
245. Hypervelocity stars: part 3

THIS IS MY THIRD essay on the subject of hypervelocity stars, following essay 22 in May 2021 (when the Gaia DR2 studies were still somewhat in their infancy), and essay 166 in March 2024 (when significantly more DR3 results had become available).

To briefly re-introduce the topic, hypervelocity stars were predicted by Hills (1988), who 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 such candidate, HVS1, with a radial velocity of $\sim 800 \text{ km s}^{-1}$, was discovered from SDSS. At a distance of $\sim 55 \text{ kpc}$, 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 (Brown et al., 2005).

SOME 30–40 such hypervelocity stars have since been discovered in the Galaxy halo. The dedicated HVS Survey targeted (young) main-sequence B stars, the underlying logic being that young stars in the halo – in the absence of ongoing star formation – must have been propelled there. The survey, in a well-defined sky region corresponding to the SDSS survey footprint, has discovered 21 ($2.5 - 4 M_{\odot}$) objects at distances 50–120 kpc.

In essay 166 I noted 4 discoveries with LAMOST, the first in 2017, with 10 more recently reported by Sun et al. (2025). Others have been found by AAT-2dF and Gaia.

All are too distant even for their Gaia parallax-based distances to be of value, but their spectroscopic radial velocities along with their Gaia proper motions, combined with distance estimated from (main-sequence) stellar evolutionary models, provide the all-important estimates of their space motions.

But these new discoveries have introduced new complexities. For example it became clear, from their space motions, that a number of these hypervelocity objects could not have originated from the Galactic centre. Gualandris & Portegies Zwart (2007) inferred that HE 0437–5439 was directed from the LMC, although this was later refuted by Brown et al. (2010).

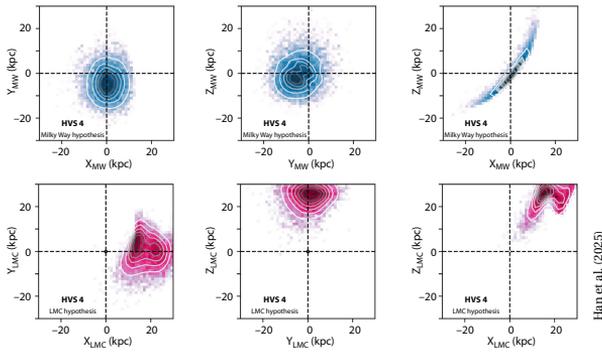
BUT STRONGER EVIDENCE that HVS3 originated in the LMC (Erkal et al., 2019) prompted further investigations. Evans et al. (2021) modelled stars ejected from the Milky Way and the LMC via the Hills mechanism, propagated in a combined potential in which the LMC is on its first infall. They identified hypervelocity proxies which should be recognisable in the stellar halo. And at least two others have been suggested as originating from the Sagittarius dwarf galaxy (Li et al., 2022).

Another complication is that other highly disruptive ejection mechanisms have been proposed to explain such extreme velocities, although they struggle to model the ejection rates observed. These include single star encounters with a binary black hole, as well as 3-body processes in globular clusters. One mechanism that has been considered in some detail is an extension of the binary-supernova scenario, BSS, itself put forward half a century ago to explain ‘runaway stars’.

Specifically, in the ‘dynamically driven double-degenerate double-detonation’ (D6) mechanism, which I said more on in essay 166, type Ia supernovae may occur during mass transfer between two white dwarfs in a binary. If the donor survives the explosion, it can be released with the velocity of its $1000\text{--}3000 \text{ km s}^{-1}$ pre-supernova orbital speed. But while such high velocities seem achievable for white dwarfs, this mechanism is not considered of relevance for main-sequence stars (e.g. Braudo & Soker, 2024; Glanz et al., 2025).

ONE FEATURE of the HVS Survey sample that has been difficult to explain is their anisotropic distribution on the sky: about half are found around the Leo constellation (aka the ‘Leo overdensity’), with 52% (11/21) clustered within only 5% of the HVS Survey footprint.

By restricting their study to the 21 hypervelocity stars from the well-defined selection function of the HVS Survey, Han et al. (2025) aimed to address whether the supermassive black hole at the centre of our Galaxy (Sgr A*), combined with a hypothesised supermassive black hole in the LMC (LMC*), can together explain the majority of these hypervelocity stars.



FOR THEIR model of the Milky Way–LMC system, they adopted specific masses given by one of the simulations of Garavito-Camargo et al. (2019), in which the LMC is just past its first pericentric passage. Orbits of the individual hypervelocity stars are propagated in a specific (and widely-adopted) Galactic potential, assuming that the Milky Way and LMC disks have not changed their orientation significantly in the past 400 Myr.

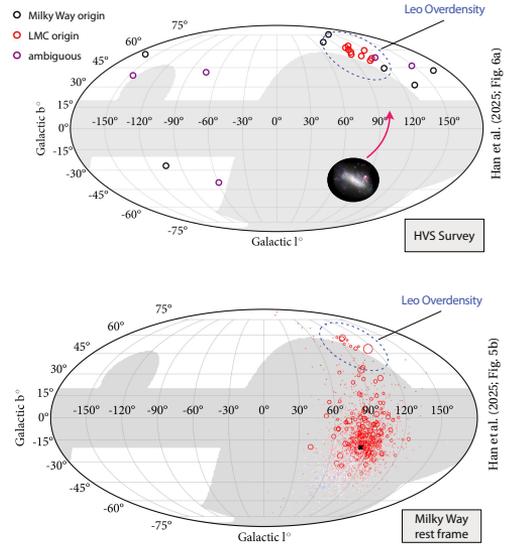
For each star, Han et al. (2025) drew 10 000 samples from the object’s radial velocity, distance, and proper motion uncertainties, recording the closest approach of each to the centres of both the Milky Way, and the LMC.

An example for HVS 4 is shown above in all three projections (top row, closest approach to the Milky Way in blue; bottom row, closest approach to the LMC in magenta). In this case, the star’s origin is clearly assigned to the Milky Way. Among the hypervelocity stars that could be confidently classified in this way, 9 out of 16 are most likely to have originated from the centre of the LMC.

AN IMPORTANT outstanding problem, however, was to explain the sky distribution of the 21 hypervelocity stars identified from the HVS Survey, which is shown in the first of the two figures opposite. The grey-shaded areas are the sky regions excluded from the survey.

The hypervelocity stars which they attributed to a Milky Way origin are shown as small black circles, those to a Large Magellanic Cloud origin in red, and those of an ambiguous origin in magenta. The current position of the LMC is illustrated with a representative image, and its approximate orbital trajectory is shown as a red arrow. Noticeable is the concentration of objects in what they refer to as the ‘Leo overdensity’.

In the Hills mechanism, the main parameters influencing the ejection probability, and the (terminal) ejection velocity, are the mass of the supermassive black hole, the masses of the binary components, the binary separation prior to disruption, and the binary’s pericentre distance around the black hole. The model predictions require certain assumptions (for example, that the distribution of binary separations is given by that of the local Galactic field), which they detail.



THEIR SIMULATION RESULTS, designed to predict the spatial and kinematic distributions of the simulated hypervelocity stars, are shown in the second figure above, where the velocities are given in the Milky Way rest frame, and the circle size is proportional to the excess velocity over the local Galactic escape velocity.

And here is the decisive point. Only ejected stars that are aligned with the LMC orbit are boosted beyond the local escape velocity, by about 300 km s^{-1} , resulting in a trail of hypervelocity stars leading ahead of the LMC orbit. And only the leading tip of the ejected hypervelocity stars make it into the HVS Survey footprint. Since this concentration of predicted hypervelocity stars closely replicates the observed Leo Overdensity, they conclude that a significant fraction of the hypervelocity stars discovered to date do, indeed, originate from the LMC.

TWO OTHER POINTS are worth emphasising. The first is that Han et al. (2025) also demonstrated that the birth rate and clustering of the Large Magellanic Cloud hypervelocity stars cannot be explained by supernova runaways, or dynamical ejection scenarios, not involving a supermassive black hole. Indeed, from the ejection velocities and relative number of Magellanic versus Galactic hypervelocity stars, they constrained the mass of the LMC’s central black hole to be $6 \times 10^5 M_{\odot}$.

Second, a major uncertainty in the LMC orbit comes from observational uncertainties in the positions, velocities, and masses of the Magellanic Clouds, with a 50% change in the LMC total mass resulting in a difference of up to 40 km s^{-1} in the hypervelocity star velocities. Using the hypervelocity stars inferred to have originated from the LMC will, they say, be used in a future study to further constrain its true orbit.

I will defer mention of other hypervelocity discoveries, and Gaia’s contribution to them, to a future essay.