131. Double white dwarf mergers

Over the past 5–10 years, fascinating results have been emerging on the occurrence of white dwarf–white dwarf binary systems, and on the observational consequences of the eventual merger of the two white dwarfs. The story involves gravitational waves, the unusual properties of 'ultra-massive' white dwarfs, and the precursors of (some) type Ia supernovae. With its various complexities, a little background is appropriate.

White dwarfs are the 'end of the road' for stars with initial masses $\lesssim 9 M_\odot$, and they account for some 97% of all evolved stars. For progenitor main-sequence masses $0.5 - 8 M_\odot$, the core will become sufficiently hot to fuse helium into carbon and oxygen, but not to fuse carbon into neon. When the star's outer material is expelled during the asymptotic giant branch planetary nebula phase, a C–O white dwarf core, the most common of the white dwarf spectral types, is left to cool.

Less commonly (and not so relevant to this story), in the progenitor range $8 - 10 M_\odot$, the fusion process may result in a remnant white dwarf composed chiefly of O, Ne, and Mg. But generally the most massive stars continue to fuse C to Ne, and then Ne to Fe, the process generally leading to a core-collapse (type II) supernova along with a remnant neutron star or black hole.

Magnetic fields, the result of surface magnetic flux conservation as the star contracts, are also relevant to the study of white dwarf mergers. Determined spectroscopically through Zeeman splitting, magnetic fields ranging from $0.2 - 10^5$ T have been measured for some hundreds of objects. About 10% of isolated white dwarfs have particularly high magnetic fields, $\gtrsim 10^2$ T.

Although white dwarfs are known with masses in the range $0.17 - 1.33 M_\odot$, the distribution is peaked at $0.6 M_\odot$, and the majority lie between $0.5 - 0.7 M_\odot$. The physics of degeneracy yields a maximum mass for a non-rotating white dwarf, the Chandrasekhar limit, $\sim 1.44 M_\odot$, beyond which it cannot be supported by electron degeneracy pressure. A C–O white dwarf that approaches this mass limit, typically by mass transfer from a companion star, may explode as a type Ia supernova.

White dwarf–white dwarf binaries are a late evolutionary stage of the wider class of stellar binaries. Initially with both stars on the main sequence, one component will evolve into a giant or a white dwarf and, unless the binary is disrupted, and ignoring the complexities of Roche-lobe overflow, the system will eventually evolve into a double white dwarf.

Double white dwarfs are the main source of low-frequency gravitational waves detectable by future space missions such as LISA and Tian-Qin. Indeed, it is only gravitational wave energy loss that determines the binary's subsequent orbital evolution and final merging. Some 400 short-period candidates have been identified on the basis of Gaia EDR3 by Ren et al. (2023).

Double white dwarfs are also considered as possible progenitors of some type Ia supernovae (e.g. Webbink, 1984; Guillochon et al., 2010; Maoz et al., 2014).

Theoretical work suggests that many double white dwarfs should merge within a Hubble time, and that their merger products should then exist in the solar neighbourhood (e.g. Maoz et al., 2018). Many of these mergers are expected to produce a single white dwarf of higher mass (Lorén-Aguilar et al., 2009). In consequence, some fraction of the highest mass white dwarfs in the solar neighbourhood are expected to be double-white dwarf merger products (Toonen et al., 2017).

With white dwarfs resulting from binary mergers perhaps making up 10–30% of all single white dwarfs, and 30–50% of massive white dwarfs, one consequence could be an underestimate of the age of some of the more massive 'single' objects (Temmink et al., 2020).

There are various approaches that have been used to verify the existence of these predicted merger products. One is to use number counts to search for an excess of high-mass white dwarfs (e.g. Rebassa-Mansergas et al., 2015; Tremblay et al., 2016). This method has been limited in its success by large systematic errors from the adopted initial–final mass-relation for white dwarfs, as well as sample incompleteness.

A SECOND APPROACH is to search for the *kinematic* signatures of these merged objects. This makes use of the fact that high-mass mergers are in general older than singly-evolved white dwarfs because of their binary evolution phase (Wegg & Phinney, 2012; Dunlap & Clemens, 2015). As a result, and as a consequence of the age–velocity-dispersion relation found for the Milky Way disk (Nordström et al., 2004), these older merged white dwarfs are expected to have a higher velocity dispersion.

Pre-Gaia, Wegg & Phinney (2012) had used proper motions from the colour-selected catalogues of the Sloan Digital Sky Survey and the Palomar–Green Survey, finding that the dispersion *decreases* with increasing white dwarf mass, and that the kinematics are consistent with the majority of high-mass white dwarfs being formed through single-star evolution.

This approach has also been limited by the paucity of good white dwarf kinematics. This has changed with Gaia (see essay #29), where some 260 000 candidates were identified in DR2 (Gentile Fusillo et al., 2019). And the EDR3 catalogue of resolved binaries within 1 kpc (El-Badry et al., 2021), contains more than a million systems, including 16 000 white dwarf + main-sequence binaries, and 1400 double white dwarf binaries.

THE FIRST Gaia search for the kinematic signatures of white dwarf–white dwarfs mergers was made in DR2 by Cheng et al. (2019). They selected white dwarfs in the range $1.08-1.23M_{\odot}$ to investigate the 'Q branch', the overdensity of white dwarfs in the HR diagram caused by anomalous cooling due to core crystallisation (essay #42). A by-product of their kinematic analysis was that the fraction of double-white dwarf mergers in their mass range was some 22%.

Cheng et al. (2020) extended the analysis to a sample some 30 times larger than that available to Wegg & Phinney (2012), over a wider mass range, and with a more detailed prescription for the binary system's evolution. From the transverse-velocities of more than 1000 high-mass white dwarfs (in the range $0.8-1.3M_{\odot}$) they estimated that the fraction of double-white dwarf merger products in their sample is about 20%.

Fleury et al. (2023) reported further work on the anomalous transverse velocities of ultra-massive white dwarfs using data from Gaia EDR3.

Cheng et al. (2020) converted their fraction of inferred mergers into a Galactic white dwarf merger rate, per unit stellar mass, of $1.1\pm0.3\times10^{-13}M_{\odot}^{-1}\,\mathrm{yr}^{-1}$, a factor 2–3 more accurate than previous determinations.

This merger rate supports the idea that double-white dwarf mergers may contribute to a significant fraction of type Ia supernovae. These are predicted to occur during unstable mass transfer between them: the D^6 (or 'dynamically driven double-degenerate double-detonation') mechanism (Guillochon et al., 2010).

IN THIS D^6 scenario, the supernova detonation fully disrupts the accreting white dwarf, and possibly releases the donor white dwarf from the binary as a hypervelocity runaway star at its former orbital velocity.

Using Gaia DR2, Shen et al. (2018) identified three candidate D^6 remnants, all with Galactocentric velocities > 1000 km s^{-1}. These three objects were confirmed with Gaia EDR3 (Bauer et al., 2021), providing new constraints on the mass and radius of the donor white dwarf that becomes the hypervelocity runaway.

GAIA IS ALSO being used to identify specific massive white dwarfs likely to be such merger products. Kilic et al. (2021), and later Kilic et al. (2023), searched the Montreal White Dwarf Database 100 pc sample, using Gaia DR2 parallaxes and proper motions to identify 4–5 outliers in transverse velocity (as well as 4 possible candidate mergers from their magnetic field, and one with rapid rotation). Of 25 'ultra-massive' objects with $M>1.3M_{\odot}$, they concluded that at least 8 are likely to be the result of mergers. Others are being identified from SDSS and ZTF candidates (Sousa et al., 2022).

ANOTHER WAY of statistically identifying merger products was taken by Fleury et al. (2022) using Gaia EDR3. From white dwarfs within 200 pc, in the range $0.95-1.25M_{\odot}$, they compared the cooling age distributions to the (Gaia-derived) time-varying star formation rate for main sequence stars, for each of three mass bins.

For white dwarfs in the range $0.95-1.15M_{\odot}$, they found a cooling age distribution consistent with the star formation rate found from Gaia DR2 by Mor et al. (2019). For the most massive, $1.15-1.25M_{\odot}$, the distribution was better matched by a contribution from double white dwarf mergers, assuming that 40–50% of the white dwarfs formed over the past 4 Gyr are produced through double white dwarf mergers.

With the growing evidence for the existence of a number of ultra-massive CO white dwarfs arising from double white dwarf mergers, Neopane et al. (2022) have shown that the merger process naturally produce highly magnetised, uniformly rotating white dwarfs, including a substantial population within a narrow mass range close to the Chandrasekhar mass.

And Camisassa et al. (2022) have modelled evolutionary (cooling) sequences, accounting for realistic initial chemical profiles, the energy released by latent heat and phase separation during crystallisation, and the energy released by the slow sedimentation of ^{22}Ne.

TODAY, Gaia is providing accurate distances and space motions of huge numbers of white dwarfs in the solar neighbourhood. From them, the properties of a subset of the most massive are confirming them to be the products of double white dwarf mergers. Nice!