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Search and identification of high-velocity stars by dynamical ejection and supernovae from multiple stars

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Abstract

The project, funded by Science Committee of RA (ARPI program), intended to search, detection, kinematic study and identification of the birth places of the high-velocity and isolated neutron stars that encountered in the past with a stellar groups (multiple stars, stellar clusters, associations, etc.) closer than 10 pc, i.e. to test the concept: a high-velocity star and a stellar group or some of its members in the past were "in the same place at the same time".

We plan to use stars with the high-quality astrometry and radial velocities from the very recently released *Gaia* DR3 catalogue and empirically select high-velocity candidates. Next, by using full gravitational potential of the Galaxy to calculate the motion of a stellar groups and a candidate of high-velocity star from their current positions to the proximity epoch. For numerical integration we will utilize the fast and accurate numerical integration.

1. Introduction

In this project, we plan to search, detection, kinematic study and identification of the birth places (star clusters, associations and multiple stars, Ambartsumian, 1947, 1955) of the high-velocity stars in the Galaxy.

High-velocity stars, such as all high-mass OB-stars, are thought to have formed in the stellar groups and a certain part of them (see, e.g., Renzo et al., 2019) were ejected into the general Galactic field either Dynamical Ejection (in a Trapezium type young multiple systems, Ambartsumian, 1954, Poveda et al., 1967) or Binary Ejection Mechanisms (the secondary star of a close binary receives its ejection velocity and becomes unbound when the primary explodes as a supernova, Blaauw, 1961). The proper motion of a high-velocity star often points exactly away from a stellar group, of which the star was formerly a member. The majority of these stars in the literature are high-mass O and B type stars (see, e.g., Hoogerwerf et al., 2000, 2001, Tetzlaff et al., 2010) with ejection velocities less than 200 kms^{-1} (Perets & Šubr, 2012). Recent results show it is possible for low-mass G/K type stars with ejection velocities up to ~ 1300 kms^{-1}(Tauris, 2015).

Obviously, the definition of a high-velocity star (a star moving faster than 60-100 km/s relative to the average motion of the stars in its neighbourhood) is somewhat arbitrary and it depends on the many factors (for example, star mass, age, origin, galactic potential, velocity distribution model, etc.). Therefore, empirical (i.e. outliers from multivariate distribution of kinematic parameters of stars depending on the distance from the center of the Galaxy, see, e.g., Hambaryan (2018)) determination of them might be more robust given the huge number of stars with reliable astrometric parameters and radial velocities provided by *Gaia* mission (Gaia Collaboration et al., 2018).

Hyper-velocity stars (HVSs): are another subclass of high velocity stars, the fastest stars in our Galaxy, which have extreme velocities above the escape speed of the Milky Way. HVSs can obtain their large velocity from a number of different processes. Hills (1988) first theoretically predicted the formation of HVSs via three-body interactions between a binary star system and the massive nucleous in the Galactic Center (GC). Hyper-velocity stars are stars with velocities that are substantially different from that expected for a star belonging to the normal distribution of stars in a galaxy. Such stars may have velocities on the order of 1000 km/s.

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Pulsars: Some neutron stars are inferred to be traveling with similar speeds as HVSs. This could be related to runaway-stars and their ejection mechanism. Neutron stars are the remnants of supernova explosions, and their extreme speeds are very likely the result of an asymmetric supernova explosion or the loss of their near partner during the supernova explosions that forms them.

1.1. Origin mechanisms

High space *peculiar* velocities of stars are explained mainly by two different mechanisms: dynamical ejection due to gravitational interaction in multiple stellar systems or clusters (Poveda et al., 1967) and disruption of a multiple stellar system as result of a SN explosion of a massive star (Blaauw, 1961); a binary companion would get unbound, if at least half of the mass of the binary system is lost in the SN. In both such cases, the ejected star(s) are then called *runaway stars*, e.g. the former companion of the SN progenitor travels roughly with its former orbital velocity – a neutron star formed in the SN obtains a high kick velocity from the SN. See Boubert et al. (2017) and Renzo et al. (2019) for more details about runaway stars from SNe.

While runaway stars are often thought to have higher than normal space velocities, it is also possible to get unbound by leaving the system with normal to small velocity, sometimes then called *walkaway stars*; furthermore, runaway stars are not always single stars, as close binaries can also get unbound.

Depending on the separation of a multiple stars and component masses prior to the explosion (i.e. phase of mass transfer before the supernova, and the subsequent inversion of the mass ratio) and the amount of asymmetry involved (i.e. the magnitude of the kick velocity imparted to the neutron star during the explosion), the progenitor binary will either get unbound (ejecting a single high-velocity star and neutron star) or it will remain bound (see, e.g., Tauris & Takens, 1998). In case of the latter, its center of gravity will be accelerated and one could expect to observe a binary system, either as a member of a stellar association or runaway close binary nearby to a parental stellar group, comprised by a neutron star and a normal star as High- or Low-Mass X-ray Binary (HMXB or LMXB, respectively), if the separation is sufficiently small for accretion to occur (Ankay et al., 2001, Hambaryan et al., 2022).

In addition we will investigate a neutron star/high-velocity star pairs very likely both ejected from multiple stellar system during supernova event.

In order to disentangle between different scenarios of the origin of high-velocity stars or high-velocity binaries we plan to model ejection mechanism in multiple stellar systems, i.e. simulation of the dynamics of a *nbody* system as well as supernova explosion of progenitors, providing kick velocities of them. Moreover, these models we plan to apply for fitting individual cases, to asses progenitor mass and evolution. Finally, these parameters will provide an important input to estimate robust initial mass functions of a stellar group and to obtain more realistic star formation picture of individual stellar groups as well as in the Galaxy in general.

2. Project Aims and Objectives

The **three main goals** of this project are:

1) Compilation of a catalog of runaway stars from Gaia data and an investigation of the frequency of runaway stars around young stellar groups:
   - Which percentage of runaway stars (or mass) gets ejected ?
   - What are the mass and velocity distributions of ejected stars ?
2) Search for runaway star-neutron star pairs indicating binary SN ejection (e.g.: what is the kick velocity distribution of neutron stars ?)
3) Search for pairs (or higher order multiples) of runaway stars which got dynamically ejected. A comparison of (2) with (3) will then also show how effective these two mechanisms are to produce runaway stars (Hoogerwerf et al., 2000, 2001, had only one case each, at least one of them is dubious).
4) Search and identification of the places of origin of *hyper-velocity stars* (such stars may have velocities on the order of 1000 km/s, first theoretically predicted the formation of them via three-body interactions between a binary star system and the massive nucleous in the Galactic Center) yet another subtask of our project which may shed

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It is also well possible that for some SNe, we can find more than just one runaway star, because many pre-SN systems are expected to be higher order multiples than binary stars (we search for both early- and late-type runaways).

Furthermore, whenever a pair of runaway star and neutron star is found, we can estimate the following parameters:

- Lifetime of SN progenitor from the difference between cluster age and flight time since the SN.
- The current peculiar space velocity of the runaway star is roughly equal to its orbital velocity at the time of the SN; hence, from the masses of the runaway and the SN progenitor we can estimate the orbital separation and period (e.g. assuming a circular orbit).
- The orbital separation (or perihelion separation) can then be compared to the Roche lobe of the SN progenitor shortly before the SN, to investigate possible binary evolution and interaction.
- For neutron stars, in the same way, we can estimate the kick velocity due to the SN (taking into account a possible gravitational pull from a massive runaway for a short period after the SN).
- We can then search for SN debris (α elements etc) on the runaway star atmosphere.
- For each 3D location of a SN, we will check for cavities in the ISM, ^{26}Al sources, and soft X-ray emission.

3. Selection of new runaway stars from Gaia

Identifying true high-velocity outliers in the Gaia archive is challenging.

First of all, we will select among ~ 33 million stars *Gaia DR3* (Gaia Collaboration, 2022, Gaia Collaboration et al., 2022) sources for which astrometric parameters (positions, parallax and proper motions) and RV have relative measurement uncertainties not exceeding 10%. Further, these sources will be converted into galacto-centric cartesian coordinates (X,Y,Z,U,V,W). Then their space velocity will be analyzed for each component, the empirical distribution in a spherical/cylindrical ring of 5-10 pc width around center of the Galaxy. The estimates of distribution parameters (median, most probable value, the highest posterior density (HPD) intervals[1] of the total velocity in a spherical ring, having at least 100 sources, will be performed with kernel-density estimates. From this distribution, high-velocity candidates will be selected as outliers which have a value $V_{space} > V_{HPD_{hi}}(99\%)$. Note, that this is a conservative criterion with higher confidence for a high-velocity candidate star. In addition, we will also use Mahalanobis distance (Leys et al., 2018) and Sigma-clipping algorithms to identify outliers.

Next, we will use *Gaia DR3* astrometric data and will utilise a number of methods (e.g., the UPMASK (Unsupervised Photometric Membership Assignment in Stellar Clusters; Krone-Martins & Moitinho, 2014), non-parametric (e.g., Clusterix 2.0; Balaguer-Núñez et al., 2020) and parametric (e.g., BANYAN-Sigma Gagné et al., 2018)) to calculate membership probabilities of the selected stars for any stellar group (cluster, association, multiple stars) by using bonafide members of them.

The application of these methods and using major astronomical databases (e.g. SIMBAD) and imaging surveys (from infrared to X-rays) will allow us roughly classify types of selected stars and their environment.

For very promising candidates of *high-velocity stars* we are planning to perform additional photometric and spectroscopic follow up observations for detection of possible bow-shocks and peculiar chemical composition suggesting interaction of a SN shell and runaway star.

4. Methods

To study the Galactocentric motion of a single point mass (a star, binary or cluster) we use a numerical integration of its equations of motion in the gravitational field of the Galaxy expressed in a rectangular Galactocentric frame. Namely, for the Galactocentric motion of *high-velocity* candidate star and the possible parental stellar group we will use of the code described in Neuhäuser et al. (2020), which computes the orbits by a numerical integration of their equations of motion as defined by the Galactic gravitational potential.

[1]The highest posterior density interval is determined as a probabilistic region around a posterior mode, and is similar to a confidence interval in a classical statistics (Gregory, 2005, Gregory & Loredo, 1992).

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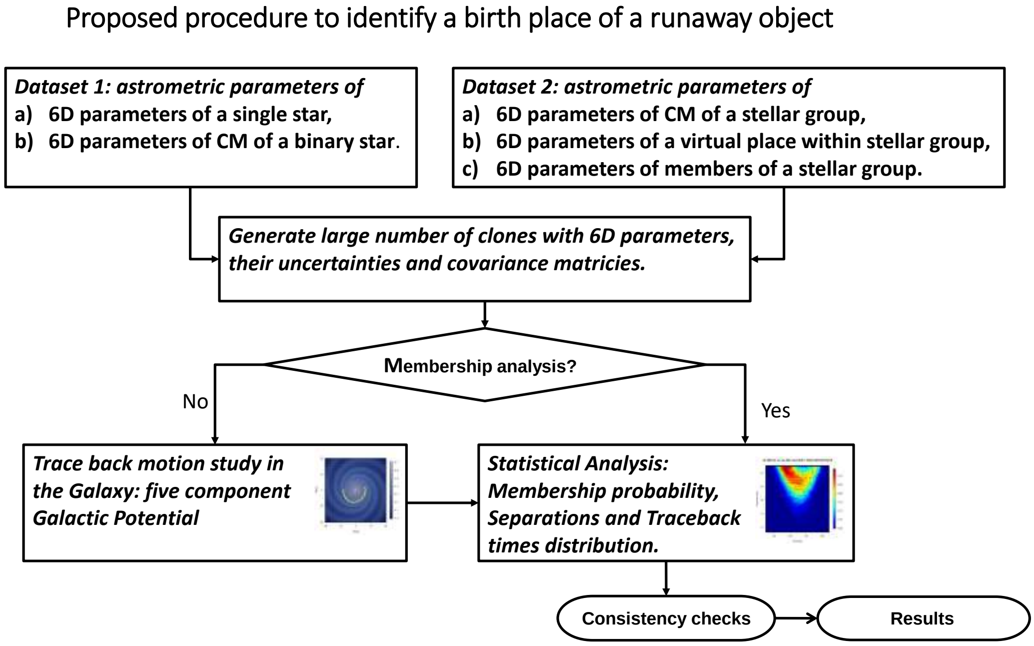

Figure 1. The flowchart of the proposed processing for identification of the birth place of runaway object (the concept "in the same place at the same time").

Further, to identify a probable parental stellar group as a correct counterpart of a *high-velocity* candidate star we will follow to the algorithm depicted in Fig. 1. Moreover, it is obvious, that using as an input astrometric and kinematic parameters and their uncertainties of both one can get, in principle, only certain number of trajectories satisfying some of the criteria (e.g., minimum separation) of the close stellar passage. In each case, one clearly gets a probabilistic output (see, e.g., Hoogerwerf et al., 2000, 2001, Neuhäuser et al., 2020, Tetzlaff et al., 2010). Whether this number is expected from a real pair or by chance, i.e. occured in the same volume of the space during some time interval in the past, needs further statistical analysis, given the above mentioned uncertainties of parameters. Finally, further consistency checks must be performed as listed in Neuhäuser et al. (2020), e.g. that there should not be any more massive (O-type) star in the host group left that is not yet exploded or that the flight time should not be larger than the age of a hosting group or neutron star (if known).

In preparation of this new project and to be ready for the new Gaia data, a new software was written from scratch to trace back the orbits of stars through the Galaxy.

A sample application of it is to find possible common origins of runaway stars and neutron stars at their birth place – from dynamical ejection or in a supernova, e.g. those which contributed to the ^{60}Fe on Earth (Neuhäuser et al., 2020).

To trace back of a star's orbit the well-known equation of motion is numerically integrated backwards in time for the Galactic potential. The number of simulated orbits per star (here: 3 million) as well as the number of steps and step width (here: 1000 years) for the integration are configurable. After each step the mutual separations between the objects are calculated and the minimum separations are determined.

The 'success' of a simulation run can be rated according to certain criteria such as the number of close encounters within, e.g., 10 pc (Hoogerwerf et al., 2000, 2001) or 15 pc (Tetzlaff et al., 2010). We also compute the likelihood for each run: in order to determine most likely past flight path of runaway stars, neutron stars, and associations among the many simulations, we used as measure the multivariate Gaussian likelihood. This likelihood is the sum of likelihoods of the input parameters and their uncertainties (with covariance matrices), as well as output parameters, i.e. positions and the time of a close approach within a stellar association or subgroup.

The Galactic potential used is a three-component model consisting of potentials for disk, spheroid bulge, and halo from Johnston et al. (1996), quite similar (if not the same) as used by Hoogerwerf et al. (2000, 2001):with an axisymmetric disk as first term (Miyamoto & Nagai, 1975), a spherically symmetric bulge as second term (Hernquist, 1990),and a massive spherical Galactic halo as third term (Johnston et al., 1996).

Alternatively, we also used model number III from Bajkova & Bobylev (2017) as Galactic potential, also

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in Galactocentric Cartesian coordinates. with an axisymmetric disk as first term (Miyamoto & Nagai, 1975), a spherically symmetric bulge as second term (Hernquist, 1990), and a massive spherical Galactic halo as third term (Navarro et al., 1996) derived by fitting of modern data on circular velocities of Galactic objects located at distances up to 200 kpc from the Galactic center (Bajkova & Bobylev, 2017). With any of the two potentials, this leads to a first-order system of six ordinary differential equations, the integration of which is done by means of the Runge-Kutta-Fehlberg (order 4,5) method. Alternatively, we also used the Gauss-Everhardt orbit integrator (Avdyushev, 2010). Further, we plan to supplement the Galactic gravitational potential with the more realistic, non-axisymmetric and time dependent terms, which take into account the influence of the central bar of the Galaxy and the spiral density wave (Bajkova & Bobylev, 2019, Fernández et al., 2008, Palous et al., 1993). Alternatively, we will use empirically determined Galactic gravitational potential based on the *Gaia* data.

Positions, distances (and/or parallaxes), and proper motions for neutron stars are listed in the Australian Telescope National Facility (ATNF) Pulsar Catalogue (Manchester et al., 2005, Taylor et al., 1993); proper motions in Galactic longitude and latitude have been transformed to equatorial proper motions with the usual Galactic parameters as above; there are currently 395 neutron stars with both a distance estimate and a transverse velocity – having excluded those which are either too young to be connected to the ^{60}Fe deposition (those related to SN remnants) or too old to be related to young OB associations (milli-second pulsars); more are expected to be found during the project duration, maybe already by SKA; pulsar distances are either independent estimates (like a parallax) with measurement uncertainties or, otherwise, from the dispersion measure (Yao et al., 2017).Among the above mentioned 395 neutron stars, there are 68 pulsars for which there is a Gaia DR2 star at the same position (as listed in the *Gaia DR3* catalog and Simbad), i.e. pulsars in binaries with Gaia stars; for those pulsars, we use the parallaxe and proper motion of the Gaia star also for the pulsar (and in three cases, also the Gaia RV can be used for the pulsar).

Positions, distances, proper motions, and RVs for stellar groups are compiled by (Cantat-Gaudin et al., 2020, Hunt & Reffert, 2023, Mel'nik & Dambis, 2017, Melnik & Dambis, 2020, Soubiran et al., 2018).

Given the measurement uncertainties of input parameters (i.e., astrometric and kinematic) and their covariance matrices (correlations between them), and given that the number of simulations in any Monte Carlo simulation is finite, one can expect some number of trajectories where the separations between two objects are less than a few pc (indicating a close encounter,i.e. a common origin in a binary SN or dynamical ejection, see, e.g., Hambaryan et al., 2022, Hoogerwerf et al., 2000, 2001, Neuhäuser et al., 2020, Tetzlaff et al., 2010). Note, that this number must be compared with the expected number of trajectories which is expected by chance (see, e.g., Neuhäuser et al., 2020).

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