# 261. Hypervelocity white dwarfs

I have reviewed Gaia's contributions to the study of hypervelocity stars in three previous essays (#22 in May 2021, #166 in Mar 2024, and #245 in Feb 2026). Here, I will focus on the still somewhat mysterious subset of hypervelocity white dwarfs.

Hypervelocity stars, let me recall, are the extreme high-velocity tail of the Galaxy's stellar velocity distribution, with space velocities much higher than the classical 'runaway stars' (whose velocities of 30–200 $\mathrm{km\,s^{-1}}$ originate from their ejection from star clusters, either through gravitational slingshots, or through the 'kick' of a supernova explosion in a binary system).

The even more extreme 'hypervelocities' were predicted by Hills (1988). He showed that a close encounter between a tightly bound binary, and a supermassive black hole of $\sim 10^6 M_\odot$, causes one component to become bound to the black hole, and the other to be ejected at velocities of 700–1000 $\mathrm{km\,s^{-1}}$ or more. With velocities high enough to escape the Milky Way's gravitational potential, they have become of interest as probes of the structure of the dark matter halo (e.g. Koposov et al., 2020; Gallo et al., 2022; Armstrong et al., 2025).

The first such discovery, SDSS J090745+0245077 (HVS1), was found, from SDSS, to have a radial velocity of ~800 $\mathrm{km\,s^{-1}}$ (Brown et al., 2005). At a distance of ~55 kpc, 30 kpc above the disk and 60 kpc from the Galactic centre, its space motion was consistent with ejection from the Galactic centre region. And models demonstrated consistency with its generation, via the Hills mechanism, from the $4 \times 10^6 M_\odot$ black hole (Sgr A*) at the centre of our Galaxy (Brown, 2015).

Today, around 50 hypervelocity stars have been discovered, by SDSS, LAMOST, AAT-2df, Gaia, and the dedicated HVS Survey. The latter targeted main-sequence B stars, the logic being that young halo stars – in the absence of ongoing star formation – must have been propelled there. Although their sky distribution is not fully understood, it appears that many are indeed consistent with a Galactic centre origin, while a significant fraction originate from the LMC (essay 245; Han et al., 2025).

As it became clear that many hypervelocity stars could not have originated from the Galactic centre (e.g. Irrgang et al., 2021), other similarly highly disruptive ejection mechanisms have been suggested and investigated, mostly involving black holes in one form or another (essay 166).

The mechanism of interest for hypervelocity white dwarfs is very different, and more related to the 'binary supernova scenario' (BSS), developed in the 1970s to explain runaway stars (essay 165). This 'dynamically driven double-degenerate double-detonation' (D6) mechanism (Fink et al., 2010; Guillochon et al., 2010), has also been considered as one of the most promising progenitor scenarios for Type Ia supernova (SN Ia).

In the standard degenerate-driven supernova explosion mechanism, the white dwarf companion is a non-degenerate (main sequence or red giant) star. The white dwarf explodes, through detonation of its C core, as a result of mass-transfer when it reaches the Chandrasekhar limit, $\sim 1.4 M_\odot$. The companion survives.

In the D6 mechanism, both binary components are white dwarfs (hence doubly degenerate). Roche lobe overflow of the donor provides a He-rich accretion stream onto the companion. This (dynamically driven) stream heats the companion's own He surface, which then experiences a thermonuclear detonation, which in turn triggers core C detonation (double-detonation), even for masses below the Chandrasekhar limit.

A surviving donor can be released as a hypervelocity white dwarf, with the velocity of its 1000–3000 $\mathrm{km\,s^{-1}}$ pre-supernova orbital speed (Shen et al., 2018; Evans et al., 2020; Bauer et al., 2021; Shields et al., 2022; Igoshev et al., 2023; Liu et al., 2023; Braudo & Soker, 2024).

Variations of this mechanism include the single-degenerate double-detonation scenario, in which a sufficiently massive white dwarf can accrete He from a stripped He-rich companion (Woosley et al., 1986). Recent studies appear to exclude this mechanism on the basis of ejection velocities (Liu et al., 2021; Meng & Luo, 2021), and event rates (Neunteufel et al., 2022).

| Name | $v_r$ [km s$^{-1}$] | $v_{tot}$ [km s$^{-1}$] | $v_{ejection}$ [km s$^{-1}$] | $T_{eff}$ [K] | $R$ [$R_\odot$] | $d$ [kpc] | $z$ [kpc] | $t_{disk}$ [Myr] |
|---|---|---|---|---|---|---|---|---|
| D6-1 | 1200±40 | $2045^{+251}_{-190}$ | $2254^{+248}_{-199}$ | 7000 | $0.23^{+0.04}_{-0.03}$ | $1.91^{+0.2}_{-0.2}$ | $-0.57^{+0.07}_{-0.06}$ | $0.63^{+0.04}_{-0.04}$ |
| D6-2 | 80±10 | $1151^{+59}_{-55}$ | $1051^{+62}_{-52}$ | 7000 | $0.15^{+0.01}_{-0.01}$ | $0.84^{+0.05}_{-0.04}$ | $-0.27^{+0.01}_{-0.02}$ | $-0.72^{+0.01}_{-0.01}$ |
| D6-3 | -20±80 | $2248^{+340}_{-324}$ | $2393^{+377}_{-396}$ | 7000 | $0.17^{+0.02}_{-0.02}$ | $2.26^{+0.34}_{-0.35}$ | $0.93^{+0.14}_{-0.14}$ | $2.24^{+0.21}_{-0.17}$ |
| J1235-3752 | -1694±10 | $2670^{+339}_{-250}$ | $2471^{+351}_{-256}$ | 21000 | $0.104^{+0.026}_{-0.030}$ | $4.53^{+2.17}_{-1.82}$ | $1.73^{+0.42}_{-0.50}$ | $1.87^{+0.86}_{-0.25}$ |
| J0927-6335 | -2285±20 | $2753^{+271}_{-148}$ | $2519^{+271}_{-147}$ | 60000 | $0.052^{+0.025}_{-0.020}$ | $4.07^{+1.01}_{-0.70}$ | $-0.70^{+0.27}_{-0.35}$ | $-1.32^{+0.42}_{-0.42}$ |
| J0546+0836 | 1200±20 | $1699^{+660}_{-390}$ | $1864^{+682}_{-416}$ | 95000 | $0.051^{+0.029}_{-0.021}$ | $4.02^{+2.29}_{-1.67}$ | $-0.69^{+0.29}_{-0.40}$ | $0.61^{+0.08}_{-0.08}$ |
| J1332-3541 | 1090±50 | $1464^{+707}_{-331}$ | $1619^{+707}_{-320}$ | 70000 | $0.017^{+0.013}_{-0.007}$ | $1.63^{+1.19}_{-0.68}$ | $0.74^{+0.53}_{-0.30}$ | $0.64^{+0.13}_{-0.14}$ |

Glanz et al. (2025)

IN DISCUSSING Gaia's contributions, I should stress that, while all known hypervelocity stars are too distant even for their Gaia parallaxes to be of value, their spectroscopic radial velocities along with their Gaia proper motions, combined with distance estimated from stellar evolutionary models, provide crucial estimates of their space motions.

Shen et al. (2018) reported the first search for hypervelocity runaway *white dwarfs* using Gaia DR2. This resulted in 3 sources with total Galactocentric velocities 1000–3000 km s$^{-1}$, consistent with their origin as white dwarfs in pre-SN Ia systems. The past position of one placed it within an old supernova remnant, further strengthening the interpretation. A further 4 were reported from Gaia DR3 by El-Badry et al. (2023). Properties of these 7 objects, from Supplementary Table 1 of Glanz et al. (2025b), are shown in the table above.

The observable runaway velocity of these remnant objects represents their orbital speed at the time of the supernova detonation. The orbital dynamics and Roche lobe geometry required in the D6 scenario then place specific constraints on the radius and mass of the donor white dwarf that becomes the hypervelocity runaway.

Resulting properties for the first three hypervelocity runaway white dwarfs, using Gaia EDR3, were given by Bauer et al. (2021), with more detailed simulations by Braudo & Soker (2024), and further searches based on Gaia DR3 reported by Igoshev et al. (2023).

But the D6 scenario faces difficulties in explaining the most extreme space velocities, $> 2000$ km s$^{-1}$, and their observed properties, in particular their high temperatures, and their extremely inflated radii which require '*... either an additional source of significant heating or some other physics that is not yet accounted for in the subsequent evolution*' (Bhat et al., 2025).

A VARIATION of the D6 mechanism, the 'hybrid-white dwarf reverse detonation scenario' may hold more promise. The starting point for these models are the so-called 'hybrid HeCO' white dwarfs, which also originate in close binary systems. They arise when the gravitational pull of the companion star strips away the outer H envelope prematurely, effectively interrupting the star's nuclear burning. As a result, the stripped star evolves into a remnant that bridges the gap between traditional He and CO white dwarfs (which originate from lower mass, $\lesssim 0.45 M_\odot$, and intermediate mass, $0.45 - 0.7 M_\odot$, progenitors respectively), and with 5–25% of their mass in He (Zenati et al., 2019).

As suggested by Pakmor et al. (2021), and similar to the D6 model, a highly He-enriched hybrid HeCO donor begins transferring mass onto a more massive white dwarf companion, again leading to a He surface detonation of the CO white dwarf. However, the He detonation fails to induce a detonation in the CO white dwarf. Instead, the nuclear reaction front propagates back to the donor. The shock leads to its own core detonation, leaving the primary intact, and ejected at its orbital velocity. With the less massive white dwarf being disrupted, the typical ejection velocities of the primary are lower than the D6 case, typically 1000–1500 km s$^{-1}$.

A FURTHER POSSIBILITY was identified by Glanz et al. (2025b). They constructed a 3D hydrodynamic simulation of a *merger* between two such hybrid HeCO white dwarfs, of $0.69 M_\odot$ and $0.62 M_\odot$. This leads to partial disruption of the secondary, and a double-detonation of the primary, which launches the secondary's remnant core at a some 2000 km s$^{-1}$, consistent with the systems observed. The low mass of the ejected remnant, and heating from the primary white dwarf's ejecta, seems to explain the observed luminosities and temperatures of the hot hypervelocity white dwarfs, which are otherwise difficult to reconcile with a simple D6 model (Braudo & Soker, 2025; Yamaguchi et al., 2025; Bhat et al., 2026; El-Badry et al., 2026).

As detailed in their §2, Glanz et al. (2025b) provide a movie visualising the merger of the two HeCO white dwarfs, and the subsequent ejection of the hypervelocity component. It shows the tidal disruption of the secondary, the double-detonation explosion of the primary, and the high-velocity ejection of the remnant core.

These developments also point to a pathway for producing peculiar Type Ia supernovae, and other faint explosive transients (e.g. Glanz et al., 2025a; Soker, 2025). The story is advancing, although questions remain!