agree with this confession.

Is it not reasonable to suppose that following an outburst, whether concentrated at the centre or spread throughout the disk, both the outer parts of the disk and of the lobe-filling component will be disturbed? I would expect real variations to occur following any strong outburst, both in actual mass transfer and in the regions where it is first

* A careful distinction should be drawn between the slow variability on a day to day basis in the amplitude of both spot and disk, and the behaviour during a given rise to maximum.

received; a corollary being that no particular rate apparently observed at this time is either to be trusted or treated as characteristic of the events leading up to the outburst.

One final point I wish to confess puzzlement and pessimism on is the following. If dwarf nova outbursts are a purely disk phenomenon, why do such outbursts not in fact occur in the disks present in regular novae or nova-like variables? Disk enthusiasts will presumably have to produce some convincing and significant difference in the boundary conditions for these cases. The masses of the stars involved being so similar, the differences would seem to have to lie in the state of the receiving star (rotational or magnetic), or the long term rate of mass transfer from the companion. Although the suggestion by Osaki is very intriguing, the state of our knowledge of disk behaviour and physics is rather limited. It is clear that a determination of mass transfer rates (particularly our canonical rate, with its implications) should not be allowed to rest on a theoretical matching of disk instability frequency.

4. Gravitational Radiation and HZ 29 (= AM CVn)

The object HZ 29 has been of considerable interest since Smak's discovery (Smak, 1967) that it was a variable star with a period of order 18 min. Following discovery of its flickering behaviour (Warner and Robinson, 1972), Faulkner *et al.* (1972) suggested HZ 29 was a semi-detached binary white dwarf system with one lobe-filling white dwarf transferring material to the other. If this is so, the $P\sqrt{\bar{\rho}}$ relationship for low-mass secondaries suggests $M_2 \sim 0.041 M_\odot$, with hydrogen absent from the system. Gravitational radiation losses would imply a mass transfer rate of order $\sim 10^{-9} M_\odot \text{yr}^{-1}$, with the system now *separating*, i.e., period *increasing* on a $\sim 10^8$ yr time-scale. One further, purely Newtonian prediction gives primary orbital velocities ranging, for example, from 35 km s^{-1} ($M_1 \sim 1.1 M_\odot$) to 80 km s^{-1} ($M_1 \sim 0.3 M_\odot$).

Since a number of alternative hypotheses has been advanced to explain the behaviour of HZ 29, E. L. Robinson and I observed the object with the Wampler and L. B. Robinson image-tube scanner at the Lick Observatory 120-in. telescope. Our intention was to perform a process we termed synchronous spectrophotometry, with a view to confirming the binary nature directly by observing, if possible, the motion of the primary. Upon reflection, this hope was rather optimistic; it was, in any event, unrealized. However, we did obtain a most interesting spectrum (see Figure 1). A letter on our results will appear shortly (Robinson and Faulkner, 1975); I shall limit myself to a few comments here.

The spectrum shows clearly only absorption lines of He I (the absence of hydrogen being one small crumb of comfort for the theorist). The profiles are most curious, showing a most marked and uniform asymmetry, independent of membership in the singlet or triplet series. Equivalent width ratios are unusual; coupled with observations in other wavelength regions, we find the strengths to be consistent with crudely adding an optically thin helium capture-cascade emission line spectrum to the observed relative line-strengths of normal DB white dwarfs. Such a model, with emission coming from a radially infalling gas component, would produce the observed asymmetry rather well, and at an accretion rate of $\sim 3 \times 10^{-9} M_\odot \text{yr}^{-1}$ (within a factor of ~ 3 of the prediction). Unfortunately, it would not be self-consistent, since the accretion would also surely produce a continuous emission which would swamp the white dwarf features. An alternative hypothesis we

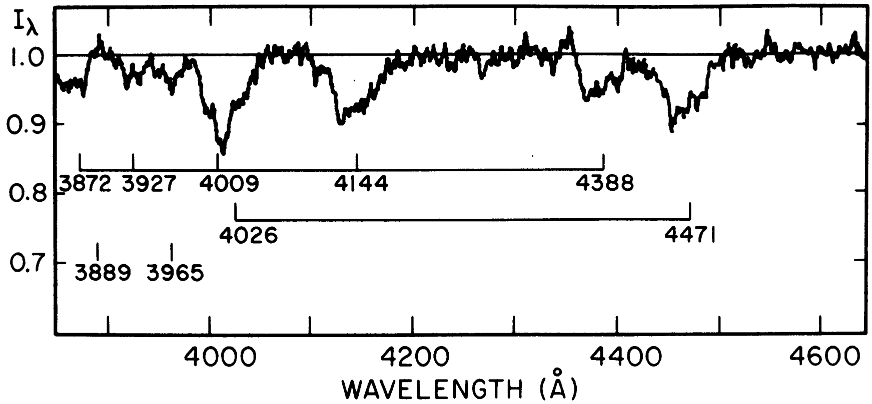

Fig. 1. The spectrum of HZ 29. The wavelengths of those helium lines normally strong in DB white dwarfs are marked. Reproduced by permission of the *Astrophysical Journal.*

briefly explore is that the lines seen actually originate entirely in the accretion disk and that their breadths correspond to the velocities ($\sim$2500–3000 km s^{-1}) expected for circular motion in the vicinity of a white dwarf. In addition to the velocities, the luminosity, dimensions etc. needed seem roughly consistent with this picture at accretion rates of $\sim 10^{-9} M_\odot \mathrm{yr}^{-1}$. With the difficulties of pinning down precisely what is going on, this can only be treated as a speculative, if tantalising suggestion.

5. The Behaviour of Stars Losing Mass

Eggleton, Taam and I have recently completed a study begun some time ago of the response of main-sequence-like stars to mass loss. Eggleton's student Webbink also worked on this problem in its early stages, but as you will learn later in this symposium, has gone on to more exciting developments.

We were concerned to learn what would happen to stars steadily and non-catastrophically losing mass for substantial periods of time. Such a situation might occur with a variety of time scales depending on the mass-ratios when a semi-detached system is formed, the nuclear state and timescales, or a gravitational radiation timescale. Most studies in the literature have taken a specific pair of models to evolve and examined what happens for that particular situation. However, there is another way of proceeding, namely to learn what the response of a star is to a set of chosen or imposed mass-loss rates and then to determine what will actually happen in a specific case by examining this pre-existing catalogue. When the application is to a semi-detached system, one can be fairly sure that the material simply eases away without a substantial back-reaction. One is losing matter which has the characteristics of the surface layers. Thus, in this context, calculations with $\dot{M}$ negative can avoid the weak justifications which (despite obvious objections) are usually invoked for $\dot{M}$ positive.

Figure 2 shows the radius-mass relationships obtained for originally main-sequence stars losing mass at instantaneous time-scales defined by $-M/\dot{M} = 10^8$, 10^7, 10^6 yr. Similar results hold for luminosity as a function of mass. Note that there is a qualitative difference in the behaviour of the models depending upon whether they are more or less

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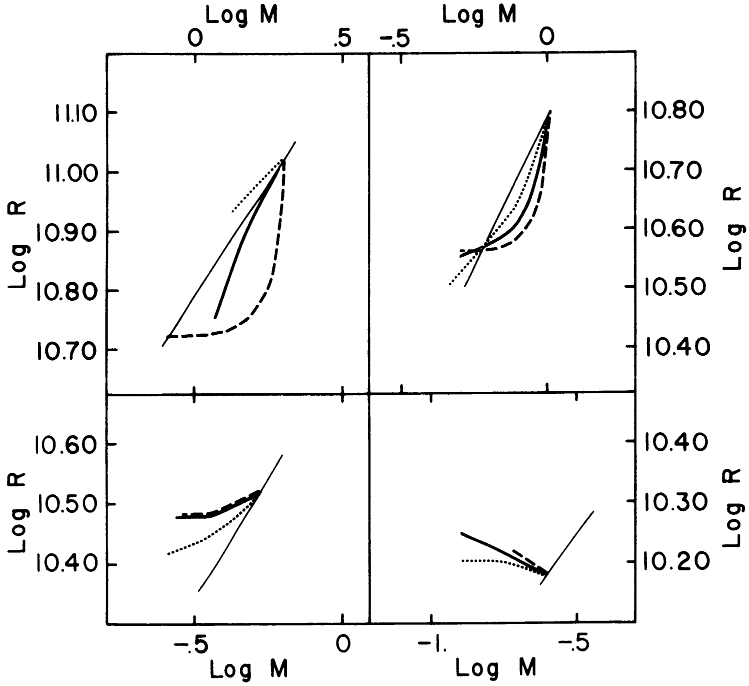

Fig. 2. The radius-mass relationships for mass-losing stars of original masses 2.0, 1.0, 0.5 and 0.25 $M_\odot$. The thin solid line shows the main sequence. Mass loss timescales are denoted as follows: 10^8 yr (dotted line), 10^7 yr (thick solid line), 10^6 yr (dashed line).

massive than a critical mass (of order ~$0.65\,M_\odot$). The more massive stars, on losing mass, become initially smaller than their main sequence counterparts (the only exception being the 10^8 yr time scale applied to the $2M_\odot$ model where nuclear evolution is still dominating the effects of thermal readjustment). The less massive stars become larger than their main sequence counterparts, and in the case of the $0.25M_\odot$, completely convective star, absolutely larger.

These differences in behaviour may be qualitatively understood as follows. Figure 3 shows the curves defined in the $\log \rho - \log T$ plane by equilibrium main-sequence models. Let us suppose that when mass is removed, there will be a tendency to relax towards the equilibrium configuration for the slightly reduced mass. What would this imply? Individual mass elements distributed throughout the star may either absorb or release energy. In Figure 4, this is shown for two sets of closely adjacent models with masses ~$1\,M_\odot$ and ~$0.5\,M_\odot$ respectively. Elements of material identified by a common value of the mass variable (*not* mass fraction) outwards from the centre are connected by arrows illustrating the implied changes. Whether energy would be abosrbed or released depends upon which side of the adiabats the arrows lie.

For the $1\,M_\odot$ case, the innermost parts of the radiative interior would release a small amount of energy. The intermediate radiative region would absorb a larger amount of energy. Finally, the convective envelope of large radial extent but little mass releases a small amount of energy. The net behaviour should be dominated by the intermediate

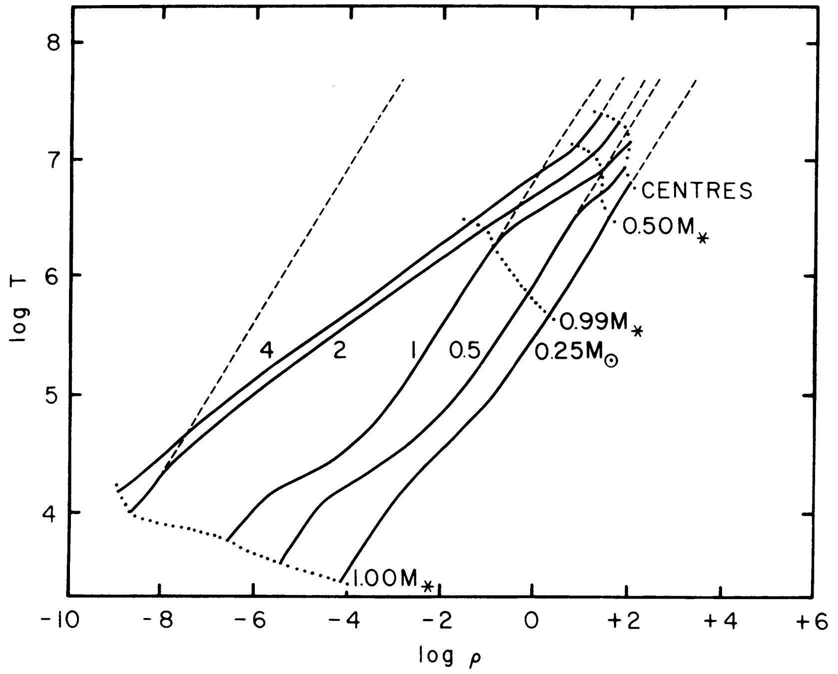

Fig. 3. The density-temperature plane for main-sequence stars. Dashed lines show extensions of adiabats. Dotted lines join points of a given mass fraction.

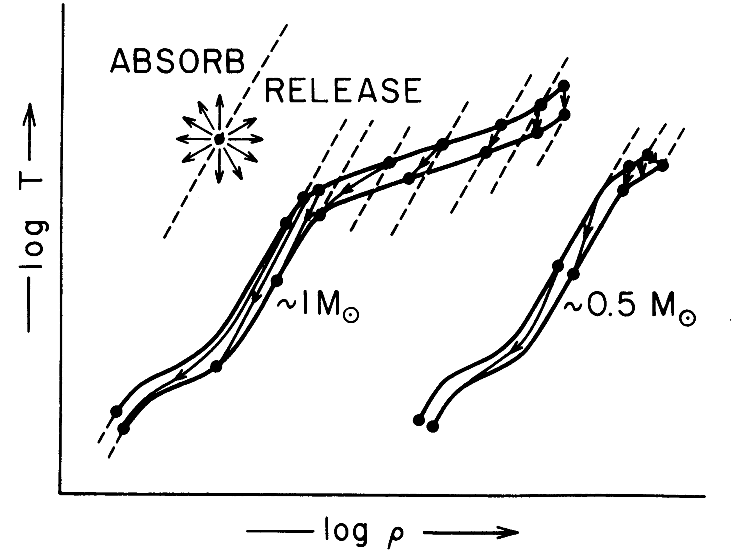

Fig. 4. A schematic representation of adjacent main-sequence models for two cases, ~1.0 and ~0.5 $M_{\odot}$. Dashed lines show adiabats. See text for further details (Section 5).

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radiative zones and their potential absorption of energy. In the $0.5 M_{\odot}$ case the convective envelope is so deep that there is essentially no intermediate radiative zone. All the arrows lie on the same side of the adiabat and energy should be released by all parts of the star. Of course, the energy flow at any given point in the star will, in the actual event, be affected by what is happening in lower regions; this will change the precise ρ-T curves and further affect the energy budget. Nevertheless, the actual behaviour closely follows that expected. The qualitative external change at $\sim 0.65 M_{\odot}$ occurs because at that point, the mass involved in the convective envelope is sufficiently large for the energy release there to overcome the absorption in the layers below. Finally, the radii follow the behaviour of the luminous flux, as is to be expected.

These results have a number of implications. Mass transfer from a massive star (well above $\sim 0.65 M_{\odot}$) to a less massive companion (but possibly not too low in mass, as remarked later) will be stable on something like the thermal time scale. However, were the Universe sufficiently old that a star less massive than $\sim 0.65 M_{\odot}$ were the most massive and meeting its Roche lobe for the first time now, a dramatic unpeeling should occur. It is not clear whether this will be so independent of the mass of the companion. Finally, a more extreme example has been studied by Webbink (1976). If a sufficiently massive star loses mass for sufficiently long at a high rate, the luminosity deficit in its outer layers causes the development of a deep outer convective zone in circumstances where none would normally be expected (e.g. in a $2.5 M_{\odot}$ remnant of an originally $4 M_{\odot}$ star). This deep outer convective zone begins to release such large amounts of energy that the external behaviour is changed drastically; the remnant expands at an ever increasing rate.

These results imply both disturbing and possibly beneficial consequences. First, for systems transferring matter on $\sim 10^7$ yr timescales (a rate favoured by many nova and dwarf nova experts), it is not appropriate to use a fixed radius-mass relation. There is a broader spectrum of possibilities. Models with high mass-transfer rates become less definitive. On the other hand, it has often puzzled investigators that systems containing apparently similar masses and periods can behave so differently. Our work opens up the new possibility that the internal state of the mass-losing stars may be very variable depending on the mass-ratio with which the system originated. As a consequence, the current mass transfer rates may themselves be quite different, possibly making all the difference required for a large range of behaviours from disk instabilities etc. We may have found the extra degree of freedom missing up until now from externally similar systems. However, it is frustrating to admit that we are unable to say categorically whether we would expect time scales of 10^7 or 10^{10} yr for mass transfer even if we knew the masses of the stars involved precisely.

6. Binary Star Evolution with Radiation Losses

Flannery, Taam and I have explicitly computed the evolution of some idealised semi-detached binary systems suffering gravitational radiation losses. These studies were undertaken with three aims in mind. First to see whether the results with more realistic models bore out the conclusions (Paczynski, 1967; Faulkner, 1971) based on crude algebraic approximations to the structure relations. Secondly, to study the simultaneous effects of relaxing one or more of the standard assumptions (e.g. constancy of mass or of angular momentum apart from the losses by gravitational radiation). Thirdly, to see whether a realistic model for HZ 29 could be produced starting with a semi-detached almost main sequence star (rather than a highly evolved star).

Since we examined a number of cases, and detailed results will appear elsewhere, I shall be brief. Figure 5 shows the period, P, as a function of secondary mass-fraction, μ. In cases 1, 2, 3, 5 and 7 the initial system consisted of a $0.8 M_\odot$ white dwarf and a $1.2 M_\odot$, ultimately lobe-filling main-sequence star. Cases 1, 2, 3 and 5 are distinguished only by initial period, i.e. separation and therefore time spent prior to mass transfer.

Both cases 1 and 5 with initial periods of 9.5 and 10.5 h respectively, show that 'gravitational radiation capture' can occur (the fiducial line 1F showing the P-μ relation which would hold if no angular momentum were radiated). On first contacting the Roche lobe, the central values of hydrogen content were reduced to 0.56 and 0.42 respectively. Terminating the calculations when the white dwarf mass became $1.4 M_\odot$, central hydrogen values were 0.28 and 0.001 respectively. Case 5 thus came very close to exhausting hydrogen, as desired. The period was however still relatively long.

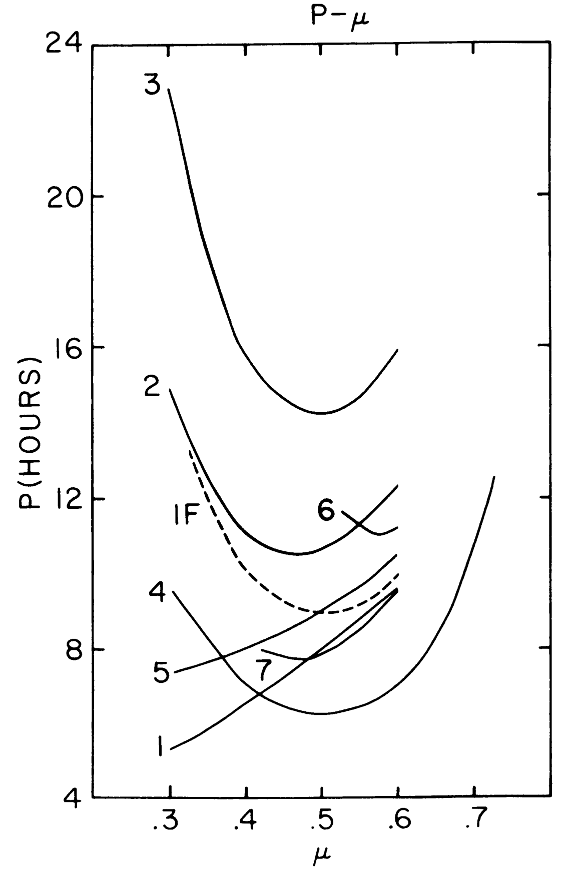

Fig. 5. The period-mass fraction relationships for evolving binary systems. See text for discussion (Section 6).

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In case 2 the initial period of 12.3 h was sufficiently long that gravitational radiation remained a small effect throughout. The minimum in P was somewhat displaced, but not significantly so, from $\mu = 0.5$. Case 4 began with a reduced white dwarf mass ($\cong 0.4 M_\odot$) and a period such that central hydrogen would be reduced to zero prior to contact, while permitting short periods when masses were equalised. However, during the low period phase, the mass transfer was so rapid that this situation was of short duration. Although the radiation rate reached a high value, little net angular momentum was radiated. Cases 6 and 7 involved mass loss from the system with 'typical' angular momentum and need not concern us here.

What do these results show? Provided we accept the existence of white dwarfs in novae or dwarf novae, gravitational radiation alone is capable of covering a good part of the observed period distributions in acceptable times (5.9 and 8.7×10^9 yr for cases 1 and 5). There is, however, difficulty in producing a model for HZ 29 by this route. Mass loss from the system appears to be less than helpful in this regard also.

Acknowledgements

I am grateful to my theoretical colleagues Peter Eggleton, Brian Flannery and Ronald Taam for their collaboration and suggestions in various aspects of this work. I am particularly indebted to Brian Warner and Edward L. Robinson, from whose great observational work and knowledge I have failed to learn enough. This research has been generously supported by the U.S. National Science Foundation, through grant no. GP-32337X.

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DISCUSSION

Smak: I have two comments to make:

(1) Recent photometry of HZ 29 (Smak, J. I.: *Acta Astron.*, in press) together with earlier photo-

metries, show such a large degree of instability in the shape of the light curve, that there seems to be little hope of detecting period variations due to the gravitational waves.

(2) The spectrum of a peculiar helium emission-line object, G61 – 29, shows complex line profiles, consisting of a double line (like in the nova-type binaries) and of a single, red-shifted component, which could possibly originate in the material accreted by the white dwarf. In any case, it is remarkable that HZ 29 and G 61 – 29, the only two (probable) nova-like binaries with no hydrogen, show a similar phenomenon of red-shifted emission lines.

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