On the origin of runaway binaries: the case of the HMXB 4U 2206+54/BD +53 2790

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Abstract

We present most probable place and time of the origin of the runaway high-mass X-ray binary 4U 2206+54 based on its *Gaia EDR3* astrometric parameters and our new systemic radial velocity. We studied the trace back motion of the system and propose that it originated in the subgroup of the Cepheus OB1 association (Age∼4-10 Myr) with its brightest star BD+53 2820 (B0V; $\mathcal{L}\sim10^{4.7}\mathcal{L}_\odot$). The kinematic age of 4U 2206+54 is about 2.8 ± 0.4 Myr, it is at a distance of 3.1-3.3 kpc and has a space velocity of 75-100 km/s with respect to this member star (BD+53 2820) of the Cep OB1 association. This runaway velocity indicates that the progenitor of the neutron star hosted by 4U 2206+54 lost about 4-9 $\mathcal{M}_\odot$ during the supernova explosion and the latter one received a kick velocity of at least 200-350 km/s . The high-mass X-ray binary 4U 2206+54/BD+53 2790 was born as a member of a subgroup of the Cep OB1 association, the initially most massive star in the system terminated its evolution within $\lesssim 7-9$ Myr, corresponding to an initial mass $\gtrsim 32\ \mathcal{M}_\odot$.

Keywords: *astrometry, stars: individual: 4U 2206+54/BD +53 2790, Cep OB1, stars: HMXB, neutron, supernovae.*

1. Introduction

It is generally accepted that most stars are formed in compact groups in gravitationally bound clusters with space densities >1 $\mathcal{M}_\odot$ pc^{-3} (Lada & Lada (2003)) or in extended gravitationally unbound stellar associations with lower space densities <0.1 $\mathcal{M}_\odot$ pc^{-3} (Wright (2020)).

Star clusters form within giant molecular clouds and remain embedded in clouds for $\sim 2-5$ Myr before the combination of massive stellar winds and Supernovae drive out the gas. The stars that are left behind after the gas expulsion relax to the new potential and attempt to return to virial equilibrium (Baumgardt & Kroupa, 2007, Goodwin & Bastian, 2006).

Ward et al. (2020) argue that the formation of OB associations did not follow this scenario and show that they are formed in-situ as relatively large-scale and gravitationally-unbound structures. The OB-associations may contain multiple groups/cores of young stars, having characteristic population of

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the massive, early spectral O-B type and also containing numerous low-mass stars. They exhibit some spatial and kinematic concentration of short-lived OB stars, a fact first realized by Ambartsumian (1947, 1955), which provided the first evidence that formation of single, double and multiple stars still ongoing in the Galaxy. Their dimensions can range from a few to a few hundred pc (for recent review see, e.g., Wright, 2020).

However, there is 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). 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). In this case it will be very hard to identify the parent star clusters by traced back motion study of the binary system or single runaway star.

However, depending on separation and component masses prior to the explosion 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. 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).

The proper motion of a runaway star or binary system often points exactly away from a stellar association, of which the star was formerly a member.

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In this context, it is very interesting to identify the parent stellar group of HMXBs in the Galaxy (see, e.g., Ankay et al., 2001, van der Meij et al., 2021).

In this work, we concentrate on the kinematic study of the unique HMXB binary 4U 2206+54, which has been suspected to contain a neutron star accreting from the wind of its optical companion BD +53 2790. This optical counterpart was identified by Steiner et al. (1984) as the early-type star. Further analysis of many space and ground based observations showed that the system hosts a neutron star accreting from the wind of its companion, BD +53 2790 (see, e.g., Finger et al., 2010, Reig et al., 2009, Torrejón et al., 2018), which also exhibits a radial velocity modulation (Stoyanov et al., 2014, see further).

The neutron star in the system is probably a magnetar - a class of rare, strongly magnetized neutron stars. The strength of the surface characteristic magnetic field is estimated of the order of $B_S \sim 2\times10^{13} - 10^{14}$ G of this neutron star with the very slow spin period of – $P_{spin} \sim (5540 - 5570)$ s and the rapid spin-down rate of $\dot{P_{spin}} = 5.6 \times 10^{-7} ss^{-1}$ (Finger et al., 2010, Reig et al., 2009, Torrejón et al., 2018). Currently, the 4U 2206+54 is only known HMXB system hosting accreting magnetar with or without fallback disk (Alpar et al., 2013, Özsükan et al., 2014). The donor star does not meet the criteria for a classical Be V star, but rather is a peculiar O9 V star with higher than normal helium abundance (Blay et al., 2006) and the double peaked H_α emission line, as typical for the decretion disks (Hainich et al., 2020). The 4U 2206+54 with the orbital period of 9.5 days is one of the shortest

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orbital periods among known HMXBs.

2. The birth place of 4U 2206+54

In order to identify the possible birth place of 4U 2206+54 one needs to determine its possible membership to a stellar group either currently or in the past. The latter also requires to perform their trace back motion study in the Galaxy to test the concept: 4U 2206+54 and a stellar group or some of its members in the past were "in the same place at the same time".

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. occurred 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 (for details, see, Hambaryan et al., 2021, and further Sec. 2.1 and Fig. 3). Finally, further consistency checks must be performed as listed in Neuhäuser et al. (2020).

First, we have cross-matched the optical companion BD+53 2790 of the HMXB with possible candidate counterparts in *Gaia DR2 and EDR3* and identified it with the source 2005653524280214400 (see, also Arnason et al., 2021).

Table 1. The parameters of the optical companion BD +53 2790 of 4U 2206+543 and its probable birth counterparts — the member stars of Cep OB1 association (BD +53 2820 or HD 235673).

Name	*Gaia EDR3* Source ID	d** [pc]	ϖ [mas]	$\mu_\alpha cos\delta$ [mas/yr]	μ_δ [mas/yr]	RV*** [km/s]
BD +53 2790	2005653524280214400	$3167.4^{+165.3}_{-120.1}$	0.3051±0.0136	-4.173±0.015	-3.317±0.014	-62.7±8.8
BD +53 2820*	2005418950349782272	$3545.4^{+286.8}_{-225.5}$	0.2681±0.0169	-2.973±0.018	-3.350±0.016	15.8±32.3
HD 235673	1981443102866159232	$4201.6^{+827.1}_{-489.4}$	0.2240±0.0292	-3.828±0.030	-3.390±0.026	-40.0±10.0

* Radial velocity of BD +53 2820 is variable, may be double–lined spectroscopic binary (Abt & Bautz, 1963).

** Distance estimates are provided by Bailer-Jones et al. (2021) using parallaxes and additionally the G magnitudes.

*** Radial velocities and their standard deviations are given according to the SIMBAD astronomical database (Wenger et al., 2000) and corresponding bibliographic entries (Abt & Bautz, 1963, Wilson, 1953).

Next, we performed a preliminary selection of the possible birth place (i.e. a stellar group) of HMXB 4U 2206+54, according to its position and distance, as well as, upper limits of the age and runaway velocity (e.g., ∼ 10-20 Myr and ∼ 100-150 km/s corresponding to the distance of ∼ 1-2 kpc), from the recent catalogues of members of stellar associations (Melnik & Dambis, 2020) and open clusters (Cantat-Gaudin et al., 2020).

The selection criteria are as follows: Galatic longitude between 80° and 120°, latitude between -10° and 10° and distance between 1500 pc and 5000 pc. With this first step of selection the list consists of 143 stellar clusters and 11 associations. Taking into account the direction of relative motion of BD+53 2790 to these stellar groups (3D or proper motion) and the most probable upper limit of its age (see, e.g., Ekström et al., 2012, Meynet & Maeder, 2003, Spectral type O9.5V, $\mathcal{M}\sim\gtrsim 15.5\,\mathcal{M}_\odot$) the reduced list includes 62 open clusters and only one stellar association (see, Fig. 1) which can be considered as the probable place of the origin of the HMXB 4U 2206+54.

For these birth place counterparts, we estimated the membership probability/likelihood of BD+53 2790 by comparison with the bona fide members of stellar groups given the astrometric and kinematic parameters and their uncertainties by *Gaia EDR3*. For this purpose we used (for details, see, Hambaryan et al., 2021) a multivariate Gaussian distribution in the five dimensional space (position, parallax and proper motions)*.

*Unfortunately, the overwhelming majority, in average $\gtrsim$ 98% (Cantat-Gaudin et al., 2020), of bona fide members

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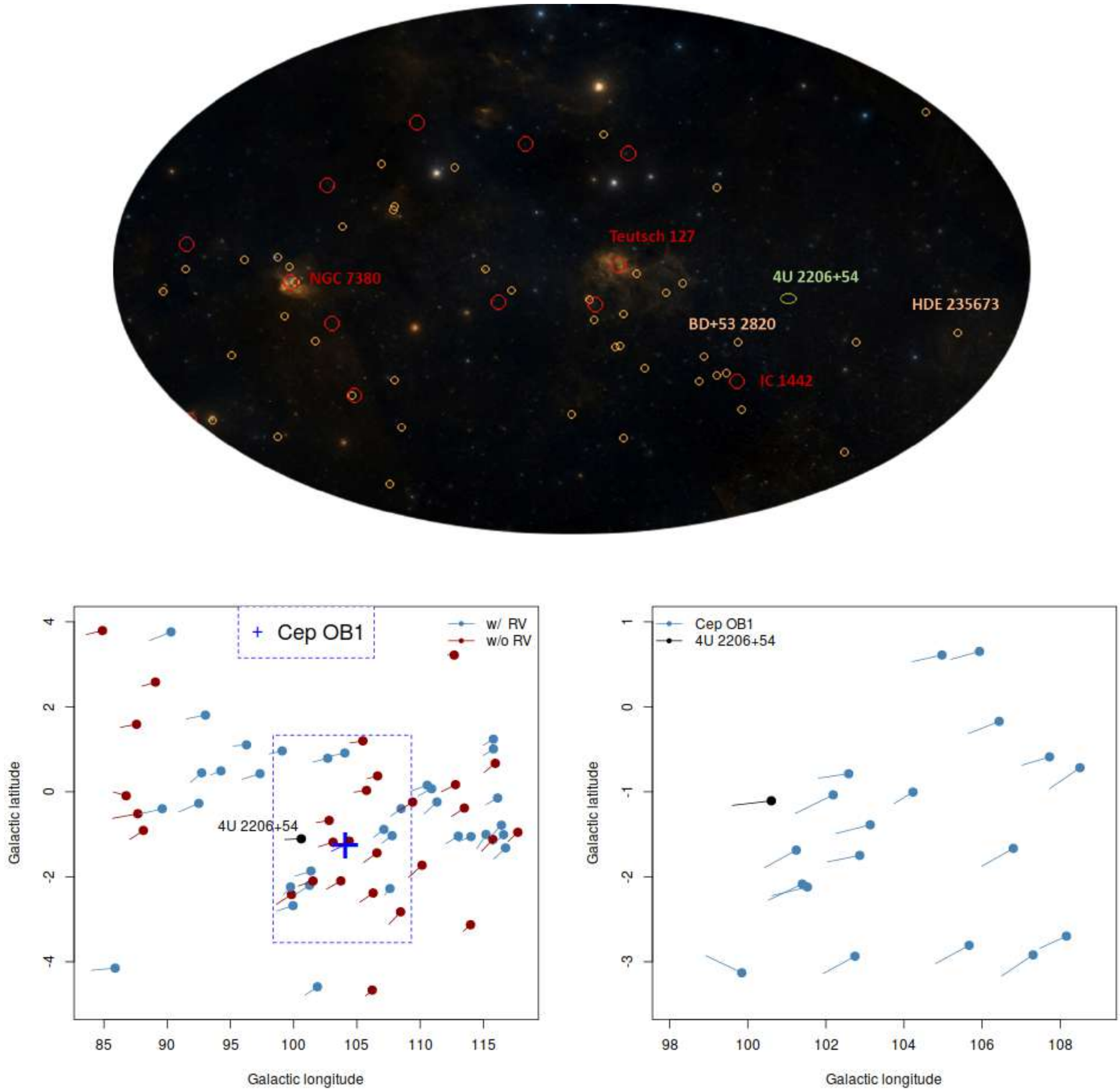

Figure 1. *Top panel:* Digitized (DSS2) color image of the region of the HMXB 4U 2206+54 (green oval) in the galactic coordinates, prepared with Aladin Desktop (Bonnarel et al., 2000). The positions of stellar clusters (large red circles, Cantat-Gaudin et al., 2020) and the Cep OB1 association member stars (brown circles, Melnik & Dambis, 2020) are also indicated. Most relevant objects for this study are annotated (for details, see text). *Bottom panel:* Galactic positions and proper motions of stellar clusters with the Cep OB1 in the center (left panel); the Cep OB1 association members are shown in the right panel, they can be considered as most probable birth counterparts of 4U 2206+54/BD+53 2790.

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It turned out, that BD+53 2790 has a very low probability to be considered as a member one of them. The logarithm of the ratio of the mean likelihoods of BD+53 2790 in comparison to the members of a stellar group is in the range of -11 to -183. Note that for the case of the Cep OB1 stellar association (the single one in the list) the logarithm of likelihood ratio is equal to -61.2.

Hence, we need to study trace back motions of this HMXB and its above mentioned probable counterparts of the place of origin, i.e. whether 4U 2206+54/BD+53 2790 and a stellar group or one of its member were in the same place at the same time in the past. In order to study the Galactocentric motion of the HMXB 4U 2206+54 for an input we used the astrometric parameters of the optical counterpart BD+53 2790 of the system presented in *Gaia EDR3*, as well as its systemic radial velocity. For the latter one, we performed additional spectral observations (Échelle spectrograph FLECHAS at the 90 cm telescope of the University Observatory Jena, Hambaryan et al., 2021, Mugrauer et al., 2014) and analyzed the combined radial velocity data set (Abt & Bautz, 1963, Stoyanov et al., 2014).

The fitted systemic velocity $\gamma = -61.5 \pm 1.55$ km/s together with other astrometric parameters presented in *Gaia EDR3* intended to serve as an input to retrace its orbits back in time to investigate the probable birth place and kinematic age of HMXB 4U 2206+54. However, to be conservative, for the study of trace back motion of HMXB 4U 2206+54 for the input parameter systemic radial velocity we used a relatively large interval, i.e. the randomly generated V_{sys} values were drawn from Gaussian distribution with the mean value equal to the fitted systemic velocity $V_{sys} \equiv \gamma = -61.5$ km/s with standard deviation of $SD_{V sys} = 15.0$ km/s.

2.1. Motion of 4U 2206+54 in the Galaxy

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 4U 2206+54/BD+53 2790, the possible parental stellar cluster and association we make 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 consisting of a three component (bulge, disk and halo) axisymmetric model (Model III from Bajkova & Bobylev, 2017). In addition, the Galactic 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).

In order to take account of the uncertainties in the astrometric parameters of the star and stellar group, each one was replaced by a large number of clones, each with astrometric parameters drawn from a multivariate normal distribution. This is done by making use of the covariance matrix of the astrometric parameters from *Gaia EDR3* for the star and from a stellar cluster/association centroid parameters (Cantat-Gaudin et al., 2020, Melnik & Dambis, 2020, Soubiran et al., 2018) or the astrometric parameters of the individual member star (Gaia Collaboration, 2020, Gaia Collaboration et al., 2018). Such a procedure is superior to the individual, independent random drawing of each parameter that ignores their mutual dependence and result in to the more realistic probability distribution functions of the separation between 4U 2206+54 and the centre of stellar group or any member star (see, e.g., Fig. 3 and Sec. 2.2). For numerical integration we utilise the fast and accurate Gauss-Everhart orbit integrator provided by Avdyushev (2010).

Based on the *Hipparcos* proper motion of the HMXB HD153919/4U1700-37 Ankay et al. (2001) propose that it originates in the OB association Sco OB1 within $\lesssim$6 Myr (kinematic age being τ = 2.0 ± 0.5 Myr). We applied our approach to this system based on the more precise *Gaia EDR3* data and confirmed that both the place of origin in Sco OB1 and the kinematic age of HMXB HD153919/4U1700-37 (τ = 2.33 ± 0.05 Myr).

2.2. Results

Our trace back motion study of 4U 2206+54 and its possible parental stellar groups (see, Sec. 2) revealed that only the association Cep OB1 can be considered as a candidate. The astrometric and

of the stellar groups have no significant number of radial velocity measurements.

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kinematic parameters of its centroid was determined by member stars (Melnik & Dambis, 2020) present in the *Gaia EDR3* catalogue. Note, that the used distances of member stars and their uncertainties are provided by Bailer-Jones et al. (2021) using parallaxes and additionally the G magnitudes. It turned out that the trace back times of the pair (i.e. the HMXB 4U 2206+54 within the association Cep OB1, ∼ 150 pc) are distributed almost uniformly over a range from 1.3 Myr to 15 Myr. Given the fact that Cep OB1 association has a relatively large size (with a distance ∼ 2.7-3.5 kpc and several degrees on the sky), and that it is very elongated in the direction of the Galactic longitude (see Fig. 1), suggesting that it may include a chain of OB associations (Melnik & Dambis, 2020) or cores of different ages (see, Sec. 3), we performed also a trace back motion study of 4U 2206+54 and each member star to identify the most probable common birth place inside of the Cep OB1 association. Note that from 58 member stars (Melnik & Dambis, 2020) of Cep OB1 46 have an entry in *Gaia EDR3* and only 23 have also radial velocity measurements. It turned out that only 2 member stars, HD 235673 and BD+53 2820, with spectral types of O6.5V and B0V, respectively, show a significant number of close passages with BD+53 2790. Namely, from 1 million Monte-Carlo simulations 1234 (0.12%) and 52936 (5.3%) rated as success, i.e. the minimum separation does not exceed 15 pc within 20 Myr in the past, accordingly.

Moreover, the distributions of the trace back times of these “small” fractions of successful cases are unimodal (see, e.g., Fig.3) and a significant amount of them, namely 692 (∼56%) and 36929 (∼70%), is concentrated within relatively narrow time intervals δt=2.8 (12.4-15.2) Myr and δt=0.8 (2.4-3.2) Myr in the past, respectively.

In order to compare the obtained numbers of successful cases with the expected numbers of cases when our HMXB and a Cep OB1 member star (4U 2206+54–BD+53 2820 or 4U 2206+54–HD 235673) in reality were at the same place at the same time, we created virtual pairs inside the Cep OB1 association at the positions corresponding to BD+53 2820 and HD 235673. We ran them forward with the kinematic properties (proper motions and RVs, see Table 1) of flight times from 2.4 to 3.2 Myr and from 12.4 to 15.2 Myr in steps of 0.05 Myr. For each of the times in the interval, we traced back the pair starting from their virtual positions and using the kinematic properties (proper motions and RVs) – and varying them within their measurement uncertainties (i.e. according to the covariance matrices provided in *Gaia EDR3*, including as well corresponding parallax/distance errors) for 1 million trials each. For each such trial, we then obtained as usual the minimum distance between pairs. This procedure thus yields the number of expected close approaches (within e.g. 15 pc) for the above mentioned time intervals. As a result, with 95% confidence interval under the assumption of binomial distribution, we obtained (and, thus, expect at least) close meetings within 15 pc in 2.3 (2.0-2.7)% and 0.29 (0.21-0.33)% cases from of 1 million runs corresponding to the pairs 4U 2206+54–BD+53 2820 and 4U 2206+54–HD 235673, accordingly. Shortly, these fractions can be considered as lower thresholds in favour of the hypothesis that a pair of HMXB and member star of the Cep OB1 were at the same place during the above mentioned time intervals.

Also, we simulated a large number of random ”HMXB”s with mean astrometric and kinematic parameters and their covariance matrices of neighboring stars of 4U 2206+54/BD+53 2790 within 10 arcmin extracted from *Gaia EDR3* and calculated traced back orbits and compared them with the real trajectories of BD+53 2820 and HD 235673. It turned out that for such a “random” 4U 2206+54 in one million trials only 8 and 2 cases are successful ones (i.e. separation not exceeding 15 pc) with BD+53 2820 and HD 235673 in the trace back time range of 2.4-3.2 Myr and 12.4-15.2 Myr, respectively, i.e. with 95% confidence interval under the assumption of binomial distribution, we expect close meetings within 15 pc in 0.0008 (0.0003-0.001)% and 0.0002 (0.00002-0.0007)% successful cases even with this conservative randomization.

Thus, statistically the vicinity of both member stars (BD+53 2820 and HD 235673) of the Cep OB1 association in the past can be considered as probable place of the origin of the HMXB 4U 2206+54, thus indicating the probable coeval formation of the progenitor binary system and one of these stars. Note, that the case of BD+53 2820 can be considered as more probable one than the one of HD 235673 (see, further Sec. 3).

In Figure 2, the past 3D trajectories are displayed for the member star BD+53 2820 of Cep OB1 and for BD+53 2790 itself. The analysis of separations and corresponding times (see, Fig. 3) shows

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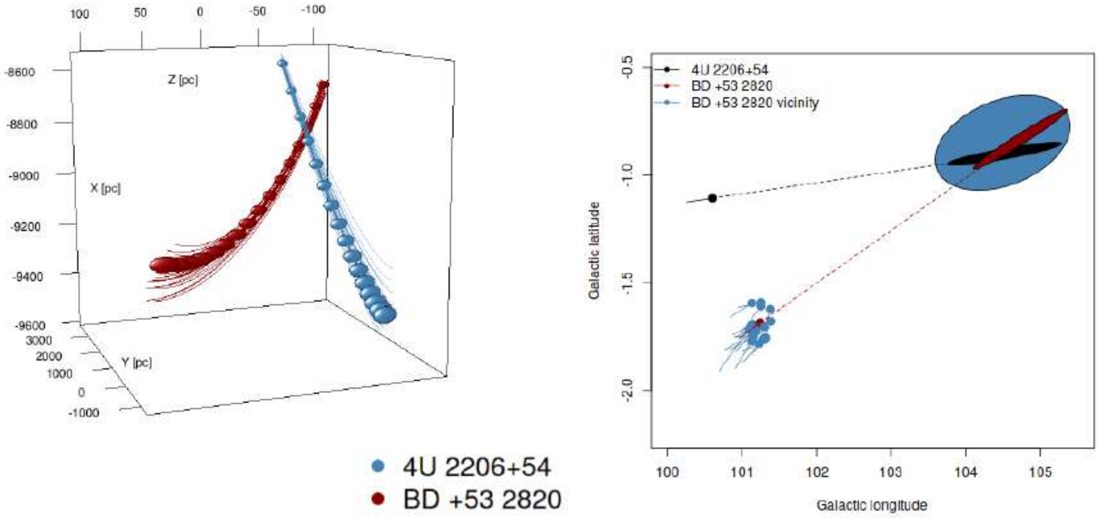

Figure 2. *Left panel:* The 3D trajectories of 4U 2206+54/BD+53 2790 and BD +53 2820 ≡ Gaia EDR3 2005418950349782272, a member of the Cep OB1 association, in Galactocentric Cartesian coordinates in the past. *Right panel:* The positions and proper motions of 4U 2206+54/BD+53 2790 and subgroup of stars in the Cep OB1 association with its brightest star BD +53 2820 in Galactic coordinates. With filled colors of ellipses are indicated the most probable positions of corresponding stars at 2.4-3.2 Myr ago.

that BD+53 2790 and BD+53 2820 in reality were both inside of the same volume (sphere with radius of $\sim$ 15pc) $\tau = 2.8 \pm 0.4$ Myr ago. We observe a similar picture for the neighboring stars of BD+53 2820 in the projection on the sky, i.e. purely using position, distance and proper motions of them (see, Fig. 2, left panel).

Figure 3 shows the distribution of the minimum separations, $D_{\min}(\tau_0)$, and the kinematic ages, τ_0, of the 52 936 simulations mentioned above.

In addition, we studied also the trace back motion of the pair (4U 2206+54–BD+53 2820) with number of input systemic radial velocities corresponding to the observed mean radial velocity values and standard deviations with different instruments Note that these parameters serving for an input to generate random systemic velocity are independent of the fitting results and cover a relatively large interval (see, e.g. Table 4 Hambaryan et al., 2021). It turned out that all of these cases confirmed our previous result, i.e. very similar kinematic age of the 4U 2206 and statistically significant success rate (Hambaryan et al., 2021).

3. Discussion

Based on the parameters of BD+53 2790 provided by *Gaia EDR3*, we calculated its absolute magnitude $M_V = -4.44 \pm 0.70$ mag (V = 9.84±0.2 mag, B = 10.11±0.19 mag, d = 3135.8±91.7 pc, Av = 1.8±0.70 mag, Reig & Fabregat, 2015) at first. Taking into account the bolometric correction (BC = -3.2 mag, see, e.g., Pecaut & Mamajek, 2013) for an O9.5V spectral type star we estimated the mass to be $\mathcal{M}= 23.5^{+14.5}_{-8.0}\mathcal{M}_{\odot}$using the luminosity-mass relation for main-sequence stars selected from the components of detached eclipsing spectroscopic binaries in the solar neighborhood (Eker et al., 2018, $\log \mathcal{L} = (2.726 \pm 0.203) \times \log \mathcal{M} + (1.237 \pm 0.228)$). With this initial mass there may be an upper limit for its lifetime in the range of 10-12 Myr according to non-rotating and rotating stellar evolution models (Ekström et al., 2012, Meynet & Maeder, 2003, Weidner & Vink, 2010). Hence, the primary of the progenitor of 4U 2206+54 may have an upper lifetime limit of 7-9 Myr.

Already Humphreys (1978) lists 11 O-stars within the large Cep OB1 association, which is located

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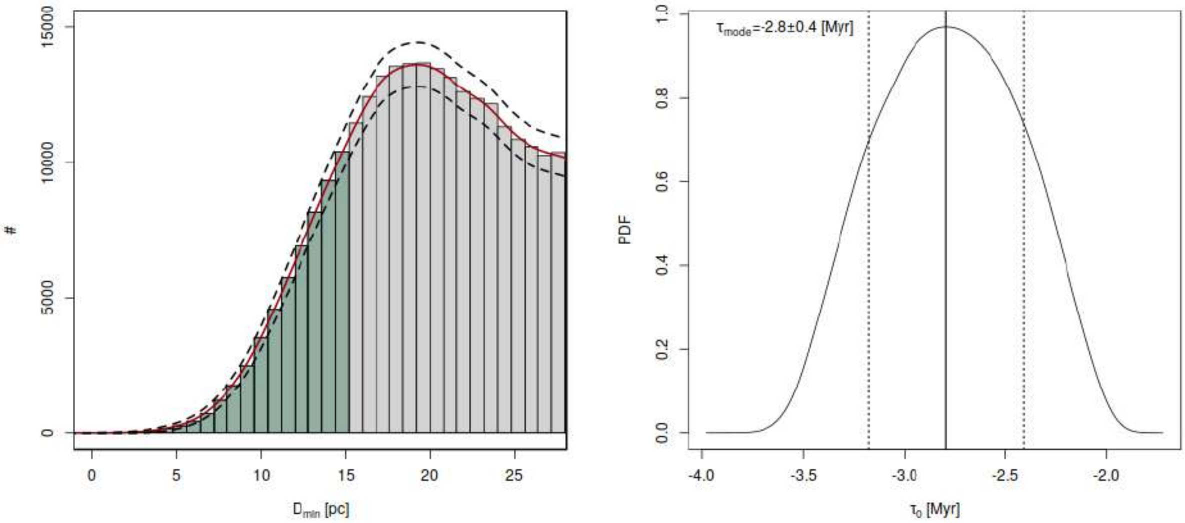

Figure 3. Distributions of minimum separations (D_{min}) and corresponding flight times (τ_0) of closest stellar passage of 4U 2206+53 and BD+53 2820 ($\leq$ 15 pc separation, rated as success, marked as filled green area) according to the trace back motion study of them in the Galaxy. The red curve with enveloping dashed curves show the fit of expected distribution of minimum separations for the 3D case (Eq. A3 in Appendix, Hoogerwerf et al., 2001). The highest posterior density (HPD) interval, 68% of area, is determined as a probabilistic region around a posterior mode of kinematic age of 4U 2206+53 and depicted as vertical dashed-lines (for details, see in the text).

at a distance of 3470 pc. According to Massey et al. (1995) the stellar association Cep OB1/NGC 7380 containing the highest mass stars has formed over a short time span, no longer than 4-6 Myr. Despite the fact that most of the massive stars are born during a period of $\Delta\tau$ <3 Myr in this association, some star formation has clearly preceded this event, as evidenced by the presence of evolved ($\tau \sim 10$ Myr) 15 $\mathcal{M}_{\odot}$ stars (Massey et al., 1995). Most recently Melnik & Dambis (2020) studied the motions inside 28 OB associations with the use of Gaia DR2 proper motions and lists 58 member stars of the Cep OB1 association having luminosity classes in the range of I to V, with spectral types of O6.5-M4. On the other hand, Kharchenko et al. (2005a,b) identifies 3 ionising star clusters related to the Cep OB1 association: NGC 7380, IC 1442, and MWSC 3632. Moreover, according to the most recent catalogues of stellar groups (Cantat-Gaudin et al., 2020, Soubiran et al., 2018) in the region of the Cep OB1 there are more groups in the age range of 4-10 Myr (see, Fig. 1).

The estimated ages of the Cep OB1 and 4U 2206+54 already are excluding HD 235673 as a birth counterpart owing to the longer flight time ($\tau = 13.2^{+2.0}_{-0.8}$ Myr, Sec. 2.2). Moreover, if this O6.5V spectral type star and the progenitor of 4U 2206+54 were born together then for the primary mass we would expect at least 40 $\mathcal{M}_{\odot}$and maximum lifetime of 4-10 Myr, much shorter than the flight time of 4U 2206+54 and HD 235673 to the hypothetical place of the common origin.

Thus, $\tau = 2.8 \pm 0.4$ Myr can be considered as the most probable kinematic age of 4U 2206+54, which suggests a coeval formation of the progenitor binary system of that HMXB and a subgroup of stars from the Cep OB1 association with its brightest member BD+53 2820.

Having estimates of the age range of the Cep OB1, the conservative lifetime of the donor star of the HMXB BD+53 2790 and the flight time to the probable birth place, we estimated the upper limit of the lifetime and hence, the initial mass of the primary before the SN for all models provided by Ekström et al. (2012), Meynet & Maeder (2003) to be $\mathcal{M}_{initial} \sim$ 32-60 $\mathcal{M}_{\odot}$.

It is difficult to reconstruct the evolution of the massive binary before the SN explosion. Nevertheless, with our results for the kinematic age and the orbital parameters of 4U 2206+54 we may put some constraints on it (Hambaryan et al., 2021, Hurley et al., 2002, Nelemans et al., 1999, Postnov & Yungelson, 2014, Tauris & Takens, 1998, van den Heuvel et al., 2000).

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Our analysis of motion shows that 4U 2206+54 originates in the OB association Cep OB1, from which it escaped about 2.8±0.4 Myr ago due to the SN of 4U 2206+54's progenitor. Using parameters of calculated 36 929 traced back orbits for the relative space velocity one obtains $\vartheta \equiv \mathrm{V_{relative}} = 92.6^{+14.6}_{-16.2}$ km/s with respect to BD+53 2820 or its vicinity stars and hence, the mass of the ejected material during the SN event $\Delta\mathcal{M} = 5.6^{+3.6}_{-2.2}\ \mathcal{M}_\odot$ for the neutron star of mass $\mathcal{M}_2 = 1.4\ \mathcal{M}_\odot$. Note, that the estimate of $\Delta\mathcal{M}$ is not changing significantly depending on the mass of a neutron star (1.2-2.2 $\mathcal{M}_\odot$). Thus, at the moment of the SN instantaneous explosion the collapsing core would have a mass of $7.0^{+4.2}_{-2.6}\ \mathcal{M}_\odot$, which explodes as a SN, becomes a neutron star or black hole, and receives a velocity kick, due to any asymmetry in the explosion. Evidence for such a kick for non-disrupted systems are large eccentricities of X-ray binary systems (see, e.g., Kaspi et al., 1996) or observed velocities of radio pulsars (Lyne & Lorimer, 1994). Clearly, the state of the binary after the SN depends on the orbital parameters at the moment of explosion and the kick velocity. For the case of 4U 2206+54 we estimated the required minimum kick velocity of a typical neutron star (Eq. A14 in Appendix, Hurley et al., 2002) $\sim$ 200–350 km/s for the simple case, i.e. imparted in the orbital plane and in the direction of motion of the pre-SN star, for parameters of the mass range of BD+53 2790, mass of the ejected material $\Delta\mathcal{M}$, orbital velocity (465-530 km/s) of the binary at the moment of explosion and post–SN runaway systemic velocity ($\mathrm{V_{relative}}$) of 4U 2206+54. Note that the above estimated kick velocity of a neutron star is compatible with kick velocities expected from a unimodal or bimodal Maxwellian distribution of pulsars (see, e.g., Hobbs et al., 2005, Igoshev, 2020).

On the other hand, the evolution of massive close binaries is driven by case B mass transfer (van den Heuvel et al., 2000). In this case, the mass transfer starts after the primary star has finished its core-hydrogen burning, and before the core-helium ignition. Resulting from the mass transfer, the remnant of the primary star is its helium core, while its entire hydrogen-rich envelope has been transferred to the secondary star, which became the more massive component of the system (conservative mass transfer as the dominant mode, see, e.g., van den Heuvel et al., 2000). Following Iben & Tutukov (1985) for the initial mass ($\geq$32 $\mathcal{M}_\odot$) of a star that will explode as a SN with helium core mass $\mathcal{M}_{He} \geq 13.4\ \mathcal{M}_\odot$ and $\mathcal{M}_{lost} \geq 6.4\ \mathcal{M}_\odot$ (the fraction of mass lost $\sim$ 0.2 van den Heuvel et al., 2000).

4. Summary

We presented the following study and results:

- We found that the member star of the Cep OB1 association BD+53 2820 (spectral type B0 and luminosity class IV) and runaway HMXB 4U 2206+54/BD+53 2790 pair satisfies all our criteria for a close meeting in the past, namely they were at the same time (2.8 ± 0.4 Myr ago) at the same place (distance of 3435 ± 67 pc). It is therefore most likely, that at this location and time, a SN in a close massive binary took place and can be considered as the place and time of the origin of the currently observed HMXB. For the HMXB 4U 2206+54/BD+53 2790, we obtained a runaway velocity of 75-100 km/s at the moment of SN explosion. Our conclusions hold for a wide range of radial velocity of BD+53 2820 of 23 ± 16 km/s.

- Given current orbital parameters of the HMXB 4U 2206+54/BD+53 2790 and using approaches described by Hurley et al. (2002), Nelemans et al. (1999), Postnov & Yungelson (2014), Tauris & Takens (1998), van den Heuvel et al. (2000) we estimated a number of parameters of the progenitor binary system, i.e. mass of the SN progenitor: $\gtrsim 32\ \mathcal{M}_\odot$ ($\mathcal{M}_{He} \geq 13.4\ \mathcal{M}_\odot$, $\mathcal{M}_{lost} \geq 6.4\ \mathcal{M}_\odot$), mass of the ejected SN shell $\Delta\mathcal{M} \gtrsim 5\ \mathcal{M}_\odot$, required minimum kick velocity of the produced neutron star $\mathrm{v}_{kick} \sim$200-350 km/s.

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