166. Hypervelocity stars: part 2

JUST OVER two years has elapsed since my essay 22 on hypervelocity stars in mid-2021. But with more than 30 Gaia papers since then, an update is timely. Let me start with the context, and the status at that time.

Classical 'runaway' stars have been known for more than 60 years (see essay 165). Their space velocities, of 30–100 $km\,s^{-1}$, are sufficiently distinct from the overall stellar velocity distribution that they must have been imparted by some particular formation mechanism(s).

Two such processes appear to operate: a dynamical ejection scenario (DES), in which a star is ejected via dynamical interactions in a young compact cluster, and the binary-supernova scenario (BSS), where velocities are imparted in a supernova-driven binary disruption.

Even more extreme velocities in a related but more extreme environment were predicted by Hills (1988). He showed that a close encounter between a tightly bound binary, and a $10^6 M_\odot$ black hole, causes one component to become bound to the black hole, and the other to be ejected at up to 4000 $km\,s^{-1}$, or 1% of the speed of light!

THE FIRST hypervelocity star, SDSS J090745+0245077 (HVS1), was discovered, from SDSS, to have a radial velocity of ~800 $km\,s^{-1}$ (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 it having been ejected from the Galactic centre. 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).

In essay 22 I described the radial velocity surveys, at the MMT and LAMOST, set up to discover more of these stars, recalled estimates of their production rate, and mentioned their potential use as tracers of the Galaxy's potential as they escape its confines over some 300 Myr.

SINCE DR2 in April 2018, Gaia has been providing proper motions and distances of unprecedented accuracies, helping to confirm candidates (and refute others, e.g. Quispe-Huaynasi et al., 2022), and pinpointing their origins, while searching the entire sky for others.

A number of the other 30–40 early Gaia discoveries were also provisionally considered to be consistent with a Galactic-centre origin, such as HVS 22 with v ~1500 $km\,s^{-1}$. But at least one, HVS3, appeared to come from the Large Magellanic Cloud, suggesting that it harbours a massive black hole of its own.

Others appeared to come from elsewhere in the Galaxy disk (e.g. Li et al., 2018; Du et al., 2019; Marchetti et al., 2019). Amongst these are at least four white dwarfs (Shen et al., 2018; Ruffini & Casey, 2019), conjectured to be companions to primary white dwarfs that exploded as Type Ia supernovae, and suggesting that some may originate from extreme binary supernova ejections.

IN BRINGING the topic up-to-date, let me first mention the other (non-Gaia) discoveries, all since making use of Gaia for their further interpretation.

Following HVS1 came a number of other B-type hypervelocity halo stars: HVS2 (Hirsch et al., 2005), HVS3 (Edelmann et al., 2005), HVS4–HVS24 (Brown et al., 2006; Brown et al., 2007; Brown et al., 2014), HD 271791 (Heber et al., 2008), HIP 60350 (Irrgang et al., 2010), and LAMOST–HVS1 through LAMOST–HVS4 (Zheng et al., 2014; Huang et al., 2017; Li et al., 2018).

The AAT–2dF S5 project (Southern Stellar Stream Spectroscopic Survey) found its first, S5–HVS1 (Koposov et al., 2020), a $G = 16$ star with radial velocity 1020 $km\,s^{-1}$ (and with a Gaia DR2 proper motion $\mu_\alpha = 35.328 \pm 0.084$, $\mu_\delta = 0.587 \pm 0.125$ mas/yr). Together this yields a 3-d Galactocentric velocity 1755 ± 50 $km\,s^{-1}$ and, according to the authors, the *'only hypervelocity star confidently associated with the Galactic Centre'* at that time.

With the availability of Gaia DR2, Boubert et al. (2018) revisited ~500 (mainly late-type) high-velocity stars identified in the literature over the years, and found that most do not fall into the category of true hypervelocity stars. Li et al. (2021) emphasised the distinction between hypervelocity stars, 'hyper'-runaways (runaways that are unbound to the Galaxy), runaways, and fast halo stars (often simply reflecting the different rotation states of the disk and halo).

ADDITIONAL CONSTRAINTS on formation models are the 40 or so 'S stars' in close orbit around Sgr A* (e.g. Gillessen et al., 2017), which may represent the remaining captured stars (Generozov & Madigan, 2020).

Meanwhile, progress in characterising hypervelocity stars originating from the Galactic centre has led to an improved understanding of the conditions in the inner few parsecs of the Milky Way (Evans et al., 2022a; Evans et al., 2022b; Evans et al., 2023; Generozov et al., 2022; Generozov & Perets, 2022; Chu et al., 2023).

For example, from his models, Generozov (2020) suggested that S5–HVS1 is part of a larger stream, and predicted its spatial and velocity distributions.

AS IT BECAME clearer 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 put forward.

In addition to the original hypothesis of tidal disruption of binary stars by a single massive black hole in the Galactic centre (Hills, 1988; Yu & Tremaine, 2003; Bromley et al., 2006), these include single star encounters with a binary black hole (Yu & Tremaine, 2003; Sesana et al., 2006; Sesana et al., 2007); single star encounters with a cluster of stellar mass black holes around a massive black hole (O'Leary & Loeb, 2008); or the interaction between a globular cluster with a single or binary black hole (Fragione & Capuzzo-Dolcetta, 2016).

Additionally, three-body processes may dominate the high-velocity ejection from globular clusters, perhaps explaining some of the known hypervelocity stars (Weatherford et al., 2023; Cabrera & Rodriguez, 2023).

In the very different 'dynamically driven double-degenerate double-detonation' (D6) mechanism (for details and history, see Shen et al., 2018, §1), Type Ia supernovae may occur during unstable mass transfer between two white dwarfs in a binary. If the donor survives the explosion, it can be released as a hypervelocity star, with the velocity of its 1000–3000 km s^{-1} pre-supernova orbital speed. Further studies continue (e.g. Evans et al., 2020; Bauer et al., 2021; Shields et al., 2022; Braudo & Soker, 2023; Igoshev et al., 2023; Liu et al., 2023).

I SHOULD STRESS that the kinematic interpretation of most of these hypervelocity star candidates, including their confirmation (or otherwise), has used the Gaia distances and proper motions to determine the transverse component of the star's space velocity.

Of Gaia searches, the earliest were based on DR2 (Du et al., 2019; Marchetti et al., 2019; de la Fuente Marcos & de la Fuente Marcos, 2019; Li et al., 2021). Subsequent searches used EDR3 (Marchetti, 2021; Irrgang et al., 2021; Li et al., 2023), and most recently DR3 (Marchetti et al., 2022; Liao et al., 2023; El-Badry et al., 2023; Igoshev et al., 2023; Parthasarathy, 2023).

THE GAIA STUDIES are a mix of identifying previously known candidates, unbound stars not originating from the Galactic centre, and others of a possible extragalactic origin. El-Badry et al. (2023), for example, found six new runaways, including four with radial velocities >1000 km s^{-1} and total space velocities >1300 km s^{-1}, most likely the survivors of the 'D6-driven' scenario.

AS FOR THOSE originating from *beyond* our Galaxy, Gualandris & Portegies Zwart (2007) inferred that HE 0437–5439 was directed from the LMC, although this was later refuted by Brown et al. (2010). But stronger evidence that HVS3 originated in the LMC (Erkal et al., 2019) has prompted further work in this direction.

Evans et al. (2021) modelled stars ejected from the Milky Way and the LMC via the Hills mechanism, propagated in a combined potential in which the LMC is on its first infall. They identified simulated hypervelocity stars which should be recognisable in the stellar halo.

Lin et al. (2023) used DR3 to examine the space motions of 3119 massive O-B2-type stars in the LMC, and identified 98 as possibly escaping. They concluded that dynamical ejection is the dominant mechanism for the hypervelocity runaway stars in the LMC.

Montanari et al. (2019) used DR2 to identify the orbital intersection of two known stars, 20–40 Myr ago, with the Sagittarius dwarf spheroidal galaxy.

Li et al. (2022) used EDR3 astrometry, radial velocities, and [Fe/H], to find 60 high-velocity stars probably from the Sagittarius dwarf galaxy. Two are hypervelocity stars, possibly produced by the Hills mechanism.

Gülzow et al. (2023) modelled hypervelocity stars being generated in Andromeda. They estimated that their number, in *our* Galaxy, is between 12–3910.

Meanwhile, studies have continued into their use as probes of the detailed gravitational potential of the dark matter halo (e.g. Koposov et al., 2020, §6; Gallo et al., 2022), and in probing MOND (Chakrabarty et al., 2022).

FOLLOW-UP observations of hypervelocity stars include spectroscopy of 14 candidates from the MMT, where the results indicated that all but one are main sequence B stars of mass $2.5-5.M_\odot$, with ages 90–400 Myr and distances 30–100 kpc (Irrgang et al., 2018).

Martinez et al. (2022) modelled the hydrodynamical interaction between the stellar wind and surrounding material, demonstrating that this leads to strong particle acceleration and non-thermal radiation. They account for perhaps 0.1% of the sub-TeV Galactic cosmic ray flux.

I'M NOT AWARE of a recent synthesis, so I can't give the number of s*ecure* hypervelocity stars: perhaps 50? Nor are we clear how many originate in the Galactic centre, or via the D6 mechanism, or from other galaxies. But Gaia is making a substantial contribution to their study!