Hunting for the fastest stars in the Milky Way

Marchetti, T.

Author: Marchetti, T.
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English Summary

The Sun is just one star among the hundreds of billions living in our Galaxy, the Milky Way. While most of these stars rotate around the Galactic centre on almost circular orbits, a few others do not follow this motion, but move through the Galaxy with a surprising high speed. The fastest of these stars are known as *hypervelocity stars*, and travel through the Galaxy with velocities of thousands of kilometers per second. This corresponds to a few millions of kilometers per hour, more than six thousand times faster than the fastest train on Earth!

The reason why we think these stars have such an incredibly high velocity is that they come from the centre of our Galaxy. These stars were originally part of a binary system: two stars orbiting around each other. The centre of our Galaxy is the residence of the most massive single object in the Milky Way, Sagittarius A*, a black hole with a total mass of more than four million times the one of our Sun. The interaction with such an incredible massive object can break the binary system, separating the two stars forever. One of the two will start orbiting around Sagittarius A*, while the other one, the hypervelocity star, will be ejected with an incredibly high velocity. This velocity is so high that these stars do not feel anymore the gravitational pull of the Galaxy, but fly away forever from it. Figure S.3 shows an artistic impression of hypervelocity stars flying away from the centre of the Milky Way.

The reason why hypervelocity stars are interesting is that they can be used to gain knowledge on different environments of our Galaxy. The Galactic centre is very difficult to observe because of interstellar dust, so detecting hypervelocity stars far from it can tell us something on how stars form and interact in the vicinity of the massive black hole. Moving to a completely different scale, the Galaxy is embedded into a vast halo composed of dark matter: a particular kind of matter that does not interact with the electromagnetic radiation, and is thus invisible to our eyes (and

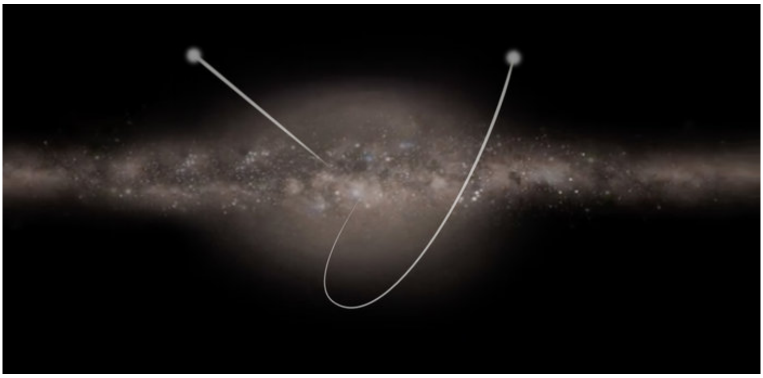

Figure S.3: Artistic impression of hypervelocity stars ejected from the centre of the Milky Way. Image credits: ESA.

telescopes). The dark matter halo is so massive that it bends the trajectories of hypervelocity stars, so that these stars can be used to determine some of its fundamental parameters (such as mass and shape) and investigate on the puzzling nature of this invisible component. Until now, only a few hypervelocity stars have been identified, but the advent of the European Space Agency (ESA) satellite *Gaia* is currently revolutionizing our knowledge on the fastest stars in the Galaxy. The aim of *Gaia* is to reconstruct the evolutionary history of the Milky Way by providing the largest and most precise stellar catalogue ever produced: positions, distances, and projected velocities for more than one billion stars.

This work

The goal of this thesis is to search for and characterize the population of the fastest stars in our Galaxy, and to show how these incredible objects can be used to probe different Galactic environments. To do that, we make use of data mining techniques, astrometric, photometric and spectroscopic datasets, observations, and theoretical modelling. In particular, this thesis aims at answering these four questions:

- **Chapter 2:** How many hypervelocity stars are we expecting to find in the *Gaia* catalogue?

- **Chapter 3:** Can we find any hypervelocity star candidates in the first *Gaia* data release?

- **Chapter 4:** What is the origin of the fastest stars in the second *Gaia* data release?
- **Chapter 5:** What can we learn about the centre of the Milky Way and its dark matter halo using the known sample of hypervelocity stars?

In the following we will present a short summary of the content of each scientific chapter, illustrating how we answer each of the questions above.

The first question we want to answer concerns how many hypervelocity stars we expect to find in the stellar catalogue provided by the *Gaia* satellite. To do so, in **Chapter 2** we create simulated catalogues of hypervelocity stars, to quantify and characterize the predicted population. We make three different assumptions on the ejection mechanism responsible for their extreme velocities: i) we populate the whole Galaxy with unbound stars on radial orbits from the Galactic Centre, ii) we assume hypervelocity stars to be the result of the interaction between a binary star and the massive black hole in the Galactic Centre (the *Hills mechanism*), and iii) we model the orbital decay of a massive black hole binary, ejecting single stars interacting with it. We use simple stellar evolution prescriptions to derive the apparent magnitude of each hypervelocity star. This allows us to estimate the error with which *Gaia* will measure its astrometric parameters. In all cases, our predictions are extremely encouraging: we find hundreds to thousands of precisely measured hypervelocity stars to be contained in the final *Gaia* catalogue, but the majority of these stars will not be bright enough to have a radial velocity determination from *Gaia*.

In **Chapter 3** we introduce and develop a novel data mining technique, based on artificial neural networks, to identify hypervelocity stars in the first data release of the *Gaia* satellite. We create a binary classifier algorithm which, taking in input the position, parallax, and proper motions of a star (no radial velocity), outputs a single real number which we can interpret as the probability of the star being a hypervelocity star. The algorithm is trained on mock populations built in Chapter 1, and on a simulated *Gaia* catalogue. The application to the data results in 80 stars with a high probability to be hypervelocity stars. To confirm the goodness of our candidates, we observe a subset of stars at the Isaac Newton Telescope in La Palma, Canary Islands, deriving radial velocities, distances and stellar parameters (mass, temperature, age and metallicity). The spectroscopic observations confirm the working of the data mining routine, which succeeded in find-

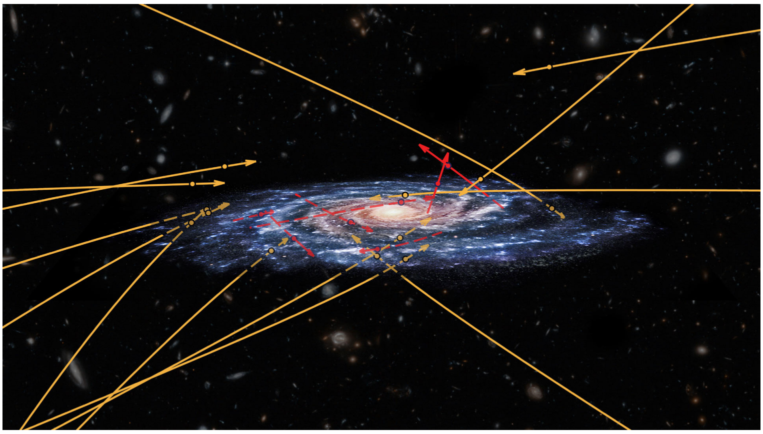

Figure S.4: Past orbits of runaway (red) and extragalactic (yellow) unbound candidates, on top of an artistic impression of the Milky Way. Image credits: ESA / NASA / Hubble / Marchetti et al. 2018.

ing high velocity stars: we report the discovery of 6 stars might be ejected from the centre of our Galaxy.

In **Chapter 4** we use the precise data provided by the second data release of *Gaia* to characterize the high velocity tail of the velocity distribution of more than 7 million stars in the Milky Way. We derive distances and total velocities for all of the stars in the sample, and we are able to discover a sample of 20 stars with unbound velocities. Particular care is taken to filter out spurious measurements and instrumental artifacts, which might mimic high velocity stars. We use the precise *Gaia* data to reconstruct the past trajectories of these stars in the Galaxy, to identify their birth place. Some of these are consistent with coming from the stellar disk of the Milky Way. Surprisingly, the remaining majority of stars is not consistent with coming from any known Galactic star forming region, suggesting an extragalactic origin. These stars were previously predicted in numerical simulation following the gravitational interaction of other small galaxies with our Milky Way. An artistic impression of these intergalactic interlopers is shown in Fig. S.4.

Finally, the aim of **Chapter 5** is to quantify the power of known hypervelocity stars to constrain the binary properties in the Galactic Centre and the characteristic parameters of the dark matter halo. Using a statistical approach, we compare the velocity distribution of the sample of ~ 20 unbound hypervelocity stars with analytic predictions assuming the Hills mechanism. We find that the number of known hypervelocity stars is not sufficient to give tight constraints on both these environments. Assuming that binaries in the Galactic Centre have similar properties to binaries in other star forming regions, we find a good match between the data and the model for haloes consistent with predictions from cosmological structure formation simulations. The sample of thousands of hypervelocity stars in the *Gaia* catalogue will be crucial to unveil the power of this new, exciting tool to study the Galaxy we are living in.