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Identification of birth places of high-velocity stars: CepOB2 association

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Abstract

We have searched high-velocity stars (runaway, walk-away, pulsars, HMXBs and LMXBs), which could have, most probably, originated in the complex CepOB2 association, i.e. in the cores (small clusters or multiple stellar systems) of it. With the trace-back motion study of them we found at least two pairs consisting of a runaway star and pulsar, which were within stellar groups in the Cep OB2 association $\sim$ 1.5-5.5 Myr ago.

1. Introduction

Ambartsumian (1947, 1955) provided the first evidence that formation of single, double and multiple stars still ongoing in the Galaxy in an extended gravitationally unbound stellar associations. Their dimensions can range from a few to a few hundred pc with space densities <0.1 $\mathcal{M}_\odot$ pc^{-3} (for recent review see, e.g., Wright, 2020).

On the other hand, stars are also formed in compact (up to a few dozens pc) groups in gravitationally bound clusters with a relatively higher space densities >1 $\mathcal{M}_\odot$ pc^{-3} (Lada & Lada, 2003).

However, there are also a significant number (10–30%, see, e.g., Renzo et al., 2019, Stone, 1979) of young massive stars which are observed in the Galactic general field and called "Runaway stars", a term first introduced by Blaauw (1961). Runaway stars are thought to have formed in the stellar associations and have been ejected into the general Galactic field by two proposed mechanisms: dynamical ejection or binary supernova. The first mechanism, proposed by Ambartsumian (1954) in a Trapezium type (non-hierarchical) young multiple, dynamically non-stable systems, was further developed by Poveda et al. (1967). In contrary, the binary ejection mechanism was first proposed by Blaauw (1961) to explain the ejection of runaway O and B stars out of galactic plane. In this scenario the secondary star of a close binary becomes unbound when the primary explodes as a supernova (SN).

On the other hand, depending on separation and component masses prior to the explosion (i.e. phase of mass transfer before the SN, 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 binary will either get unbound (ejecting a single runaway 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.

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Note that the magnitude of the kick velocity also depends on the evolutionary status of the pre-explosion close binary system (dynamical stability of mass transfer to the secondary, see, e.g., Hainich et al., 2020).

Note, also, on the possibility of the so-called two-step-ejection scenario, i.e. massive binary ejection from star clusters and a second acceleration of a massive star during a subsequent supernova explosion (Dorigo Jones et al., 2020, Pflamm-Altenburg & Kroupa, 2010).

Thanks to the unprecedent highly precise *Gaia* data, we can now trace back the motion of runaway stars in 3D. With the newly available *Gaia DR3* data, we can expect a large step forward in the understanding of the origin of runaway stars, SNe in binaries, and their dynamics.

It is worth to note that recent systematic search and identification of stellar clusters (Hunt & Reffert, 2023) based on the *Gaia DR3* data revealed a number of groups, sometimes, including also previously known members of extended stellar associations (see, e.g. Melnik & Dambis, 2020b).

In this context, it is very interesting to identify the parent stellar group of high-velocity stars (runaway, walk-away, pulsars, HMXBs and LMXBs), which could have, most probably, originated in these stellar groups, i.e. cores of an extended star forming region.

In this work, we concentrate on the search, identification and kinematic study of high velocity stars, former members of the stellar groups of the complex and extended CepOB2 association (Szilágyi et al., 2023).

2. Selection of runaway targets and parental stellar groups

To find candidates for runaway stars around CepOB2 association, the average center of the CepOB2 association with 30 degree radius has been taken and the runaway candidates from our list of known runaway stars (Hoogerwerf et al., 2001, Maíz Apellániz et al., 2018, Mdzinarishvili, 2004, Mdzinarishvili & Chargeishvili, 2005, Tetzlaff et al., 2011a,b, Tetzlaff et al., 2012, Tetzlaff et al., 2013, 2014) were filtered. As a result, from 392 known runaway stars 67 runaway candidates were filtered. Later on, we chose among them the ones, which are in up to 2000 pc distance and got 52 candidates. For each of the 13 stellar groups the mean velocity was calculated. In order to understand the directions of motion of stars and stellar groups, we calculated for each of 52 runaway candidates and 13 stellar groups the ratio of the difference of their distances to the difference of their velocities. Finally, 20 runaway candidates were chosen. The cross-match with Melnik's field stars (Melnik & Dambis, 2020a) has been done and as a result we got 26 runaway candidates. Eight of them had bow shocks.

To search for runaway pulsars, High Mass X-ray binaries (HMXB) and Low Mass X-ray binaries (LMXB), from ATNF 1.70 catalogue (Manchester et al., 2005), which consists from 3389 pulsars, 398 pulsars were chosen, which transverse velocities were given. Among them, 64 candidates were chosen with 60 degree radius and 4000 pc distance criteria assumption, and finally 15 candidates were selected. For HMXB's Fortin's catalogue (Fortin et al., 2023) was used and by the same criteria 14 HMXBs were chosen. For LMXB's Liu's catalogue (Liu et al., 2001) was used and again by the same criteria two runaway LMXBs were chosen.

3. Trace-back motion study

In order to identify former members of young stellar groups within extended stellar association Cep OB2 we performed trace-back motion study of probable candidates of runaway stars and pulsars (see previous sections). For this purpose using the present-day positions and velocities of them we trace back and compared with the positions of the known young stellar groups in the past. With the distribution of times corresponding to the minimum separation of a pair of runaway star and pulsar within stellar group one may determine significance/probability that the triple were "in the same place at the same time".

To study the Galactocentric motion of selected candidates we use 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 Galaxy gravitational potential consisting of a three component (bulge, disc, and halo) axisymmetric model (Model III from Bajkova & Bobylev, 2017). In addition, the Galaxy gravitational potential is supplemented with the more realistic, non-axisymmetric, and time-dependent terms, which take into account the influence of the central bar and the spiral density wave (Bajkova & Bobylev, 2019, Fernández et al., 2008, Palous et al., 1993).

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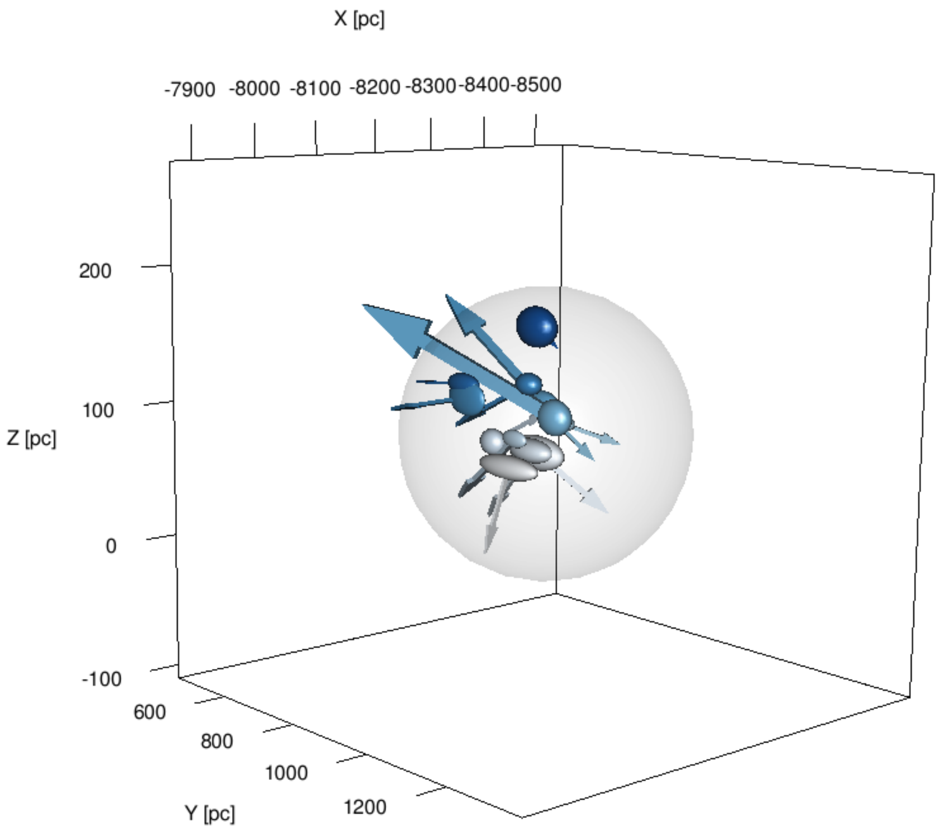

Figure 1. Galactocentric cartesian coordinates of the centers of Cep OB2 extended association (grey ellipsoid,see Table 1 Melnik & Dambis, 2020b) and stellar groups (Szilágyi et al., 2023) within it based on the astrometric and kinematic parameters of their members according to the *Gaia DR3*. Arrows length are corresponding to the expected positions after 15 Myr and the color of each stellar group are coded according to their ages (see, Szilágyi et al., 2023, 2-15 Myr), the darker is younger one.

In order to take account of the uncertainties in the astrometric parameters of the star and associations, each one was replaced by large number of clones, each with astrometric parameters drawn from a multivariate normal distribution. This is done using the covariance matrix of astrometric parameters from *Gaia DR3* (Gaia Collaboration 2018) for the runaway star, for pulsars five astrometric parameters from the catalog of pulsars (Manchester et al., 2005, radial velocities were drawn from the Maxwell's distribution taking into account transverse velocities) and for the stellar groups with the parameters determined by us (see Table 1). Such a procedure is superior to the individual, independent random drawing of each parameter that ignores their mutual dependence.

An application of this procedure to the selected candidates of runaway star, pulsar and young stellar groups lead to the results presented in the Table 2 (see also Fig. 2).

4. Conclusions and outlook

Thus, for the most probable birth place of two runaway stars (*Gaia DR3* 2179226690440773888 and 2203102516722685184) and three pulsars (B0011+47, J2053+4650 and J1431-4715) can be considered Cep OB2 extended association, i.e. within five young stellar groups (see, Table 2). All these runaway star and pulsar pairs with close approve show significant number of orbits (column Nsuc in the Table 2 out of 3 Giga simulations) within a certain young stellar group in the past. Indeed, the probabilities that such a triple

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Table 1. Galactocentric cartesian coordinates of the centers of Cep OB2 extended association (Melnik & Dambis, 2020b) and stellar groups (Szilágyi et al., 2023) within it based on the astrometric and kinematic parameters of their members according to the *Gaia DR3*.

Name		X [pc]	Y [pc]	Z [pc]	U [pc/Myr]	W [pc/Myr]	W [pc/Myr]
Cep OB2	median	-8211.27	916.36	82.13	32.50	240.84	2.16
	mad	68.92	91.82	38.50	4.30	7.93	5.74
Group 1	median	-8235.12	855.58	156.32	30.34	241.48	0.99
	mad	7.14	16.59	5.52	8.09	18.18	5.47
Group 2	median	-8125.07	831.75	118.77	32.71	232.67	1.86
	mad	3.89	14.11	2.88	1.99	12.80	1.92
Group 3	median	-8198.78	890.17	117.84	33.05	228.69	-0.57
	mad	5.32	9.83	2.98	4.54	21.79	3.12
Group 4	median	-8123.05	843.65	109.66	33.67	228.85	0.96
	mad	3.21	16.52	4.75	5.90	39.63	5.08
Group 5	median	-8221.91	889.62	102.52	34.47	226.51	6.91
	mad	4.45	14.46	3.39	3.98	13.78	3.74
Group 6	median	-8212.18	937.48	94.91	38.34	215.09	6.80
	mad	6.31	13.20	4.83	3.82	22.76	1.99
Group 7	median	-8235.97	895.66	91.23	27.77	241.71	-0.31
	mad	4.24	10.34	4.10	6.08	20.42	2.88
Group 8	median	-8263.45	883.77	84.08	27.09	243.46	0.91
	mad	5.34	9.49	2.21	13.24	42.33	3.80
Group 9	median	-8158.97	913.60	81.40	30.81	228.44	-1.69
	mad	2.48	10.60	2.34	6.45	38.30	3.71
Group 10	median	-8171.07	839.36	73.81	26.66	241.63	3.36
	mad	5.04	9.78	3.52	4.18	21.94	1.86
Group 11	median	-8222.75	862.91	65.15	31.47	231.74	-1.87
	mad	6.30	18.68	3.26	5.76	23.04	2.03
Group 12	median	-8235.46	859.03	62.40	26.00	244.40	-1.20
	mad	7.03	23.76	4.68	8.90	31.18	2.90
Group 13	median	-8150.05	912.29	61.05	35.12	240.87	-1.86
	mad	5.77	25.81	3.19	4.83	23.31	2.37

(stellar group, runaway star and pulsar) might be by a chance (owing to the uncertainties of the astrometric parameters) are lower by several orders of the magnitude in comparison to the observed probabilities and if they, in reality, were at that time in the same place.

Whether they originated in a binary or multiple stellar system needs further study and performing this type of an analysis is out of the scope of this presentation. In order to study the possibility of different ejection mechanisms of stars from a stellar system we have prepared (still in development) a simulation code in C++. The code takes into account the gravitational forces between the stars, gravitational potential of the Galaxy and the star cluster, and the evolution of the a star (including mass loss over time and potentially asymmetrical supernova explosion). The code uses Yoshida 4 numerical integration method (Yoshida, 1990) to numerically solve the differential equations of motion, and it adjusts the integration timestep using regularization methods. Among the output results we get the exact parameters of supernova explosions that happened (the time, direction and magnitude of the kick velocity), as well as the escape parameters of the stars.

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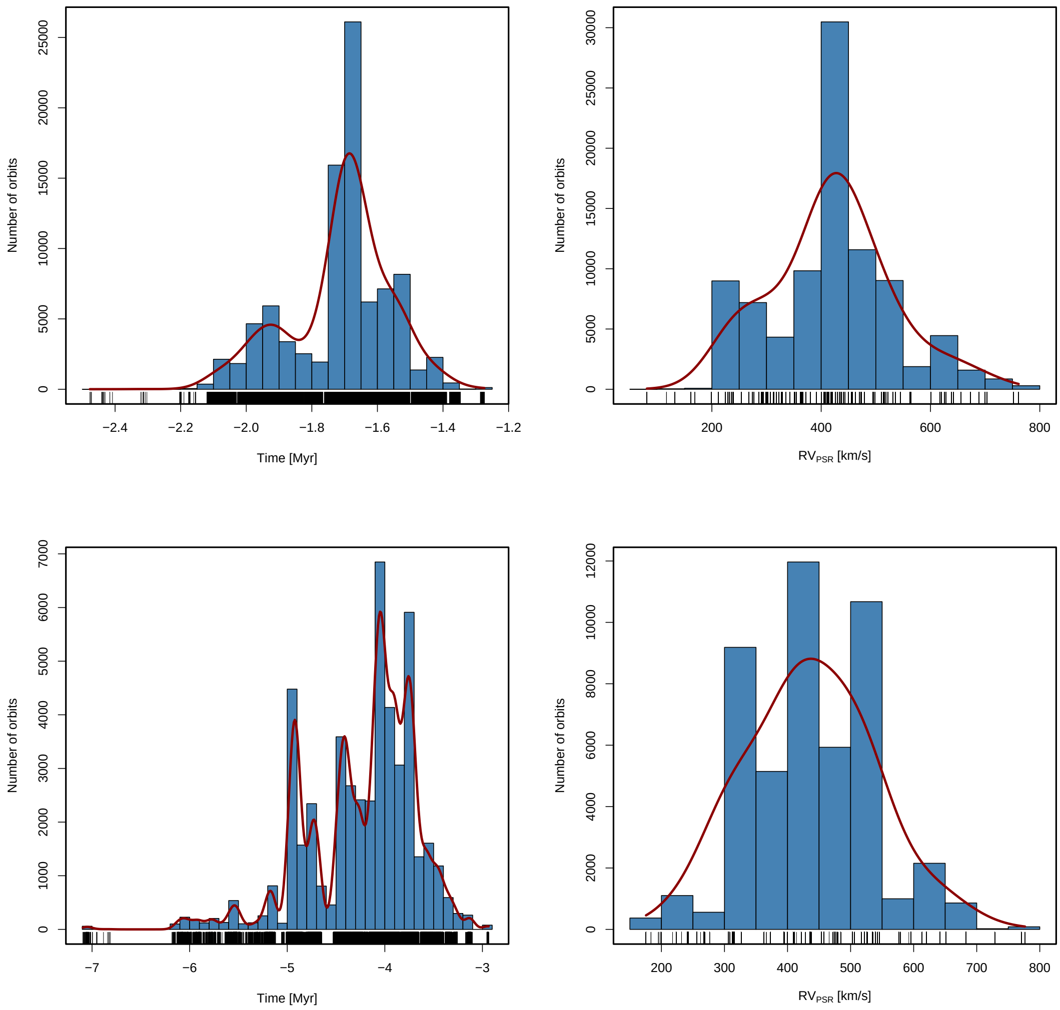

Figure 2. *Left panels:* flight times between pairs of runaway star *Gaia DR3* 2179226690440773888, PSR B0011+47 and *Gaia DR3* 2179226690440773888, PSR J2053+4650 and stellar groups No. 10 and 11 (Szilágyi et al., 2023) peaking at -1.7 and -4.4 Myr, respectively and having minimum separation less than 3pc. *Right panels:* Distributions of radial velocities of pulsars drawn from the Maxwell's distribution (see, Table 2).

Table 2. Most probable birth places of a stellar pairs consisting of a runaway star and pulsar in the Cep OB2 extended association (Melnik & Dambis, 2020b) and stellar groups (Szilágyi et al., 2023).

Group #	Gaia DR3	PSR	Nsuc	Tmin [Myr]	RVpsr [km/s]
10	2179226690440773888	B0011+47	90644	$-1.69^{-0.06}_{+0.17}$	$427.9^{-105.6}_{+94.5}$
11	2203102516722685184	B0011+47	76252	$-1.79^{-0.13}_{+0.27}$	$335.4^{-163.8}_{+21.4}$
5	2203102516722685184	J2053+4650	55922	$-3.40^{-0.39}_{+0.01}$	$673.2^{-143.3}_{+4.1}$
11	2203102516722685184	J2053+4650	36899	$-4.04^{-0.47}_{+0.47}$	$436.4^{-63.2}_{+106.5}$
12	2179226690440773888	J2053+4650	44210	$-3.43^{-0.62}_{+0.03}$	$505.7^{-78.4}_{+30.7}$
11	2179226690440773888	J2053+4650	42560	$-4.40^{-0.08}_{+0.31}$	$482.9^{-24.2}_{+47.4}$
12	2179226690440773888	J1431-4715	14513	$-4.51^{-0.33}_{+0.95}$	$384.9^{-105.9}_{+166.0}$
12	2203102516722685184	J2053+4650	11907	$-4.23^{-0.71}_{+0.06}$	$416.4^{-114.0}_{+24.7}$

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