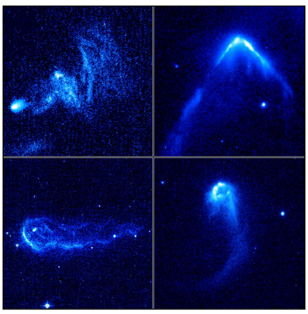
# 22. Hypervelocity stars

HYPERVELOCITY STARS are a rare and exotic type of star, racing through our Galaxy with velocities of 500–1000 km s$^{-1}$ or more. How did they acquire these enormous speeds, how and where were they formed, where are they going, and what can they tell us about the structure and origin of our Galaxy?

TYPICAL STARS IN OUR Galactic precinct move, somewhat randomly, at around 20–30 km s$^{-1}$ with respect to the bulk rotation of our Galaxy's disk. Their velocities arise from conditions of their birth in star clusters and star associations, and these are later modified by interactions with other mass structures of the Galaxy. 'Runaway stars', moving through the Galaxy disk with much higher velocities, of 100 km s$^{-1}$ or more, have been known since the 1960s.



*Bow waves from runaway stars*

They acquired these velocities from binary supernova ejections, or dynamical ejections from star clusters, in which extreme gravitational encounters hurl one of the interacting stars outwards at enormous speeds. Their motions often point away from known star clusters or stellar associations, providing clear signposts as to their birthplaces. They often create 'bow shocks' as they plough through the interstellar medium.

HYPERVELOCITY STARS have even more extreme velocities, velocities which cannot be reached even with these violent ejection mechanisms. They require some formation mechanism to provide them with their huge velocities which is even more extreme.

Black holes provide the answer. Black holes are objects that have undergone catastrophic gravitational collapse, leaving behind spheroidal regions of space from which nothing can escape. The most massive, perhaps millions (or even billions) times the mass of the Sun, are referred to as 'supermassive black holes'. A range of modern observations indicate that almost every large galaxy has a supermassive black hole at its centre.

Evidence for a massive black hole at the centre of our own Galaxy started to emerge in the 1930s. Radio observations by Karl Jansky suggested a highly unusual object at its centre, now known as Sagittarius A* (or Sgr A*). A large body of theoretical and observational evidence for its existence has been gathered since. Some of the most compelling are high-angular resolution optical images, published in 2009 from 16 years of data with the European Southern Observatory's Very Large Telescope, revealing a number of stars orbiting this central object. One of these, star S2, orbits the black hole in just 16 years, and was moving at 7650 km s$^{-1}$, or 2.5% the speed of light, at its closest approach. The mass of this central supermassive black hole is estimated to be a little over 4 million times that of our Sun.

HYPERVELOCITY STARS are an extreme type of runaway star which originate near a supermassive black hole. In this so-called Hills ejection mechanism, predicted by Jack Hills in 1988, the black hole acts as a gravitational slingshot. Simulations show that stars can be ejected from the deep potential well of a massive black hole, either as a result of scattering with another star, or through tidal breakup of a binary star system.

Stars could be ejected at 1000–2000 km s$^{-1}$ or more, greatly exceeding speeds that could arise from either binary supernova or star cluster mechanisms. The most extreme velocity objects would not be gravitationally bound to our Galaxy, and will escape the confines of even its vast boundaries after some 300 Myr.

THE FIRST SUCH hypervelocity star, SDSS J0907, was discovered, serendipitously from the Sloan Digital Sky Survey, only in 2005 (Brown et al., 2005). Spectroscopy showed that it is a late B-type main-sequence star, with a radial velocity of more than 800 km s$^{-1}$. The discovery paper placed the star at a distance of about 55 kpc, some 30 kpc above the Galactic disk, some 60 kpc from the Galactic centre, and with a motion through space consistent with it having been ejected from the Galactic centre. If so, it should have a proper motion of about 0.3 mas yr$^{-1}$, tiny compared with the accuracies available at the time, but which should be measurable, and so able to confirm its birthplace, by Gaia.

FINDING OTHER hypervelocity stars would open other avenues of study of our Galaxy's structure. They would throw light on their production rate at the Galactic centre, providing a better understanding of the conditions – and stellar populations – which exist there.

As a result of the enormous distances travelled on their journey through the Galaxy halo, in different directions and now at a vast range of distances from their origin, they probe the Galaxy's gravitational potential, making them possible tracers of the matter distribution in the Milky Way (Gnedin et al., 2005; Sesana et al., 2006).

Astrometric measurements with Gaia can also help pin down the Sun's position and velocity through space: if the wrong assumptions are made, the star would *appear* to originate slightly displaced from the Galactic centre (Hattori et al., 2018).

Hypervelocity stars will, however, be rare: estimates of the ejection rate from Sgr A*, of about $10^{-4}$ yr$^{-1}$, suggest that out of the Milky Way's $10^{11}$ stars, there should only be one hypervelocity star within 1 kpc of the Sun.

FOLLOWING THE DISCOVERY of the first hypervelocity star, a wide-field spectroscopic survey was set up at the 6.5-m Multi-Mirror Telescope (MMT), to search for others of similar spectral type and mass ($2.5-4M_\odot$). Covering over 12 000 square degrees of the northern sky, and completed in 2014, a few dozen bound and unbound candidates were discovered from their extreme radial velocities, at distances varying between 50 kpc and 100 kpc from the Galactic centre. Other surveys have been made with the Chinese LAMOST telescope (Huang et al., 2017), and a number followed-up with the Hubble Space Telescope (Brown et al., 2015).

SINCE THE DR2 RESULTS were made available in April 2018, Gaia is providing proper motions and distances of previously known hypervelocity star candidates with unprecedented accuracies, in turn helping to pinpoint their origin, while also searching the entire sky for other examples of these very rare objects.

Although the picture is still far from being complete, some of the previous candidates are indeed confirmed as having a high probability of originating close to the Galaxy centre. Amongst these are the object known as HVS 22, with a velocity of some 1500 km s$^{-1}$.

But others do not appear to have originated from the Galactic centre, hence suggesting that other extreme ejection mechanisms might also be at work.

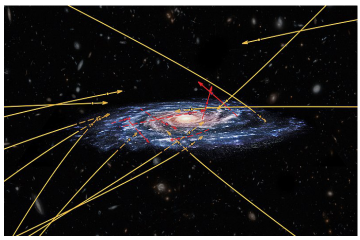
Amongst these, HVS3, appears to be coming from the centre of the Large Magellanic Cloud, and moving with a velocity of more than 800 km s$^{-1}$ (Irrgang et al., 2017; Erkal et al., 2017). This large velocity, consistent with the Hills mechanism, provides strong direct evidence that the Large Magellanic Cloud itself harbours a massive black hole of at least $4\times10^3-10^4M_\odot$.

NOTWITHSTANDING THEIR rarity, detailed modeling suggests that Gaia could find several hundred new hypervelocity stars within some tens of kpc from the Sun (Marchetti et al., 2018).

Amongst new discoveries from the Gaia DR2 data release, a number are believed to originate from the Galactic centre, while others are not (Li et al., 2018; Du et al., 2019; Marchetti et al., 2019). The present haul includes three hypervelocity white dwarfs, conjectured to be the companions to primary white dwarfs that exploded as Type Ia supernovae (Shen et al., 2015). The orbit of at least one of these can be traced back to a faint old supernova remnant, strengthening the idea that some hypervelocity stars may originate from extreme binary supernova ejection events (Ruffini & Casey, 2019).

Are there still other exotic ejection mechanisms, not restricted to the Galactic centre, that might be generating at least some of these hypervelocity objects?

Amongst ideas recently put forward are the existence of (less massive) intermediate-mass black holes within the Galactic disk, resulting in similar but less extreme gravitational slingshot-type ejections (Fragione & Gualandris, 2019).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And perhaps yet others resulted from tidal interactions when smaller infalling galaxies were 'swallowed' and merged with our own Galaxy much earlier in its formation history (Boubert et al., 2020).

THE GAIA RESULTS on hypervelocity stars could provide a significant ingredient for refining cosmological models. In the 'concordance ΛCDM model', galaxies are embedded within extended halo structures, largely made of some 'non-viscous' dark matter, visible only through its gravitational effects. Over cosmic time, haloes grow in mass and size through hierarchical clustering, starting from the initial perturbations of a slightly inhomogeneous matter density field, but with resulting shapes and masses depending on the model details.

The motion of hypervelocity stars as they race outwards through the Galaxy halo may provide a unique probe of our Galaxy's actual gravitational potential.