THE COALESCENCE OF WHITE DWARFS AND TYPE I SUPERNOVAE

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ABSTRACT: In the context of the white dwarf coalescence model for type Ia supernovae, we compute post-coalescence configurations involving a thick disk, rotating around a central white dwarf (the original primary), having the same total mass, angular momentum and energy as the initial system. We show that carbon ignition in rather low density material ($10^5 - 10^6$ g.cm^{-3}) can be triggered during the merging process itself or later, by dissipation due to turbulence in the disk. The evolution of the object following carbon ignition is very uncertain.

1. INTRODUCTION

Exploding white dwarfs are generally considered to be responsible for type Ia supernovae (SN Ia) for a number of observational and theoretical evidences: SNe Ia have progenitors belonging to the old galactic population and spectra without hydrogen lines; SN Ia light curves are nicely explained by the radioactive energy release of $0.5 - 0.7$ $M_\odot$ of ^{56}Ni resulting from the combustion of a fraction of the white dwarf to nuclear statistical equilibrium [1,2]; uncomplete nuclear burning in the outer layers produces intermediate mass elements and the resulting abundances together with the dynamics of the ejecta give synthetic spectra which fit rather well with the observations [3]; the burning front propagates from the center to the surface by a deflagration wave, with expansion velocities which can reach 20000 km.s^{-1} and leaving no compact remnant [4], in agreement with the absence of neutron star in the two historical SNe I Tycho and Kepler.

The carbon deflagration model therefore appears quite successfull in accounting for many of the observed features of SNe Ia but the main problem which remains is related to the presupernova evolution and can be summarized by the following two questions: (i) is it really possible to bring a white dwarf by accretion sufficiently close to the Chandrasekhar limit to allow central carbon ignition? (ii) if it is possible, does it occur in a large enough number of systems to explain the SN Ia rate, which is estimated to be of the order of 6.8 10^{-14} pc^{-3}.yr^{-1} in our Galaxy?

The answer to these two questions is very uncertain. It may indeed be difficult to reach the Chandrasekhar limit by accretion of hydrogen-rich material, due to periodic mass ejection by hydrogen shell flashes [5]. Accumulation of helium appears to be possible only for accretion rates larger than 10^{-8} $M_\odot$.yr^{-1}. However, even in this case, mass loss by a stellar wind during the reccurent helium shell flashes could also reduce the efficiency of accretion and prevent the white dwarf mass from growing [6]. For a discussion of point (ii), the evolution of close binaries must be followed from their birth (with an assumed IMF and distribution function of initial orbital separation) until the eventual explosion of one of their components as a SN Ia. Such a study may include periods of non-conservative mass transfer, loss of angular momentum by magnetic breaking, accretion from a stellar wind, etc... In spite of uncertainties in the theoretical modelling of these proccesses, it seems that no (at least classical) evolutionary path can be found, which could bring a large enough number of systems to the SN Ia stage [7]. This has led to the search for (a priori) more "exotic" scenarios, such white dwarf coalescence [7,8]. Binary white dwarfs (BWD) are produced after the second period of mass transfer in systems of initial semi-major axis from a few tens to a few hundreds $R_\odot$ and with components of intermediate mass. If the white dwarfs are formed with a separation in the range $2 - 3$ $R_\odot$, they can be brought in contact by the emission of gravitational radiation within a Hubble time or less. For two carbon-oxygen white dwarfs the total mass involved is often larger than the Chandrasekhar limit and some explosive outcome can be expected. Both observational [9] and theoretical [7,8,10] estimates of the BWD birthrate have been obtained, but the results are still contradictory so that no reliable comparison with the SN Ia rate can be made. We did not address this problem in the present work. We focused on the structure and possible evolution of post-coalescence configurations, assuming conservation of total mass, angular momentum and energy in the merging process. These assumptions have been confirmed by the very recent 3 D numerical simulation of Benz et al. [11].

2. COMPUTATIONAL METHOD

A post-coalescence configuration consists of a central white dwarf (the original primary) surrounded by a thick disk coming from its disrupted companion. To compute its structure, we used the classical self-consistent field approach for differentially rotating, self-gravitating systems [12]. If the material behaves as a barotrope, which is the case for the fully degenerate white dwarf interior and has been assumed for the partially or non-degenerate disk, the specific angular momentum must be constant along axial cylinders. We have then $j = j(\tilde{\omega})$, with the constaint that this distribution must satisfy the Rayleigh criterion $dj/d\tilde{\omega} > 0$, $\tilde{\omega}$ being the polar radial coordinate. For practical purposes, the mass coordinate $m(\tilde{\omega})$ has been adopted instead of $\tilde{\omega}$ and the following expression has been used for $j(m)$ in the disk

$$j(m) = j_o \cdot \frac{(m - M_1)}{M_1 + M_2 + b(m - M_1)} \; . \tag{1}$$

M_1 and M_2 are respectively the mass of the central white dwarf and the mass of the disk. The constant j_o is determined for any b by the condition $\int_{M_1}^{M_1+M_2} j(m)dm = J$, where $J = J_{orb} + J_2$ is the sum of the orbital angular momentum (before coalescence) and the proper angular momentum of the disrupted white dwarf. We assume that the central white dwarf is non-rotating since it is less affected by tidal interaction due to its smaller radius (even in synchronized systems, its angular momentum remains moderate compared to J with therefore little effect on the final results).

We take into account the thermal contribution to the pressure by adopting a polytropic relation, $P = A\rho^\gamma$ with $\gamma < 5/3$ (i.e. smaller than the value for degenerate, non-relativistic electrons only), when the density goes below a given limit ρ_o. If we take for ρ_o the density at which the thermal and degenerate electron contributions are equal, this gives a transition temperature,

$T_o \approx 10^5 \rho_o^{2/3}$ K. The value of A is obtained from the continuity of pressure at $\rho = \rho_o$.

3. RESULTS AND DISCUSSION

We considered systems with a primary of mass 1 $M_\odot$ and 0.6 or 0.8 $M_\odot$ companions. We then searched for white dwarf plus thick disk configurations with distributions of angular momentum given by (1) and $\gamma = 1.4$. The central and transition densities ρ_c and ρ_o were adjusted so as to conserve mass and energy while angular momentum conservation is automatic when (1) is adopted. For infinite b, i.e. a uniform angular momentum distribution, no solution can be found, in agreement with the work of Hachisu et al. [13]. However, a uniform j disk is detached or just in contact with the central white dwarf, which is not the most likely configuration to be produced in the merging process. The primary occupies a large fraction of its Roche lobe before coalescence and the transferred material strikes it directly. We therefore believe that configurations in which the disk takes some pressure support on the central white dwarf are more probable. It is then possible to find solutions conserving mass, angular momentum and energy for $b < b_{max}$ ($b_{max} = 75$ for $M_2 = 0.6$ $M_\odot$, $b_{max} = 20$ for $M_2 = 0.8$ $M_\odot$). The solution with $b = b_{max}$ is entirely degenerate, while for $b < b_{max}$, the transition density and temperature increase, which corresponds to a growing lift of degeneracy in the disk. We also found that for $b < b_{ign}$ ($b_{ign} = 17$ for $M_2 = 0.6$ $M_\odot$, $b_{ign} = 5$ for $M_2 = 0.8$ $M_\odot$), the transition point (ρ_o, T_o) lies above the carbon ignition line which means that dissipation during coalescence has triggered carbon burning in the disk. We have represented in Fig. 1 an intermediate solution for the $M_2 = 0.8$ $M_\odot$ case, corresponding to $b = 12$.

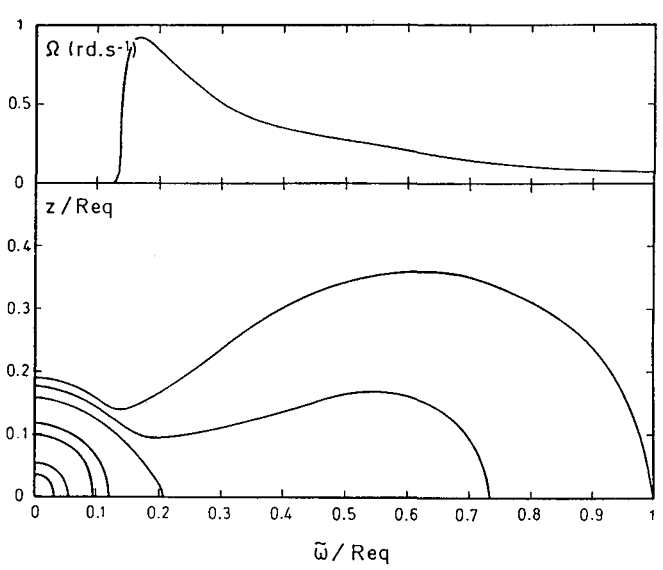

Figure 1: Equilibrium configuration after coalescence obtained with $\gamma = 1.4$ and $b = 12$. The total mass, central density, transition density and temperature and equatorial radius are respectively M = 1.8 $M_\odot$, $\rho_c = 4.5\ 10^7$ g.cm^{-3}, $\rho_o = 2.5\ 10^5$ g.cm^{-3}, $T_o = 3.7\ 10^8$ K, $R_{eq} = 2.6\ 10^9$ cm. The upper curve gives the distribution of angular velocity ($\Omega = 0$ in the inner 1 $M_\odot$) and the lower figure shows the shape of isodensity contours $\rho/\rho_c =$ 0.8, 0.5, 0.2, 0.1, 0.01, 0.001 and 0.

Even if such a model does not ignite carbon during coalescence, it will probably do it shortly after in the boundary layer and inner disk region where a very high shear is present and turbulence is likely to develop (the Richardson criterion for stability is strongly violated there). With an α-type prescription for the turbulent viscosity, values of ν_{turb} as large as $10^{11} - 10^{12}$ cm^2.s^{-1} are obtained, leading to a dissipation rate which can reach 10^{11} erg.g^{-1}.s^{-1} in the boundary layer and 10^9 erg.g^{-1}.s^{-1} in the inner disk.

We then conclude that carbon will be ignited off-center, in a relatively low density, partially or non degenerate material ($10^5 - 10^6$ g.cm^{-3}) either during the merging process itself, or later on in the just-formed disk. Such physical conditions cannot directly give a SN Ia explosion. It is not clear at all whether carbon burning (to O – Ne – Mg composition) will propagate inward into the white dwarf or outward in the disk (or both !) or if it will be rapidly quenched, for example by material expansion. In the first case, the O – Ne – Mg white dwarf which is formed can collapse to become a neutron star with only a weak explosion [14], while in the second case, the nuclear energy which is still available may not be large enough to power a SN Ia [15].

It finally appears that the evolution which follows carbon ignition remains very uncertain. Now that the possibility of dynamical merging has been confirmed [11], an important theoretical effort is still to be made to prove that a SN Ia can indeed result from white dwarf coalescence.

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