THE FORMATION OF MASSIVE WHITE DWARFS IN CATACLYSMIC BINARIES

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Abstract

In contrast to the mass spectrum of single white dwarfs which has a single narrow peak at $\sim 0.6\ M_{\odot}$, the observed mass spectrum of white dwarfs of cataclysmic binaries (CB's) shows a rather uniform distribution of the masses in the range $\sim 0.3\ M_{\odot}$ to $\sim 1.3\ M_{\odot}$. The formation of CB's with white dwarfs of less than about $0.8\ M_{\odot}$ can be understood as the result of a binary evolution according to low mass Case B or Case C with a subsequent spiraling-in in a common envelope. On the other hand the formation of massive white dwarfs of $M \gtrsim 1\ M_{\odot}$ can be explained as the result of a massive Case B mass transfer yielding a helium star which subsequently undergoes a second Case B mass transfer (so called Case BB evolution). The ultimate product of such an evolution is either a CO-white dwarf with a mass up to the Chandrasekhar limit or a neutron star. The formation of CB's via Case BB evolution requires the binary to undergo at least one, most probably two separate phases of spiraling-in in a common envelope.

Introduction

A cataclysmic binary (CB) is a short-period system consisting of a white dwarf primary and a low mass secondary which is filling its critical Roche-volume and is presumably a main-sequence star (Warner, 1976). According to the conventional theories of binary evolution, such a system is the descendant of an originally much wider binary which has experienced a highly nonconservative evolution of low mass Case B or Case C (Ritter, 1975, 1976; Webbink, 1975; Paczyński, 1976). The respective primary remnants are a low mass helium white dwarf with a mass of less than $0.45\ M_{\odot}$ and a CO white dwarf with a mass above $0.55\ M_{\odot}$. The mass of the white dwarf formed in a Case C evolution is determined mainly by the core evolution of the primary and in this aspect the formation of white dwarfs via Case C and in single stars are similar; the mass spectra of the white dwarfs produced in both cases therefore should also be similar. The observations of single white dwarfs show that most of the white dwarfs have a mass of

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(0.6 ± 0.1) $M_\odot$ and that massive white dwarfs with masses above ~1 $M_\odot$ are extremely rare (Koester, Schulz, Weidemann, 1979). However, massive white dwarfs seem to be formed much more frequently in CB's than in single stars (see e.g. Robinson, 1976; Warner, 1976). Since Case C evolution probably cannot account for all of the observed massive white dwarfs in CB's, these white dwarfs are likely to be formed along other evolutionary paths. The purpose of this paper is to discuss such an alternative evolution which can lead to the formation of high mass white dwarfs in CB's.

THE FORMATION OF MASSIVE WHITE DWARFS VIA CONSERVATIVE MASS TRANSFER

In a recent paper Delgado and Thomas (1981) - hereafter referred to as DT - have shown how massive white dwarfs can be formed in binaries. The evolution involves first a conservative mass transfer of high mass Case B which yields a helium star as an intermediate product. The formation of high mass white dwarfs is then a consequence of the fact that a helium star in the mass range 0.85 $M_\odot < M < 4 M_\odot$ becomes a red giant during its shell helium burning phase (Paczyński, 1971) and therefore can reduce its mass below the Chandrasekhar limit in a second mass transfer. This type of mass transfer has been referred to as Case BB.

THE FORMATION OF MASSIVE WHITE DWARFS VIA NONCONSERVATIVE CASE BB MASS TRANSFER

Since CB's are believed to be formed in a nonconservative evolution (Ritter, 1975, 1976; Webbink, 1975; Paczyński, 1976), we investigate the consequences of a Case BB mass transfer in binaries which, after the onset of the first mass transfer, went through a common envelope evolution (Meyer and Meyer-Hofmeister, 1979).

A) the Formation of Helium Stars via Nonconservative Case B Mass Transfer

A common envelope is likely to be formed whenever the primary, at the onset of the mass transfer, has a deep outer convective envelope (Webbink 1979). At present, however, the loss of the common envelope at the end of the "spiraling in" is not understood by theory. Therefore the orbital parameters of the emerging post common envelope binary (hereafter PCEB) cannot be determined theoretically. Nevertheless, due to the short duration of the common envelope phase, the mass of the helium star formed via the common envelope is not significantly different from what is obtained in a conservative evolution. Therefore, with respect to the mass of the helium star formed, we can make use of the results obtained by conventional conservative computations. The other properties of the PCEB are assumed to be qualitatively similar to those of the observed objects which are believed to be PCEB's (Law and Ritter, 1981). Accordingly, a PCEB is characterised by the following properties:

1) The primary is a helium star of roughly the same mass as predicted by a conservative evolution.
2) The secondary's mass is much lower than that in the conservative

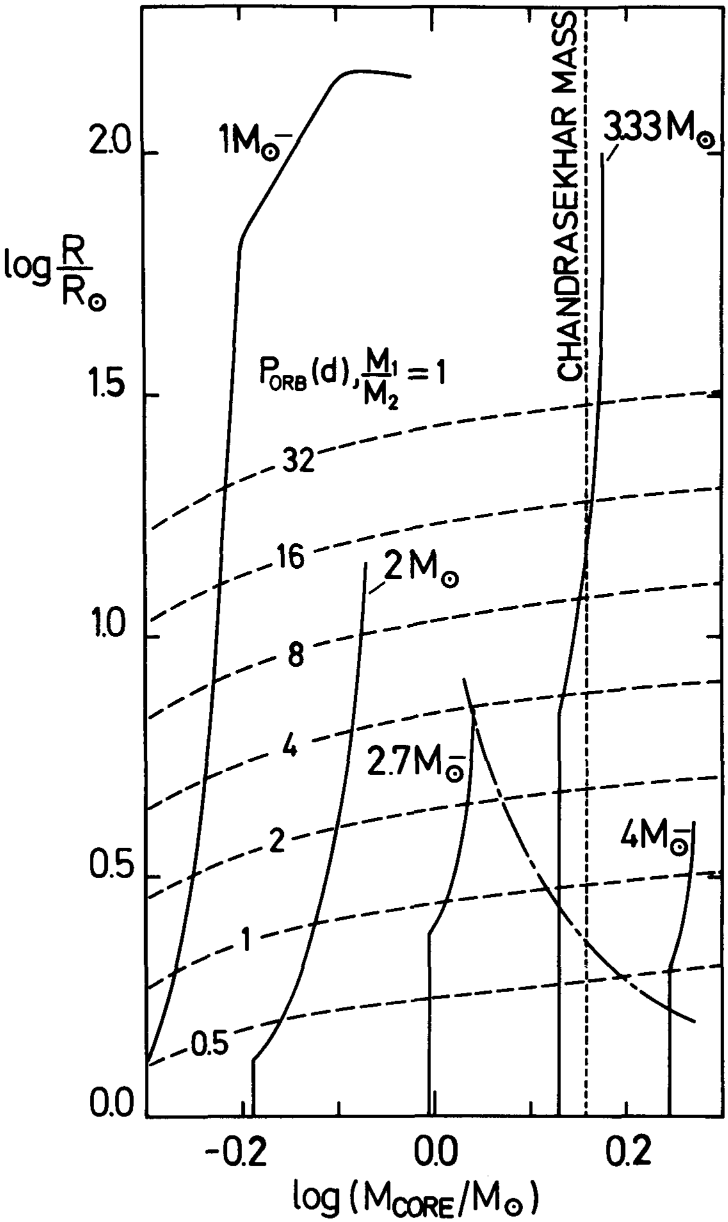

Fig. 1: Core-mass-radius-relation of shell burning helium stars of different total mass (full lines). The broken lines show the Roche-radius for an assumed mass ratio $M_1/M_2=1$ for various orbital periods. The dashed-dotted line indicates the radius at which central carbon burning sets in.

case. It is probably even lower than the mass of the helium star because of the particular properties of the common envelope phase (Law and Ritter, 1981).

3) The orbital period is of the order 0.5 - 1 day.
4) The secondary either is filling its critical Roche-volume or if it does not it is not far from doing so.

B) Case BB Mass Transfer in a Post Common Envelope Binary

Systems containing helium stars in the mass range $0.85M_\odot \lesssim M_{He} \lesssim 4M_\odot$ undergo a case BB mass transfer (see e.g. DT). Thereby the helium star is stripped down to its shell helium burning region. Since the phase of mass exchange in these binaries is likely to be very short (for reasons given below) the final mass of the primary is approximately equal to its core mass at the onset of mass transfer. The mass of the primary remnant is then essentially determined by the initial mass of the helium star and by its Roche-radius at the onset of mass transfer. The full lines in Fig. 1 show the core-mass-radius relation for helium stars of various total masses. The data have been taken from computations by DT and by Law (1981). The broken lines in Fig. 1 show the primary's Roche-radius for an assumed initial mass ratio $M_1/M_2 = 1$ and for different values of the orbital period. The dashed-dotted line indicates the radius at which central carbon burning sets in. From Fig. 1 the following conclusions about the outcome of Case BB mass transfer can be drawn:

1) High mass white dwarfs are descended from helium stars in the mass range $2M_\odot \lesssim M_{He} \lesssim 3M_\odot$.
2) Helium stars with masses above $\sim 3.5M_\odot$ cannot reduce their mass below the Chandrasekhar limit.
3) High mass CO-white dwarfs can only be formed by a Case BB mass transfer starting in a short period binary, i.e. $P \lesssim 2^d$.

The Secondary's Reaction to Helium Accretion

Since the equilibrium radius of a shell burning helium star strongly increases with decreasing envelope mass (Fig. 1), Case BB mass transfer is always connected with a phase of fast mass exchange. The secondary's reaction to the high accretion rates imposed by the primary could immediately be deduced from the work of Kippenhahn and Meyer-Hofmeister (1977), if the accreted matter consisted of hydrogen. The exchanged matter, however, consists of helium rather than of hydrogen. Therefore, the secondary's reaction might be quite different. We suggest, however, that the secondary's reaction to helium accretion during the early phases of mass transfer is qualitatively similar to that in the case of hydrogen accretion. (Law and Ritter, 1981). In the cases considered by DT the secondary's reaction is then negligible. This is because, as a consequence of the conservative evolution, the secondary has a high mass and a thermal time scale which is much shorter than the accretion time scale. However, in the PCEB's considered here, the secondary has a low mass. Its thermal timescale is much longer than the accretion timescale for the mass exchange rate of $\sim 2 \cdot 10^{-4}$ $M_\odot$/yr found by DT. Under these circumstances the secondary's radius increases sufficiently to bring the binary very quickly into a second common envelope situation. The binary emerging from the second common-envelope phase will have an even shorter orbital period, a secondary of even lower mass and a primary which will become either a high-mass white dwarf or a neutron star. The ejected second common envelope will look to a distant observer like a helium rich planetary nebula.

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