STAR-PLANET SYSTEMS AND THEIR RELATION TO LOW MASS CATACLYSMIC VARIABLES

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ABSTRACT. We investigate the possibility of forming a low mass cataclysmic binary from a star-planet system. Using certain simplifying assumptions it is shown that an analytic solution for the evolution of the separation can be obtained. The fate of the system is determined by the competition between mass loss and accretion drag. While it is found that some fine tuning is required for the formation of a close binary, such a binary can still be formed, for parameters that are not too exotic.

1. INTRODUCTION

Following an idea of Eggleton (1978) we have carried out an investigation of a possible scenario for the formation of a low mass cataclysmic binary. We describe here the results of a preliminary study (see Livio 1982).

The general idea is to start with a star-planet system. In the course of its evolution the star becomes a red giant, thus allowing the planet to start to accrete, first from a stellar wind. The increase in the planet's mass leads to an even more efficient accretion. In the more advanced stages the planet is actually embedded in the giant's envelope, accreting while spiralling in. By this process the planet is transformed into a low mass star which, as the giant loses its envelope, forms a close binary companion to the giant's core (which later becomes a white dwarf).

2. PHYSICAL ASSUMPTIONS AND EQUATIONS

We shall assume the following typical initial parameters for the star-planet system: Mass of the star $M_1 \sim M_\odot$, mass of the planet $M_2 \sim 0.01\ M_\odot$, a separation of $a \sim 10^{13}$ cm. We shall denote the mass ratio by $q \equiv M_1/M_2$ and the velocity of the wind from the giant (assumed radial) by V_W. We assume that the planet accretes a fraction β of the mass lost by the giant, namely

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$$\dot{M}_2 = -\beta\, \dot{M}_1 \tag{1}$$

The equation for relative motion can be written as (Alexander et al. 1976)

$$\ddot{\vec{r}} = -\frac{G(M_1+M_2)}{r^3}\vec{r} + \frac{1}{M_2}\vec{F} \tag{2}$$

where $\vec{F}$ is the force due to the accretion drag. Equation (1) can be transformed into an equation for the separation (Alexander et al. 1976, Choi and Vila 1981, Livio 1982)

$$\frac{\dot{a}}{a} = -\frac{(\dot{M}_1+\dot{M}_2)}{M_1+M_2} - \frac{2\dot{M}_2}{M_2}\left(1 + \ell n\,\frac{R_{max}}{R_{acc}}\right) \tag{3}$$

where R_{max} can be taken as the radius of the planets Roche lobe (Kopal 1959)

$$R_{max} \sim 10^{12}\left(\frac{q+1}{100}\right)^{-1/3}\left(\frac{a}{10^{13}\,cm}\right)\ cm \tag{4}$$

and R_{acc} is the accretion radius (Bondi and Hoyle 1944)

$$R_{acc} \sim 2x10^{11}\left(\frac{a}{10^{13}\,cm}\right)\left(\frac{q+1}{q}\right)\left(\frac{q}{100}\right)^{-1}(1+\delta)^{-1}\ cm \tag{5}$$

where δ is a small correction (Livio 1982). It turns out that

$$\varepsilon(q) \equiv 1+\ell n\,\frac{R_{max}}{R_{acc}} \simeq 2.6+\ell n\left[\left(\frac{q}{q+1}\right)^{4/3}\left(\frac{q}{100}\right)^{2/3}(1+\delta)^{-1}\right] \tag{6}$$

is an extremely slowly varying function of q, so that we make the simplifying assumption $\varepsilon(q)$ = const. = 2.587. We note that if we further assume for the moment that β=const. (which is clearly not accurate and we shall discuss this point later), then equation (3) admits an analytic solution

$$\frac{a}{a_o} = \left(\frac{1+\beta q}{1+\beta q_o}\right)^{2\varepsilon+1}\left(\frac{q_o+1}{q+1}\right) \tag{7}$$

where a_o and q_o are the initial values. The separation as a function of q is presented in Fig. 1. It can be easily checked that the behaviour of the separation is determined by the following condition

$$\beta q \gtrsim \frac{1}{2\varepsilon} \qquad \text{reduction in separation} \tag{8}$$

This condition has a very obvious physical interpretation in terms of the relevant timescales describing the problem

$$\tau_{mass\ loss} = \frac{M_1}{\dot{M}_1} \; ; \quad \tau_{acc} = \frac{M_2}{\dot{M}_2}; \quad \tau_{drag} \simeq \frac{\tau_{acc}}{2\varepsilon} \tag{9}$$

Using these definitions condition (8) can be expressed as a simple statement of the relative importance of the two competing processes

$$\tau_{drag} \lesssim \tau_{mass\ loss} \tag{10}$$

It turns out that even if $\beta=\beta(q)$, a solution of (3) can be obtained in the limit $\beta(q)\cdot q>>1$, which coincides asymptotically with (7) (Livio 1982).

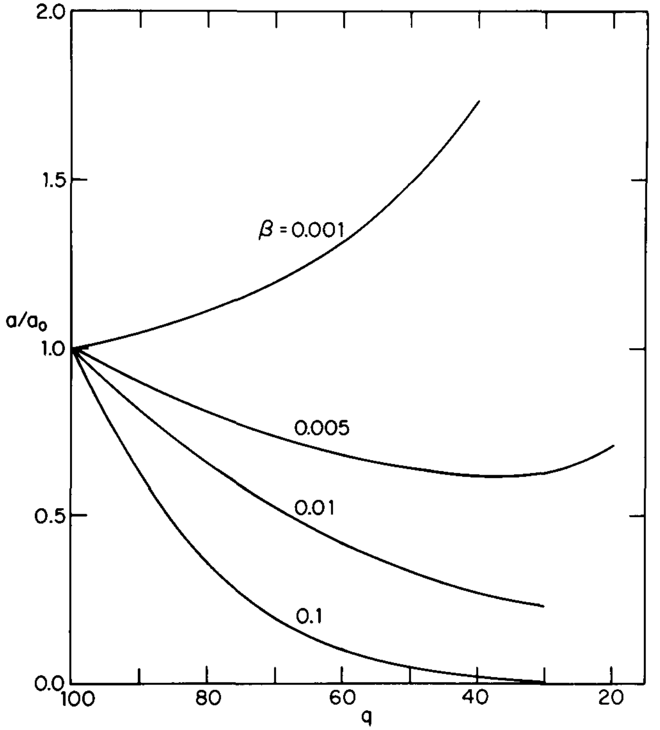

Fig. 1. The evolution of the separation as a function of the mass ratio, for several values of the fraction of accreted mass, β.

For accretion from a wind the various timescales can be estimated as (see also Kudritzki and Reimers 1978)

$$\tau_{mass\ loss} \sim 1.8\text{x}10^6 \left(\frac{M_1}{M_\odot}\right)^2 \left(\frac{L_1}{10^4 L_\odot}\right)^{-1} \left(\frac{R_1}{100R_\odot}\right)^{-1} \text{yr} \tag{11}$$

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$$\tau_{drag} \sim 1.4\times10^{7}\ \varepsilon^{-1}\left(\frac{M_2}{0.01M_\odot}\right)^{-1}\left(\frac{\dot{M}_1}{10^{-6}M_\odot/yr}\right)^{-1}\left(\frac{a}{10^{13}cm}\right)^{1/2}\left(\frac{V_W}{10^{6}cm\ s^{-1}}\right)\ x$$

$$x\ \left(\frac{M_1}{M_\odot}\right)^{3/2}\left(\frac{q}{q+1}\right)^{3/2}(1+\ )^{3/2}\ yr \qquad (12)$$

and we find

$$\beta q \sim 0.037\ \left(\frac{q}{100}\right)^{-1}\left(\frac{q+1}{q}\right)^{3/2}\left(\frac{V_W}{10^{6}cm\ s^{-1}}\right)^{-1}\left(\frac{a}{10^{13}cm}\right)^{-1/2}\left(\frac{M_1}{M_\odot}\right)^{1/2}(1+\delta)^{-3/2} \qquad (13)$$

which implies that under normal conditions accretion from a stellar wind will not result in a decrease of the separation and a close binary system will not be formed.

In contrast to this, the planet may start at such an initial separation that it will be moving inside the giant's envelope as that expands. This can lead to an accretion rate of

$$\dot{M}_2 \simeq 7.2\times10^{-7}\left(\frac{M_2}{0.01M_\odot}\right)^{2}\left(\frac{\rho}{10^{-10}gcm^{-3}}\right)\left(\frac{M_1}{M_\odot}\right)^{-3/2}\left(\frac{a}{10^{13}cm}\right)^{3/2}\left(\frac{q+1}{q}\right)^{3/2}\ M_\odot/yr \qquad (14)$$

where ρ is the local atmospheric density. Under these conditions the planet will spiral into the giant on a drag timescale that can be as short as ~600 years and may be completely dissipated, thus, again not forming a close binary system.

3. CONCLUSIONS

On the basis of this simplified preliminary study the following conclusions can be drawn:

1) A certain amount of fine tuning is required for the formation of a low mass binary system. Specifically, for $a_o \gtrsim 2000\ R_\odot$ very little accretion will take place and no reduction in the separation will result. For $a_o \lesssim 500\ R_\odot$ a spiralling-in of the planet, on a timescale that is short compared to evolutionary is inevitable, the planet will be totally dissipated in the giant.

2) In spite of conclusion (1), for a quite reasonable initial separation, $a_o \sim 900\ R_\odot$, a low mass secondary can be formed in $\tau \sim 10^5 - 10^6$ years, which is of the order of the time spent by the star in the giant phase (Eggleton 1973).

3) The amount of fine tuning needed for the formation of the binary is not excessive. A change in the initial separation by 100 $R_\odot$ results in

a change in the accretion timescale by less than an order of magnitude.

4) The virial temperature of a 0.01 $M_\odot$ planet is of the order of (Zapolski and Salpeter 1969) $T_V \sim 1.6\times10^{6}$°K so that the planet can plunge into the giant very deeply (to $r \sim 1.9\ R_\odot$, Harpaz 1981) before being evaporated.

5) The tidal evolution of the system should be explored (see Livio 1982 for a preliminary study).

6) Any star-planet system in which the initial separation is not greater than a few thousands solar radii, must inevitably undergo a situation of the type described here, the processes involved (in particular evaporation of the planet), therefore, deserve further study.

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DISCUSSION FOLLOWING M. LIVIO'S TALK

LAMB: Did you restrict your accretion rate onto the planet to be less than the Eddington limit at all times?

LIVIO: Yes. In fact, I never went to more than one fifth or so, of the Eddington limit.

LANGER: You seem to need to take this planet down inside the envelope of the red giant, can you cool the accreted mass fast enough to sort of keep settling it down onto the planet and then use the evaporation estimate, based on the radius that the planet has, for a given mass?

LIVIO: I don't know, I have not looked into this yet. However, you must realize also that the temperatures that you get from accretion onto a planet are not that high, you get to about 10^5°K and this may agree quite well with the temperature you already have, inside your medium. So this whole thing may even not have observational effects from the outside, because all the luminosity you get may be absorbed.