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## 263. The progenitors of supernovae SN Ia

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**S**UPERNOVAE are classified according to the shape of their light curves, and their absorption lines: SNe Type II show H lines, while Type I do not. Sub-classes of both types are assigned according to the presence of other spectral lines (specifically Si and He), and the light curve profile. SNe Ia are characterised by their strong Si II 615 nm line near peak light (e.g. Turatto, 2003).

Theoretical studies indicate that SNe Ia result from ‘thermal runaway’ following the rapid ignition of nuclear fusion in a white dwarf (e.g. Nomoto, 1982). In contrast, Type Ib/c (and the various sub-classes of Type II) result from the sudden gravitational collapse of a massive stellar core. SNe Ia display a fairly constant peak luminosity, underpinning their use as standard candles for establishing the cosmological distance scale.

**T**YPE IA SUPERNOVAE occur in binary systems in which one component is a white dwarf, while the other may range from a main-sequence or giant star (single-degenerate systems), or to another white dwarf (double-degenerate systems). Broadly, if the progenitor gradually accretes mass from its binary companion (or merges with another white dwarf), the core reaches the ignition temperature for C fusion as it approaches the Chandrasekhar mass ( $\sim 1.4M_{\odot}$  for a slowly rotating C–O white dwarf). Possibly following a period of convection extending over  $\sim 10^3$  years, a large fraction of the C and O then fuses into heavier elements within a few seconds, releasing sufficient energy,  $\sim 10^{44}$  J, to unbind the star.

However, the precise nature of SN Ia progenitors, how the white dwarfs reach an explosive state, and the explosion details, are still not fully established (e.g. Hillebrandt & Niemeyer, 2000; Mannucci et al., 2006; Mazzali et al., 2007; Maoz et al., 2014; Maguire, 2017).

More details of the possible progenitor scenarios are given in the review by Ruiter & Seitenzahl (2025, §1.2). A schematic of the evolutionary paths for SNe Ia in the single- and double-degenerate binary scenarios is given by Liu et al. (2023, Fig. 2), who conclude that ‘*No single published model is able to consistently explain all observational features and the full diversity of SNe Ia*’.

**O**BSERVATIONS suggest that the ‘double degenerate’ (DD, i.e. white dwarf–white dwarf) mergers account for the majority of SNe Ia. Evidence includes (i) an absence of ‘runaway’ remnants (such as a red giant or main-sequence star, expected in the single degenerate case) in searches of nearby SN Ia fields; (ii) the absence of an optical/ultraviolet flash expected if the shockwave impacts a close non-degenerate companion; (iii) the absence of H or He emission that would be expected if the supernova ejecta impacts the companion star.

Within the DD scenario, two sub-mechanisms are believed to operate: (a) dynamical mergers as the two inspiraling white dwarfs collide and detonate (such events have not yet been detected in gravitational wave signals, e.g. Sala et al., 2026); (b) ‘double detonations’, where a thin He layer accreted onto a primary C–O white dwarf detonates first, sending a shockwave into the core, and triggering core C detonation (even though the primary may be well below the Chandrasekhar mass). Believed to be the primary driver of normal Type Ia events, this leaves ‘*...the fate of rapidly accreting Chandrasekhar mass white dwarfs in the single-degenerate channel more mysterious than ever*’ (Fisher & Jumper, 2015).

**G**AIA IS CONTRIBUTING to an understanding of the origin of SNe Ia by searching for surviving (ejected) remnants of post-supernova systems; determining double degenerate orbits as an input to tests of evolutionary models; and identifying progenitor binaries.

A significant result concerning ejected remnants has been the search for *hypervelocity* white dwarfs, predicted by the so-called D6 (‘dynamically-driven double-degenerate double-detonation’) scenario. Using Gaia DR2, Shen et al. (2018) reported the first three candidates, with Galactocentric velocities  $1000\text{--}3000\text{ km s}^{-1}$ , consistent with their origin in pre-SN Ia systems. The past position of one of them lies within an old supernova remnant, further strengthening the interpretation.

Four more were reported from DR3 by El-Badry et al. (2023). I have said more on these, and follow-up observations, in essay 261 on ‘hypervelocity white dwarfs’.

THE VARIOUS SN Type Ia formation channels (single-degenerate, double-degenerate, and double-detonation) make different predictions for the numbers and properties of white dwarf binaries.

In this context, two major catalogues of binary systems including at least one white dwarf (and thus candidates for studying binary evolution and SN Ia progenitors) have been constructed from the Gaia data. In the first, Ren et al. (2020) used Gaia DR2 to construct a sample of 775 white-dwarf + AFGK-star binaries, identifying 23 close systems through radial velocity measurements.

A significant advance came with the EDR3-based catalogue of 1.1 million binaries within 1 kpc, with projected separations ranging from a few au to 1 pc, and with >99% probability of being bound (El-Badry et al., 2021). It includes 16 000 white dwarf–main sequence (WD+MS) binaries, and 1400 WD+WD binaries.

THERE ARE two related consequences of the eventual merger of these WD+WD systems. The first is that they are one of the gravitational wave classes targeted by the ESA–NASA LISA mission, and China’s TianQin. Pre-Gaia, around 25 short-period compact white dwarf binaries ( $P \lesssim$  few hours) were considered to be ‘guaranteed’ LISA sources, often referred to as ‘verification binaries’. Some 1000–10 000 are expected to be individually resolved and characterised by LISA. New candidates have been reported based on Gaia DR2 by Kupfer et al. (2018), on EDR3 by Ren et al. (2023), and on DR3 by Kupfer et al. (2024). I said more on this in essay 136.

The other related topic is that of ‘ultra-massive’ white dwarfs, formed by the non-explosive merger of a WD+WD binary. Here, theory 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 than typical mass (e.g. Lorén-Aguilar et al., 2009; Toonen et al., 2017). Again, I said more on this, and the impact of the Gaia data, in essay 131.

RETURNING TO my main topic, certain binary systems have been examined either as supernova progenitors (and testable against evolutionary models), or for surviving remnants (e.g. Ruffini & Casey, 2019; El-Badry, 2024). Presently, only three systems are known with very short orbital periods ( $\lesssim 2$  hr), and sufficiently large masses to be considered as potential supernovae.

Pelisoli et al. (2021) focused on HD 265435, comprising a hot subdwarf and white dwarf. Gaia EDR3 was used to place accurate constraints on their luminosities, masses and radii, with evolutionary models explaining the system’s origin, its expected merger via gravitational-wave radiation 71.8 Myr in the future, and with a thermonuclear supernova being the most likely outcome.

Kupfer et al. (2022) found PTF1 J2238+7430 to be a double-detonation progenitor. Again, it consists of a hot subdwarf ( $0.383 M_{\odot}$ ) and a white dwarf ( $0.725 M_{\odot}$ ), with  $P = 76$  min. High cadence light curves are dominated by ellipsoidal deformation of the sdB star and a weak eclipse of the white dwarf. From models based on spectroscopy and Gaia astrometry, they infer that the sdB formed first through stable mass transfer, followed by a common envelope phase which led to the formation of the white dwarf companion 25 Myr ago. They estimate that the sdB star will start mass transfer in 6 Myr, and in 60 Myr the white dwarf will reach a total mass of  $0.92 M_{\odot}$  with a thick He layer of  $0.17 M_{\odot}$ , leading to detonation.

Deshmukh et al. (2024) performed similar modelling of CD–30, a hot subdwarf–white dwarf binary previously identified as a double detonation progenitor (Vennes et al., 2012; Geier et al., 2013). It is viewed at high enough inclination to show both eclipses in its light curve, yielding estimates of  $\log g$  and  $T_{\text{eff}}$  for both components. Using data from Gaia EDR3, they show that, accounting for the structure of the H envelope, the inclusion of element diffusion is important for matching the observed white dwarf radius and temperature. Their model confirms CD–30 as a double detonation supernova progenitor, in which the white dwarf accretes a  $0.17 M_{\odot}$  thick He shell, which dominates the system luminosity during the final 15 Myr, resulting in a detonation in 55 Myr, and which will leave a  $0.30 M_{\odot}$  sdB star ejected at  $750 \text{ km s}^{-1}$ .

IN ADDITION TO the search for hypervelocity white dwarfs, there have been other Gaia-based searches for binary supernova survivors.

Ruffini & Casey (2019) used Gaia DR2 to investigate LP 93–21, a high-velocity white dwarf with Galactocentric velocity of  $605 \text{ km s}^{-1}$ . It has an ‘unusual’ atmospheric composition, and is inferred to be a subluminous star some 15 times larger than a typical white dwarf, and consistent with ejection from a supernova in the SN Iax sub-class. Here, the white dwarf undergoes a weaker asymmetric explosion not strong enough to fully obliterate the star (e.g. Jordan et al., 2012; Foley et al., 2013; Kromer et al., 2013; Zhang et al., 2019).

Several members of this SN Iax class are now known (e.g. Ko et al., 2026), and a number have also been investigated using the Gaia data, including LP 40–365 (Raddi et al., 2018), and Galactic SN 1181 (Uno et al., 2026).

Igoshev et al. (2023) used Gaia DR3 to identify four high-velocity white dwarfs highly likely to be unbound, and an additional 42 possibly unbound, amongst which 25 were classified as hyper-runaways. They concluded that the number of candidates, and their velocity distributions, could be consistent with the expected contributions from SNe Iax, but likely rules out the double-detonation D6-model as a main contributor to the origin of normal type SNe Ia.