THE PROGENY OF BINARY WHITE DWARF MERGERS

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1. White-dwarf white-dwarf binaries

Since 1984 it has been proposed that at least some highly-evolved stars are the product of the merger of a white-dwarf white-dwarf binary (WDB) system [31], [9]. The principle behind the idea is that orbital angular momentum is removed from the binary by means of gravitational radiation (GR) and that, within a Hubble timescale, the less massive white dwarf would come into contact with its Roche lobe and a catastrophic phase of mass transfer would begin. During the 1980’s, a serious and valid criticism was that there was no significant observable population of WDBs from which to form the number of supposed merger products. This situation changed during the 1990’s with the discovery [16] of substantial numbers of binary white dwarfs. Further discoveries are continuing as a result of large-scale white dwarf surveys [20].

These surveys now largely confirm the conclusions of theoretical stellar population synthesis studies which compute the birth-rate of WDBs in the Galaxy to be $\sim 0.05y^{-1}$, of which 20% consist of a carbon/oxygen and a helium (CO+He) white dwarf pair [22]. There should thus be approximately $1.5 \times 10^8$ CO+He WDBs in the Galaxy. The timescale for orbital decay by GR is given by

$$(\tau_m/y) = 10^7 (P/h)^{8/3} \mu^{-1} (M/M_{\odot})^{-2/3},$$

where $P$ is the orbital period, $\mu$ is the reduced mass and $M$ the total mass of the system [16]. Population synthesis studies indicate a merger frequency
for the Galaxy of between $2.3 - 4.410^{-3} \, \text{yr}^{-1}$ [22], [11]. An observed fraction of WDBs [17] indeed have periods less than a few hours and will merge within a Hubble time. Some authors argue that WDB mergers may produce type Ia supernovae, but other outcomes are more likely [9], [28], [29].

2. Binary white dwarf mergers

As a result of orbital decay by GR, the less massive and consequently larger WD will eventually fill its Roche lobe and some mass will be transferred to the companion. If the mass ratio $q \geq 0.6$, the increase of stellar radius due to the reduction of mass will exceed the increase in the Roche radius caused by the transfer of angular momentum. Since the mass-radius relation for the WD is governed by the requirement of hydrostatic equilibrium, the radius will increase on a dynamical timescale ($\sim s$), leading to runaway mass transfer. If $q \leq 0.6$, stable mass transfer will occur, possibly leading to the formation of AM CVn systems (He+He WDBs) [21].

Simulations of the merger process have been attempted using smooth particle hydrodynamics [3], [30], [12]. These demonstrate the total disruption of the low-mass WD within roughly one orbital revolution ($\sim 90$ s) and the conservation of $\sim 90\%$ of its mass within a thick disk. Our working assumption is that the more massive WD will then accrete material from this thick disk at a rate close to the Eddington accretion rate; we have generally adopted $10^{-6} \, \text{M}_\odot \, \text{yr}^{-1}$.

The evolution of a He WD rapidly accreting helium (He+He WD merger) was first considered before WD mergers were widely recognised as important [23]. This and subsequent calculations have pursued the evolution through off-centre helium ignition [24], [13], [14], [11], [29]. Our simulations [26] follow the evolution of the more massive WD as it accretes material from a thick disk. As the non-degenerate helium envelope reaches a critical mass, helium-burning reactions ($3\alpha$) are ignited at the core-envelope boundary. These raise the luminosity and radius of the star to those of a yellow supergiant. They also raise the temperature of the outer layer of the core sufficient for helium ignition. The helium-burning shell consequently propagates inwards by a series of mild flashes until it reaches the core. The stellar envelope responds to each flash by over-contracting and then relaxing until the star reaches the helium main sequence.

The evolution of a CO WD accreting a carbon-oxygen mixture (CO+CO WD merger) has also been studied extensively [13], [14], [24], [18], [29]. This case also gives rise to an off-centre ignition of carbon. The carbon-flame burns into the CO core and leads to the formation of a O-Ne-Mg WD.

In contrast, the evolution of a CO WD rapidly accreting helium (CO+He WD merger) has only been conjectured to give rise to an R CrB star or
SN Ia explosion [31], [9], [11]. Our new calculations [27] follow evolution through ignition of helium at the core-envelope boundary, which causes the star to expand rapidly (\(\sim 10^3\) y). Most accretion occurs while the star is a supergiant from a disk orbiting within the stellar envelope. Once accretion ends, and the helium shell has sufficiently reduced the helium envelope mass, the star contracts to become a white dwarf.

In all cases the numerical results are critically sensitive to the accreting WD temperature, to the accretion rate and to contamination by hydrogen. Of particular interest, however, are specific properties of the predicted merger products. These are necessary in order to make comparisons with observations of putative merger products and hence test the merger hypotheses. Note that our merger calculations are denoted by the accretor mass with the accreted mass in parentheses, e.g. 0.4(0.3) \(M_\odot\).

3. Observational identification of white dwarf merger products

Simulations of an He+He WD merger have been compared directly with observations of the extreme helium star (EHe) V652 Her [26]. This is a radially pulsating EHe for which the mass, radius, luminosity and surface chemical composition are well known [6], [8]. The evolutionary tracks for 0.4(0.2–0.3) \(M_\odot\) He+He WD mergers accurately reproduce all of these observables, including the CNO-processed helium surface and the pulsation period change [15].

The majority of EHe and RCrB stars are single low-mass supergiants with temperatures between 7000 and 35 000 K, luminosities \(\sim 10^4\) \(L_\odot\), and surface composition \(\sim 99\%\) helium and 1\% carbon (by number) [7], [2], [25]. Recent observations have added information about masses and contraction rates [7]. Our models for CO+He mergers predict a range of properties once the products complete accretion. Models for 0.6(0.2) and 0.6(0.3) \(M_\odot\) mergers give luminosities that agree very well with measurements of the 0.8 and 0.9 \(M_\odot\) EHe V2244 Oph and PV Tel [7]. Surface gravity measurements place all EHe and RCrBs on the evolutionary tracks for 0.5(0.1) – 0.6(0.3) \(M_\odot\) mergers, mostly towards the high-mass limit. Measured contraction rates for V2076, Oph, V2205 Oph, NO Ser and PV Tel [7] agree with 0.6(0.3) \(M_\odot\) merger models. Models also predict He- and C-enriched surfaces as observed. Finally, the observed space densities agree with the predicted merger rates and evolutionary time scales to within a factor three. No other models, notably the final-flash model [10], satisfactorily accounts for all of these observables.

An He+He WD merger produces helium main sequence stars of \(\sim 0.5 – 0.6\) \(M_\odot\) and has been identified as a possible progenitor of subdwarf B (sdB) stars [11]. However the merger surfaces are likely to be dominated by CNO-
processed helium from the core of the disrupted He WD, rather than the hydrogen-dominated surfaces normally seen on sdB stars. A few helium-rich sdB stars have been identified spectroscopically [5], [19]. A recent analysis [1] shows they are ~1 dex more luminous than normal sdB star and lie on our evolutionary tracks for He+He WD mergers, connecting the lowest luminosity EHe stars and helium-rich subdwarf O stars [4]. However, they appear to have C-rich surfaces and are currently more likely to be low-mass CO+He WD mergers. This question is still open.

References