Far from home: the science exploitation of the fastest Milky Way stars

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SUMMARY

The goal of this thesis is to study how the fastest stars in the Milky Way can be used as a tool to better understand violent and energetic phenomena taking place in our Galaxy.

Velocities are relative. We are used to this on Earth – our definition of 'fast' depends on the situational context, our chosen reference frame and our preconceptions about how the real world works. A 'fast' turtle is slower than a 'slow' racecar. In astronomy we play the same game. Our definitions of 'fast' and 'slow' must be adapted to new situations, like planets orbiting around a star, or an expanding supernova shockwave, or the motions of the several hundred billion stars that make up our Milky Way galaxy, or many galaxies all whizzing around each other in gigantic galaxy clusters. Since we have little familiarity with these situations in our everyday life, these speeds can be difficult to conceptualize. The Earth is moving around the Sun at slightly more than 100 000 km/h. The Sun, in turn, flies through the Milky Way at about 800 000 km/h, which itself is moving at ∼2 million km/h relative to the cosmic microwave background permeating all of space, which is the closest we can get to an 'absolute' reference frame for the Universe.

The point of this preamble is simply to stress that nearly everything in space is moving 'fast' by human standards, and so we need to adjust our definition of the word accordingly. A schematic of the structure of the Milky Way is shown in Fig. 3. We are located in the *disc* of the Milky Way about 26 000 light years from centre. The Sun and the majority of the rest of the stars in the disc are all orbiting the centre of the Galaxy at slightly more than 200 km s^{-1}. The innermost ∼7000 light years of the Galaxy is dominated by the Galactic *bulge*. Instead of the ordered rotation seen in the disc, stars in the bulge buzz around the centre of the Galaxy on eccentric, randomly-oriented orbits. There is a large variation of speeds for stars in the bulge, but the maximum speed is around 200 km s^{-1}. Surrounding the entire Galaxy out to $\gtrsim$100 000 light years is a diffuse *halo* of stars also on random orbits, mostly composed of stars 'stolen' from former dwarf galaxies which were torn up upon merging with the Milky Way. The halo is also where most of the Galactic *globular clusters*, dense conglomerations of many thousands of stars, are found. Within the stellar halo, the speeds of stars max out around ~ 300 km s^{-1}.

We can take from all this, then, that a typical star in the Galaxy travels with at most a velocity of a few hundred kilometres per second relative to the at-rest reference frame of the Milky Way. With the emergence over the last two decades of modern, sophisticated surveys of the night sky, however, many stars have now

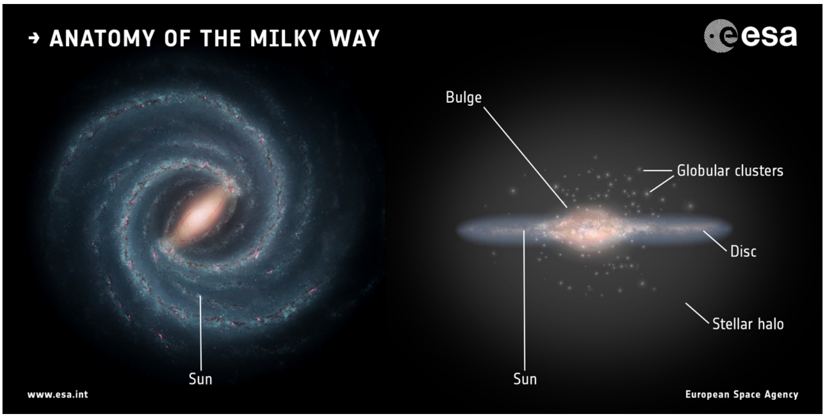

Figure 3: Artist's impression of the Milky Way galaxy seen face-on (left) and edge-on (right). The Sun and the major stellar structures of the Galaxy are labelled. Image credit: NASA/ESA/JPL-Caltech

been identified which break this cosmic 'speed limit' significantly – the fastest of these, called *hypervelocity stars* (HVSs), are moving faster than 1000 km s^{-1}! These stars are moving so fast that they are gravitationally unbound from the Galaxy, i.e. the gravity of the Milky Way is not sufficient to prevent these stars from escaping it entirely and eventually flying off into intergalactic space. Fig. 4 shows an artist's impression of a hypervelocity star ejected from the inner Milky Way.

Accelerating stars to such extreme velocities is no easy feat. To explain the origins of these very fast stars, we must invoke dramatic scenarios such as energetic supernova explosions of elderly stars, close dynamical encounters between massive stars or interactions between stars and *Sagittarius A**, the supermassive black hole which resides in the centre of the Milky Way. Directly observing these events and interactions is difficult as they are often rare, short-lived and in hard-to-see regions of the sky. Studying the fastest stars in the Galaxy provides valuable insight into these scenarios – information about still-uncertain aspects of the physics involved in these situations can be gleaned from the number of extremely fast stars in the Galaxy, their characteristics, their velocities and their locations within the Milky Way.

To date, only a handful of uncontroversial stars unbound from the Galaxy have been discovered. However, this will change in the era of cutting-edge on-

Figure 4: An artist's impression of two hypervelocity stars ejected from the innermost regions of the Miky Way. Image credit: ESA

going and future astronomical surveys such as the European Space Agency's *Gaia* mission, the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST), the William Herschel Telescope's WEAVE spectrograph, the European Southern Observatory's Four-Metre Multi-Object Spectroscopic Telescope (4MOST) and Apache Point Observatory's ongoing Sloan Digital Sky Survey (SDSS), which can provide accurate measurements for a huge amount of Milky Way objects in a short time. As more fast and hypervelocity stars are discovered, they will only become more useful as tools to understand extreme situations in our astronomical backyard.

This Work

The goal of this thesis is to use computer simulations to create realistic 'fake' populations of very fast stars. By exploring and varying the different ingredients that go in to these simulations, we can determine which assumptions are most important when it comes to the population of fast stars in the Galaxy. By comparing these simulations to current observations, we can gain some insight into hard-to-observe phenomena in our Galaxy. Finally, by making predictions for *future* observations, we can show how even more information can be extracted in the coming years.

Specifically, this thesis aims to offer partial answers to the following questions:

- We know of several stars which seem to have been ejected from the Galactic disc at $\gtrsim 400\,\mathrm{km\ s^{-1}}$. We know as well that if a massive star is in a binary system with a companion, the companion can be ejected from the system if the more massive star undergoes a core-collapse supernova. Can the ejection velocity of this companion reach several hundreds of $\mathrm{km\ s^{-1}}$? If yes, does this happen often enough to explain the known population of fast disc-ejected stars?

- It is safe to assume that some stars unbound to the Galaxy were originally ejected following a gravitational encounter with Sagittarius A* in the Galactic Centre (GC). We also have good reason to believe that a supermassive black hole is also located in the centre of the Large Magellanic Cloud (LMC), the Milky Way's largest dwarf galaxy companion. How many LMC-ejected fast stars should be detectable in current and future surveys of the night sky vs. GC-ejected ones? Is there any way we can disentangle the two populations?

- In *Gaia* Data Release 2 and Early Data Release 3 there are *zero* hypervelocity stars with full 3D measured velocities, small uncertainties on these velocities and a trajectory which hints towards an origin in the Galactic Centre. What does this lack of observations imply about the ejection of fast stars from the GC?

- *Gaia* Data Release 3 has been only very recently released. Are there promising GC-ejected unbound star candidates in this Data Release? Does this new Data Release allow us to update our knowledge about the ejection of fast stars from the GC?

In **Chapter 2** we explore whether supernovae among massive, tight binary systems in the Galactic disc eject extremely fast stars with a significant frequency. We use simulations of binary stars evolving together and determine the conditions necessary to eject very fast stars stars. We find that stars with ejection velocities above $400\,\mathrm{km\ s^{-1}}$ are produced with a sufficient frequency by binary supernovae if and only if binaries enter a *common envelope* phase shortly before the supernova, in which both stars 'share' an outer envelope and the separation between them shrinks. Following this, the black hole or neutron star remnant left behind by the collapsing star must receive a very strong 'kick' from asymmetries in the supernova shockwave. We find that the common envelope energy efficiency and the strength of supernova kicks must be large to a degree unsupported (but not entirely excluded) by current studies. We conclude therefore that binary supernovae are not likely a principle contributor to the known population of very fast stars which seem to have been ejected from the Galactic disc.

In **Chapter 3** we turn to the Large Magellanic Cloud. Inspired by the recent evidence that at least one known hypervelocity star (HVS) has been ejected from the centre of the LMC, we simulate the ejection of HVSs from both the GC and LMC centre. We compare the two populations and find that the LMC is potentially a more bountiful source of HVSs than previously appreciated, ejecting about twice as many HVSs detectable by current surveys than the GC. This prediction is not particularly sensitive to the mass of the Milky Way and the LMC or the specific properties of the supermassive black hole we assume to lie at the LMC centre. We show that LMC-ejected HVSs and GC-ejected HVSs are primarily located in different regions of the sky and move with different velocities. In the future, these predictions can be used to disentangle these two HVS populations.

In **Chapter 4** we consider the fact that no 'slam dunk' HVS candidates were discovered in the subsamples of *Gaia* DR2 and EDR3 stars for whom a radial velocity was measured. By 'slam dunk' here we mean HVSs with precisely known positions and velocities and trajectories which indicate an origin in the GC. This absence of HVSs is in itself an interesting result: some assumptions we could make about the types of stars that reside in the GC and how HVSs are ejected predict such an abundance of HVSs in the Galaxy that a null detection in DR2 or EDR3 would be improbable. We perform a suite of simulations ejecting realistic HVS population and show the rate of HVS ejections from the GC must be no larger than three per century, or else HVSs would have been detected in *Gaia* DR2 and EDR3. HVS populations uncovered in future *Gaia* data releases will also be able to constrain how the masses of stars in the GC are distributed.

Chapter 5 acts as a follow-up to Chapter 4. In this work we update our simulations to include HVSs near the end of their lives. Since evolved stars are cooler and brighter than middle-aged ones at fixed mass, evolved HVSs are more likely to appear in these catalogues. By considering the lack of *all* HVSs in the *Gaia* DR2 and EDR3 radial velocity catalogues and by considering the existence of the confident observed HVS candidate S5-HVS1, we place much-improved constraints on the HVS ejection rate from the GC and the mass distribution of stars in the GC.

Chapter 6 was written immediately after the release of *Gaia* Data Release

3. We search for new HVS candidates with precise astrometry from among the 34 million sources in the radial velocity catalogue of this data release. We were able to use our existing simulations to immediately leverage the results of this search to update constraints on the GC environment. We find no confident HVSs in this catalogue. While disappointing, this result is not unexpected given the predictions of the previous Chapter. Regardless, we further improve our constraints on the GC environment. These results indicate that the mass distribution of stars in the GC cannot be skewed towards higher-mass stars (relative to the distribution of star masses near the Sun) unless the HVS ejection rate is significantly lower than what is typically expected.