Hypervelocity Stars and Where to Find Them

Literature Review

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1 What are hypervelocity stars

Hypervelocity stars (HVS) are a subset of high velocity stars, defined as having a significantly higher velocity than the mean velocity of the surrounding objects. A 2012 article by Brown et al. defines hypervelocity stars as stars with radial velocity $v_r \geq 275\,\mathrm{km/s}$.[7][I] Since we want to study specific stars, we are currently only able to survey objects in our own Galaxy and stars that originate from the Local Group that are located within the Milky Way.

Several surveys over the years have resulted in ever-more accurate information regarding the distribution of stellar velocities. One of the latest and most comprehensive surveys was done by the Gaia space observatory. The Gaia Data Release 2,[12] released in 2018, contains velocity measurements of over 1.3 billion stars.

Figure 1 shows the velocities in the angular direction v_ϕ as well as the peculiar velocity vector $v_p = |v_{radial} + v_{planar}|$. We can see that relative to the Local Standard of Rest (LSR; mean motion of the Milky Way Galaxy), most stars have a low peculiar velocity in the order of $v \sim 100\,\mathrm{km/s}$, with the outliers having $v \sim 500\,\mathrm{km/s}$.

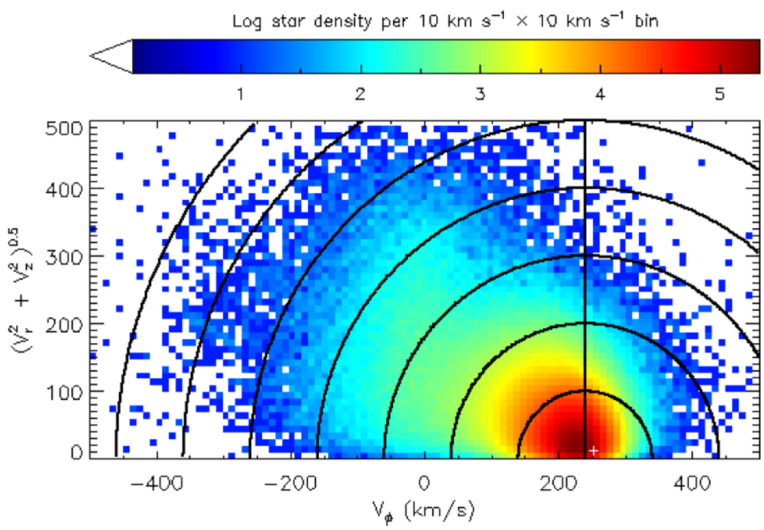

Figure 1: Gaia DR2 Toomre velocity dispersion diagram. Vertical line is centered at the LSR. Concentric rings at constant velocity magnitudes. White cross is the Sun.[12]

However, we also have to account for the fact that stars rotate around the LSR. When we compare these velocities to the rotation curves of the Milky Way in figure 2,[18] we see that the amount of stars with velocities above $\sim 100 - 200\,\mathrm{km/s}$ are extremely rare. In fact, the amount of detected hypervelocity stars today is counted in the hundreds (or about 1 in a million).

[I]There is nothing special about the value 275 km/s; although any velocity above this value should be statistically significant ($v_r > 2\sigma_v$), since HVS usually surveys have a distribution deviation $\sigma_v \sim 100\,\mathrm{km/s}$.

2 How to make a hypervelocity star

2.1 Supernova explosions within a binary system

The theory behind high velocity stars has existed for several decades. The first mention of a high velocity star mechanism comes in 1961 from A. Blaauw.[1] The proposed mechanism for creating a HVS is to have a binary system of stars, where one of the stars undergoes a supernova explosion. This results in expelling a lot of mass—sometimes up to 90% of the stellar mass[15]—which results in the other star becoming unbound, now travelling with the peculiar velocity equal to its rotational speed while it was bound in the binary system due to conservation of momentum.

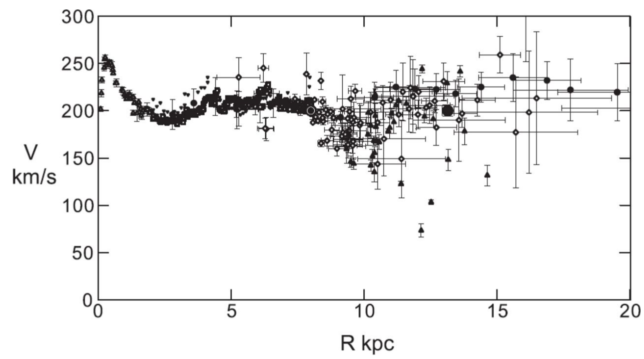

Figure 2: Rotation velocities of stars in the Milky Way, with radius being the distance from the galactic centre.[18]

The issue with this mechanism is that the maximum orbital velocity is not that large; only reaching a few hundred kilometres per second.[II] This limitation comes from the inherent mechanisms of binary star formation. A 2013 study by Zubovas et al. finds that the probability of a star being disrupted by a core collapse supernova explosion is $P_{disr} \gtrsim 0.93$, with a probability that the star will become unbound ranging from ~ 0.04 to ~ 0.25, based on the hardening of the system.[21] This results in an approximate stellar ejection rate of $\sim 8 \cdot 10^{-6}\,\mathrm{yr}^{-1}$. The distribution of ejection velocities as determined by their Monte Carlo simulation is shown in figure 3.

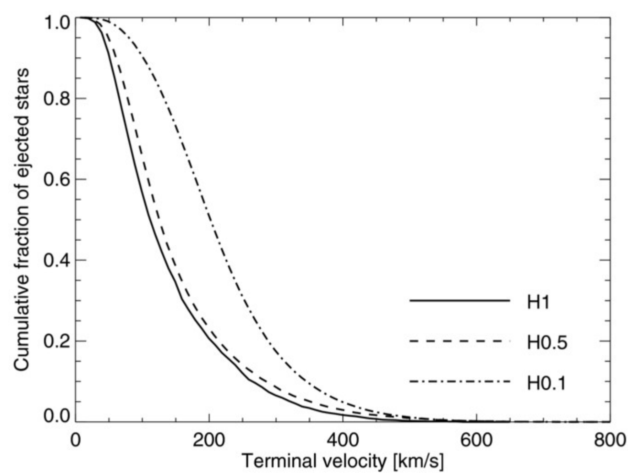

Figure 3: Simulated terminal velocity of a star ejected by a supernova explosion.[21]

[II]Currently, the fastest known binary system orbits at $v \sim 700\,\mathrm{km/s}$.[19]

2.2 Chaotic multi-body systems

A second mechanism proposed in 1967 by Poveda et al. suggests that high velocity stars could be produced as a result of the chaotic multi-body interactions in young clusters of massive stars.[17] They looked at a specific system of N stars, and found that under certain initial conditions a star could be ejected with a velocity of up to $v = 185\,\mathrm{km/s}$. Further studies like the 1990 study by Leonard and Duncan find that the most likely mechanism for high-velocity ejections is a close binary encounter, producing speeds upwards of $v \gtrsim 200\,\mathrm{km/s}$.[14] More recently, a 2016 study by Oh and Kroupa found that with certain models, we can get stellar ejection speeds of up to $\sim$500 km/s, as shown in figure 4.[16]

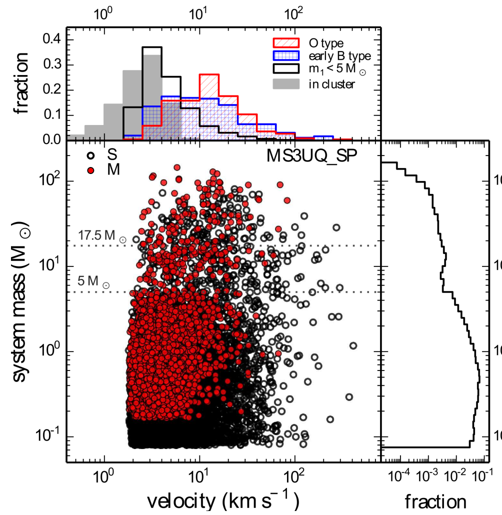

Figure 4: Distribution of ejection velocity based on the mass of a chaotic N body stellar system.[16]

2.3 Encounters with a black hole: the Hills mechanism

In 1988, a paper released by J. G. Hills described a mechanism for creating high velocity stellar ejections, and defined the term hypervelocity star.[11] This mechanism, like the two described above, requires a Newtonian encounter of a binary star system. The difference is that the Hills mechanism postulates that an encounter of a binary system with a supermassive black hole—rather than other stars—can cause one of the stars to become bound to the black hole, while the other is ejected with velocities of up to several thousands of kilometres per second. This is much higher than any velocity predicted by the aforementioned mechanisms.

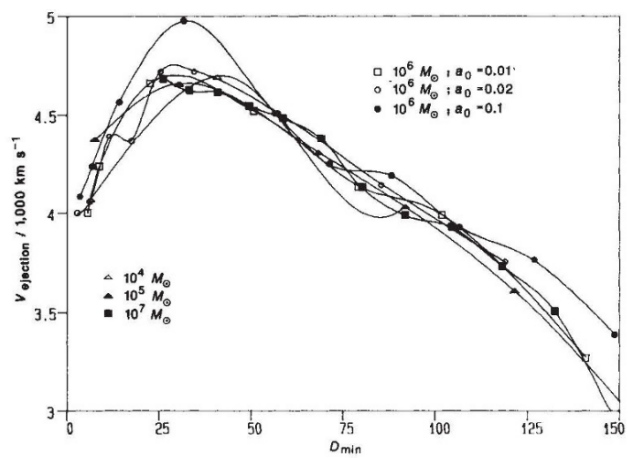

Figure 5: Maximum ejection velocities using the Hills mechanism, based on D_{min}.[11]

The paper defines a dimensionless closest approach parameter dependent on the masses of the objects, the semi-major orbit axis a_0, and the minimum radius where the star can pass by the black hole without breaking up R_{min}: $D_{min} = \frac{R_{min}}{a_0}(\frac{2M_{bh}}{M_1+M_2})^{-1/3}$. This depends on the density of the star and black hole, as well as the stellar density.[III]

3 But why are hypervelocity stars interesting?

3.1 Anisotropic distributions

There are several reasons why hypervelocity stars are interesting, even if we disregard just how statistically unlikely they are to be created. The first hypervelocity star called SDSS J090745.0+024507 with a rest-frame velocity of 709 km/s was detected in 2005 by Brown et al.[5] Just 4 years later, in another survey by Brown et al., several more hypervelocity stars were found via a targeted search (see figure 6).[6] The important trend this observation highlighted was that there were 18 stars with radial velocities $v_{rf} \geq 300$ km/s, but none with velocities smaller than $v_{rf} \leq -300$ km/s. Although this result was statistically significant, we could not tell for certain if the distribution was anisotropic since the search was targeting only stars redder than known white dwarves and bluer than known blue horizontal branch (BHB) stars; with a sample size of 910 stars, and in a specific region of the sky. Further analysis by Brown et al. in 2014 shows that the anisotropies are primarily in the galactic longitude, rather than galactic latitude.[8].

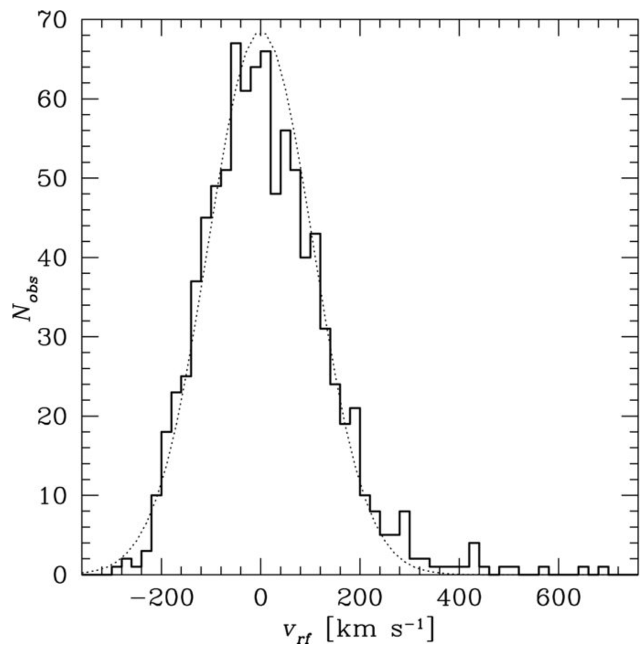

Figure 6: Velocity distribution of stars in the LSR, fitted with a normal distribution with a width $\sigma_v = 106$ km/s from a targetted survey.[6]

[III]As an example a main sequence $1M_\odot$ star passing by a $10^6 M_\odot$ black hole has a minimum radius of $R_{min} = 150R_\odot \approx 0{,}7$ au.

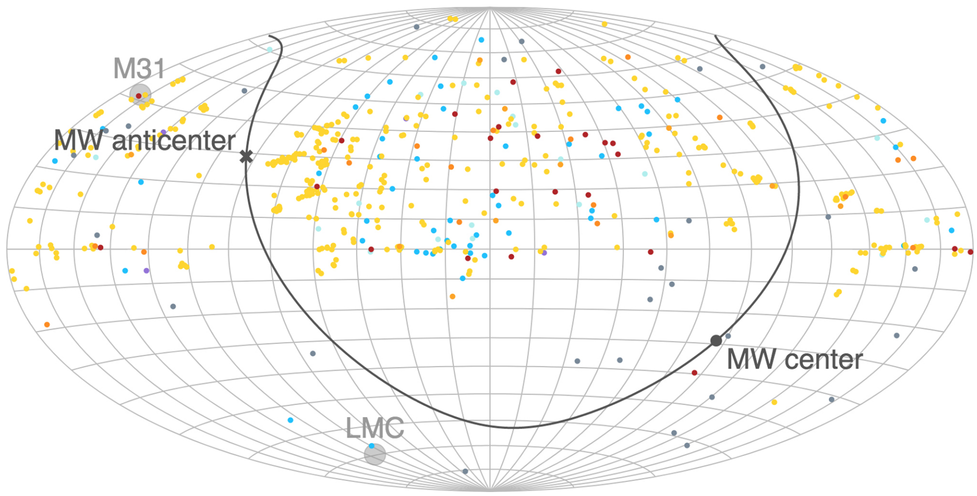

Figure 7: Hammer projection of all known hypervelocity stars, coloured by spectral type. The plane of the Milky Way is shown as a gray line, with the galactic centre labelled.[3]

The most comprehensive proof about the anisotropies of hypervelocity stars came about after the Gaia DR2 dataset was analysed for HVS candidates by Boubert et al. in 2018.[3] The total number of candidates grew from 203 to 505, and since there was less sampling bias—as the data was from a general survey rather than a targeted search[IV]—mapping the known locations and velocities of stars would give a clearer picture. In figure 7, we see that the distribution of hypervelocity stars suggests that some underlying asymmetric process is behind their creation.

Since Sagittarius A*—the supermassive black hole at the centre of the Milky Way—could in theory create hypervelocity stars in all directions, there must be some mechanism to account for this spatial anisotropy. The two most likely theories are that there is either an anisotropic cluster of stars at the galactic centre, or that the galactic potential is asymmetric.[8] In both cases, hypervelocity stars can provide us with a way to understand the structure of our galaxy in a novel way, and could be used as another tool to build upon works like the 2020 Nobel prize-winning research by Ghez et al. where they used a stellar survey to observe a supermassive object at the centre of the Milky Way, now known as Sagittarius A*.[9]

[IV]We still have to account for the fact that there is some finite resolution to the Gaia telescope.

3.2 Surpassing galactic escape velocity

Another very interesting feature of hypervelocity stars is that some of their velocities exceed the galactic escape velocity. When we plot the velocity of hypervelocity stars against the escape velocity of the galaxy (figure 8), we see that a large amount of HVS are on track to escape the Milky Way.[8]

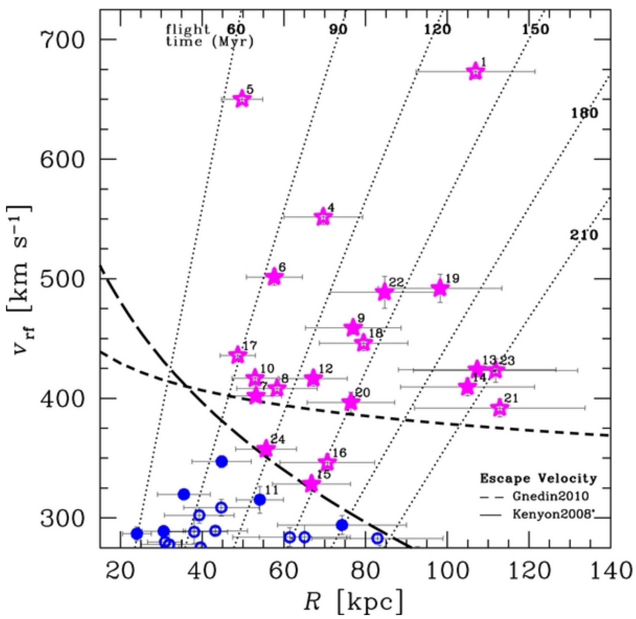

Figure 8: Magenta stars: unbound HVS; blue circles: bound HVS. Isochrones of flight time from the galactic centre shown as dotted lines.[8]

One implication is that we can potentially observe stars that were ejected in structures outside of the Milky Way, such as the Large Magellanic Cloud (LMC).[2] Another is that since these stars are travelling with relatively high velocity, we can look at their trajectories and gain information about the matter composition along their flight path; be it regular or dark matter.[4][10]

3.3 Probing the galactic centre

While studying stellar streams that orbit the Milky Way in 2019, Koposov et al. found a hypervelocity star that almost certainly originates at the galactic centre.[13] Named S5-HVS1, it was at the time of its discovery the fastest moving HVS at $v \sim 1750\,\mathrm{km/s}$.

Stellar streams are clusters of stars that are deformed by the galactic tidal waves of the Milky Way into an elongated structure as they orbit. Therefore, Koposov et al. were able to gather more information about the precise trajectory of the star, and were able to pinpoint its origin at the galactic centre with unprecedented accuracy (see figure 9). This means we can be almost certain that the star was ejected via the Hills mechanism by Sagittarius A*, the supermassive black hole at the centre of the Milky Way.

Assuming that the star was indeed ejected by Sgr A*, Koposov et al. traced back the

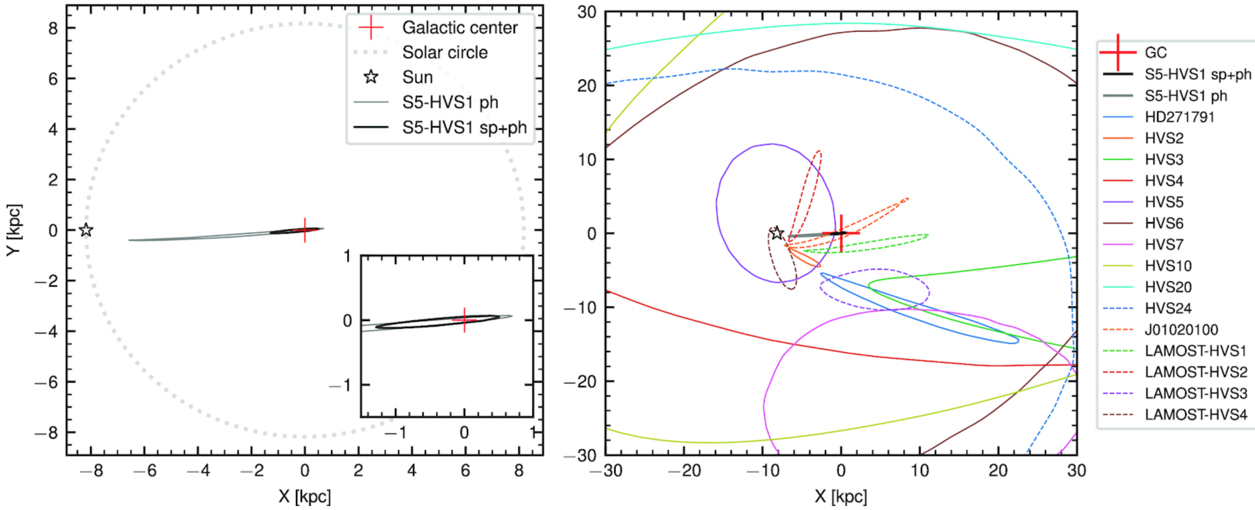

Figure 9: Ejection zones of known HVS, compared to the ejection zone of S5-HVS1. The S50HVS1 sp-ph zone is the 90% confidence zone; an ellipsoid centred on the galactic centre with axes 1500×50 parsec.[13]

trajectory of the star, and found that its initial ejection velocity was around $v \sim 1800\,\mathrm{km/s}$; about $50\,\mathrm{km/s}$ more than today. This data can then be used to get more precise bounds on the gravitational potential of the Milky Way.[10] Moreover, the researchers were even able to correlate which stars orbiting the galactic centre could be the other binary star to which S5-HSV1 used to belong, and found that it coincides with a disc of young stars in the region, suggesting a possible correlation (see figure 10).

The time frame of the ejection $\sim 5\,\mathrm{Myr}$ also coincides with a period of activity around the galactic centre since it is a similar timeframe to the emission of Fermi bubbles observed arond the galactic centre.[20] Between this discovery and the results from Gaia's DR2, we may be very close to starting to use hypervelocity stars as an observation tool, rather than just a curiosity.

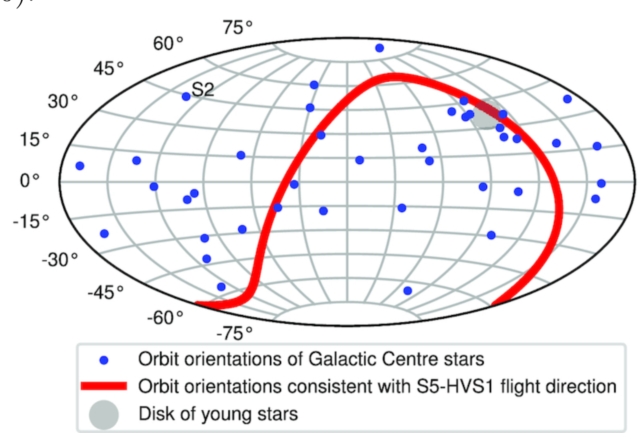

Figure 10: Angular inclinations of orbital planes of stars around the galactic centre.[13]

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