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The origin of the high-mass X-ray binary 4U 2206+54/BD+532790

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ABSTRACT

Based on the *Gaia EDR3* astrometric parameters and our new systemic radial velocity of the high-mass X-ray binary 4U 2206+54/BD+532790, 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+532820 (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^{-1} with respect to this member star (BD+532820) 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 M$_\odot$ during the supernova explosion and the latter one received a kick velocity of at least 200–350 km s^{-1} . Since the high-mass X-ray binary 4U 2206+54/BD+532790 was born as a member of a subgroup of Cep OB1, the initially most massive star in the system terminated its evolution within $\lesssim 7-9$ Myr, corresponding to an initial mass $\gtrsim$ 32 M$_\odot$.

Key words: stars: individual: HMXB 4U 2206+54/BD+53 2790 – X-ray: binaries – stars: formation – stars: evolution – stars: neutron – stars: supernovae.

1 INTRODUCTION

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

Star clusters form within giant molecular clouds and remain embedded in clouds for ∼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 (Goodwin & Bastian 2006; Baumgardt & Kroupa 2007).

Ward, Kruijssen, & Rix (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 a characteristic population of 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) and Ambartsumian (1955), which provided the first evidence that formation of single, double, and multiple stars is 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 per cent, see, e.g. Stone 1979; Renzo et al. 2019) of young massive stars that 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, Ruiz & Allen (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).

However, 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 the case of the latter, its centre 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 a 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).

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Also, note 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 (Pflamm-Altenburg & Kroupa 2010; Dorigo Jones et al. 2020).

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). Recently, the HMXB candidate 1H11255-567 (μ^1 and μ^2 Cru, spectral types B2+B5, together with a possible neutron star) was traced back to the Lower-Centaurus-Crux group, where it could have originated up to $\sim$1.8 Myr ago in a supernova at 89–112 pc (Neuhäuser, Gießler & Hambaryan 2020). However, in this system, the neutron star nature of the unseen companion is still uncertain – it could be instead a very low-mass M-type star or brown dwarf.

In this work, we concentrate on the kinematic study of the unique HMXB 4U 2206+54, which has been suspected to contain a neutron star accreting from the wind of its companion BD+532790. This optical counterpart was identified by Steiner et al. (1984), as an 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+532790 (see, e.g. Reig et al. 2009; Finger et al. 2010; Torrejón et al. 2018), which also exhibits a radial velocity modulation (for further details, see Stoyanov et al. 2014).

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 to be of the order of $B_S \sim 2 \times 10^{13} - 10^{14}$ G of this neutron star with the very slow spin period of $P_{\rm spin} \sim$ (5540–5570) s and the rapid spin-down rate of $\dot{P}_{\rm spin} = 5.6 \times 10^{-7}$ s s^{-1} (Reig et al. 2009; Finger et al. 2010; Torrejón et al. 2018). Currently, the 4U 2206+54 is the only known HMXB system hosting an accreting magnetar with or without a fallback disc (Alpar, Çalışkan & Ertan 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 a double-peaked Hα emission line, as typical for the decretion discs (Hainich et al. 2020). With an orbital period of 9.5 d, 4U 2206+54 exhibits one of the shortest orbital periods among known HMXBs.

2 THE BIRTHPLACE OF 4U 2206+54

In order to identify the possible birthplace of 4U 2206+54, one needs to determine its possible membership to a stellar group either currently or in the past. The latter is also required 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, de Bruijne & de Zeeuw 2000, 2001; Tetzlaff et al. 2010; Neuhäuser et al. 2020). 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 (see, Fig. 1, further Section 2.2). 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) stars in the host group left that are not yet exploded, or that the flight time should not be larger than the age of a hosting group or neutron star (if known).

First, we have cross-matched the optical companion BD+532790 of the HMXB with possible candidate counterparts in *Gaia DR2 and EDR3* and identified it with the source 2005653524280214400 (see, Table 1 and also Arnason et al. 2021).

Next, we performed a preliminary selection of the possible birthplace (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. $\sim$10–20 Myr and $\sim$100–150 km s^{-1} corresponding to the distance of $\sim$1–2 kpc), from the recent catalogues of members of stellar associations (Mel'nik & Dambis 2017; 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 a distance between 1500 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+532790 to these stellar groups (three-dimensional (3D) or proper motion) and the most probable upper limit of its age (see, e.g. Meynet & Maeder 2003; Ekström et al. 2012, 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. 2), which can be considered as the probable place of the origin of the HMXB 4U 2206+54.

For these birthplace counterparts, we estimated the membership probability/likelihood of 4U 2206+54/BD+532790 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 a multivariate Gaussian distribution $\mathcal{N}_n(\mu,\ \Sigma)$ with a probability density function of equation (1) in the 5D space (position, parallax, and proper motions)[1]:

$$p(z|\mu,\Sigma) = (2\pi)^{-\frac{1}{2}np}|\Sigma|^{-\frac{1}{2}} e^{(z-\mu)\Sigma^{-1}(z-\mu)^T}, \tag{1}$$

where $z = [\alpha,\ \delta,\ \varpi,\ \mu_\alpha\cos\delta,\ \mu_\delta]$ is a vector of $np = 5$ parameters either of BD+532790 or bona-fide members of any stellar group with parameters μ,Σ. The corresponding likelihoods $L(Z|\mu,\Sigma) = \prod_{i=1}^{n} p_i$ of BD+532790 or member stars were computed for a large number of generated random vectors with the above-mentioned five parameters and their corresponding covariance matrices provided by *Gaia EDR3* (Gaia Collaboration 2020) and using mvtnorm: a Multivariate Normal and *t* Distributions R package with the Cholesky method, developed by Genz et al. (2020).

It turned out that BD+532790 has a very low probability to be considered as a member. The logarithm of the ratio of the mean likelihoods of BD+532790 in comparison to the members of a stellar group is in the range from −11 to −183. Note that in the case of the Cep OB1 stellar association (the single one in the list), the logarithm of the likelihood ratio is equal to −61.2. We obtained similar results (i.e. low and negligible membership probability) also by using other methods (see, further Section 4) based on the astro-kinematic, as well as photometric parameters of the bona-fide member stars of stellar groups.

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+532790 and a stellar group or one of its members were in the same place at the same time in the past. In order

[1] Unfortunately, the overwhelming majority, on average $\gtrsim$ 98 per cent (Cantat-Gaudin et al. 2020), of bona-fide members of the stellar groups have no significant number of radial velocity measurements.

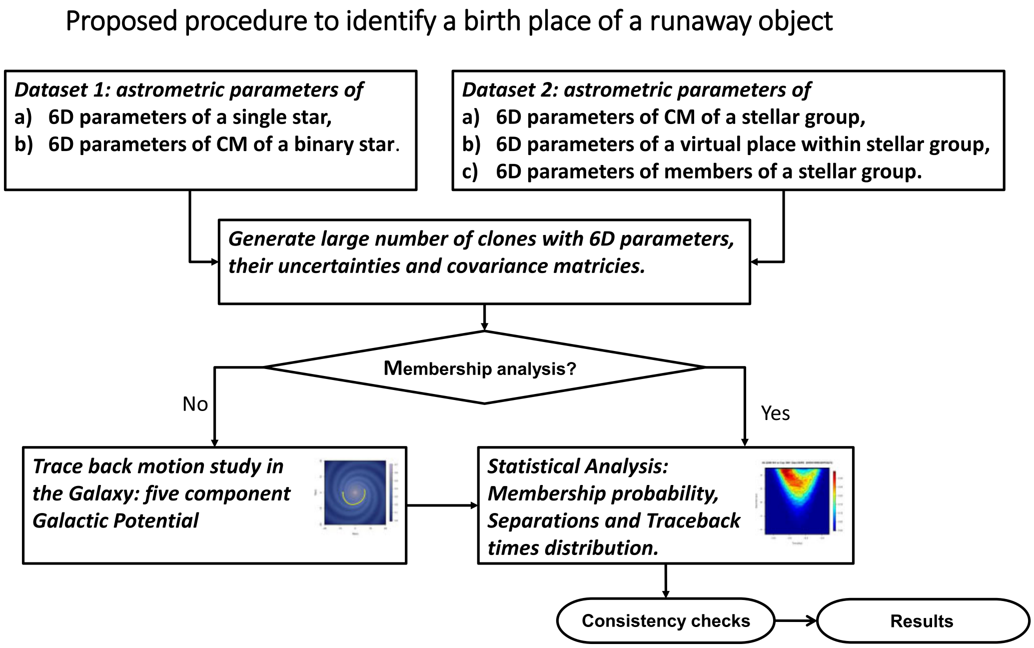

Figure 1. The flowchart of the proposed process for identification of the birthplace of runaway object (the concept 'in the same place at the same time').

Table 1. The parameters of the optical companion BD+532790 of 4U 2206+543 and its probable birth counterparts – the member stars of Cep OB1 association (BD+532820 or HD 235673).

Name	*Gaia EDR3* Source ID	Spectral Type	d^{b} (pc)	ϖ (mas)	$\mu_{\alpha} cos\delta$ (mas yr^{-1})	μ_{δ} (mas yr^{-1})	RV^{c} (km s^{-1})
BD+532790	2005653524280214400	O9.5Vep	$3167.4^{+165.3}_{-120.1}$	0.3051 ± 0.0136	-4.173 ± 0.015	-3.317 ± 0.014	-62.7 ± 8.8
BD+532820[a]	2005418950349782272	B0IVn	$3545.4^{+286.8}_{-225.5}$	0.2681 ± 0.0169	-2.973 ± 0.018	-3.350 ± 0.016	15.8 ± 32.3
HD 235673	1981443102866159232	O6.5V	$4201.6^{+827.1}_{-489.4}$	0.2240 ± 0.0292	-3.828 ± 0.030	-3.390 ± 0.026	-40.0 ± 10.0

[a]Radial velocity of BD+532820 is variable, may be double–lined spectroscopic binary (Abt & Bautz 1963).
[b]Distance estimates are provided by Bailer-Jones et al. (2021) using parallaxes and, additionally, the G magnitudes.
[c]Radial velocities and their standard deviations are given according to the SIMBAD astronomical data base (Wenger et al. 2000) and corresponding bibliographic entries (Wilson 1953; Abt & Bautz 1963)

to study the Galactocentric motion of the HMXB 4U 2206+54 for an input, we used the astrometric parameters of the optical counterpart BD+532790 of the system presented in *Gaia EDR3*, as well as its systemic radial velocity. For the latter one, we performed additional spectral observations and analysed the combined radial velocity data set (for further details, see Section 2.1 and Abt & Bautz 1963; Stoyanov et al. 2014).

2.1 Observational data and analysis (radial velocity)

We have carried out spectroscopic follow-up observations of the late O9.5Vep spectral type BD+532790, using the Échelle spectrograph FLECHAS at the 90 cm telescope of the University Observatory Jena (Mugrauer, Avila & Guirao 2014). The target was observed in 19 observing epochs between 2020 July 29 and 2020 September 22 in the 2x2 binning mode of the instrument ($<R> = 6900$), covering the spectral range between about 3900 and 8100 Å. In each observing epoch three spectra of the star, each with an exposure time of 1800 s, were taken always preceded by three spectra of a ThAr-lamp and of a tungsten-lamp for wavelength- and flatfield-calibration, respectively. As expected from its spectral type the spectrum of BD+532790 shows absorption lines of helium and hydrogen. These spectral lines are broadened and show variations of their profiles between the individual observing epochs. The Hα-line appears in emission and exhibits a prominent central absorption feature. In addition, several diffuse interstellar bands (DIBs), as well as the absorption lines of interstellar sodium (Na Iλ 5890 & 5896, alias D_2 & D_1) are detected in the spectrum of BD+532790. The radial velocity (RV) of the target was determined by measuring the central wavelength of the He I λ 5876 (D_3)-line, which is the most prominent He-line, present in the spectrum of BD+532790, which is detected with a sufficiently high signal-to-noise-ratio (SNR), required for accurate RV measurements. In order to monitor the RV stability of the instrument throughout our monitoring project, the central wavelengths of the lines of the interstellar sodium doublet were measured in all spectra, which are detected in the same spectral order as the D_3-line. The RV of the interstellar sodium lines exhibits a standard deviation of 0.5 km s^{-1}, consistent with the RV stability of the instrument, as reported in other studies (see, e.g. Bischoff et al. 2020) before. For the RV of BD+532790, we obtain -73.6 km s^{-1} on average with a standard deviation of 9.4 km s^{-1} (cf. Fig. 3). The individual RV measurements are summarized in Table 2 and are illustrated in Fig. 3.

To derive the systemic velocity of the binary system, we make use of the MCMC Bayesian approach and a code developed and provided by Gregory (2005), which compares the probabilities of

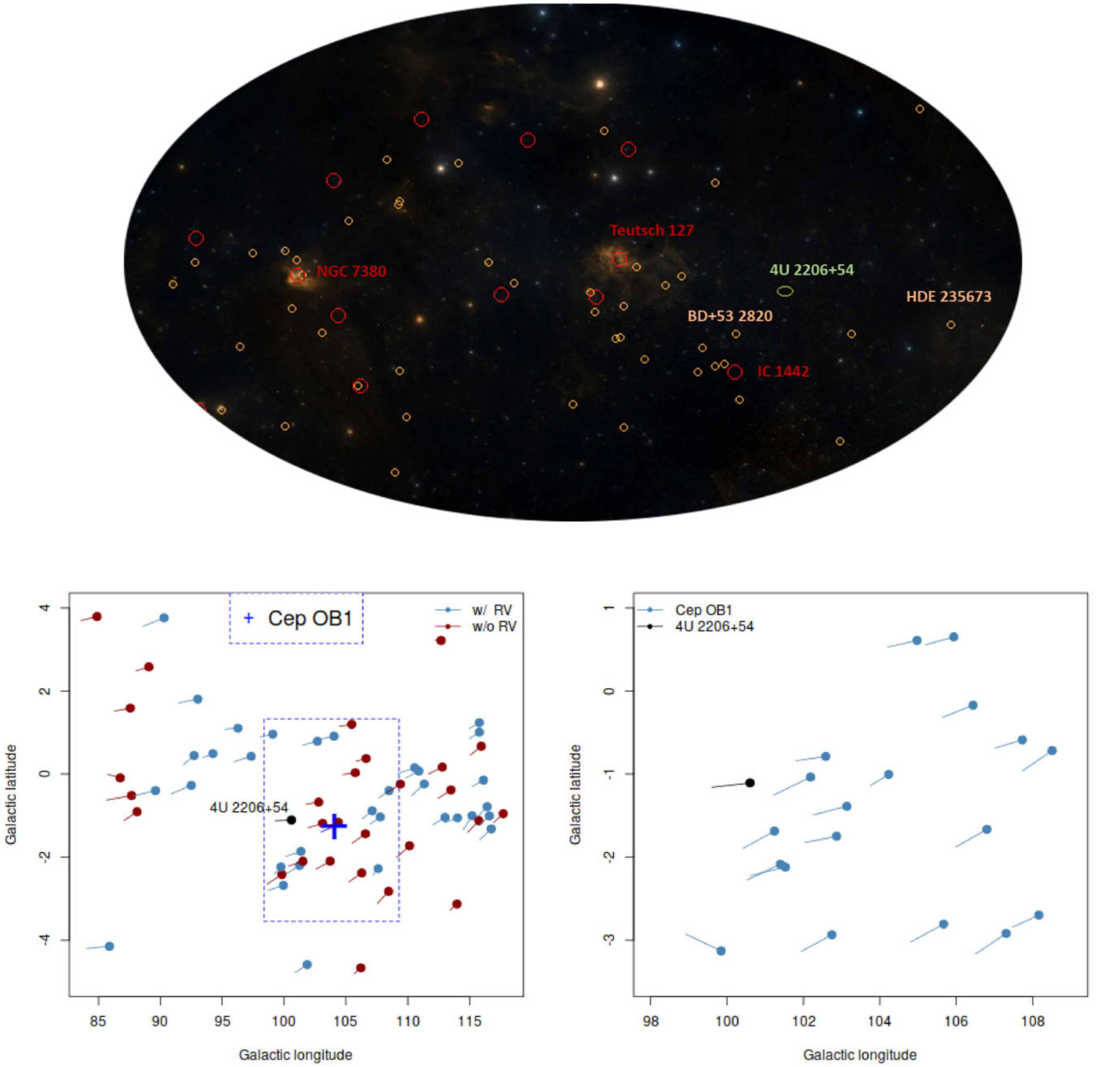

Figure 2. Top panel: digitized (DSS2) colour image of the region of the HMXB 4U 2206+54 (green oval) in the galactic coordinates, prepared with Aladin Desktop (Bonnarel et al. 2000). The positions of stellar clusters (large red circles, Cantat-Gaudin et al. 2020) and Cep OB1 association member stars (brown circles, Mel'nik & Dambis 2017; Melnik & Dambis 2020) are also indicated. Most relevant objects for this study have been annotated (for details, see the text). Bottom panel: Galactic positions and proper motions of stellar clusters with Cep OB1 in the centre (left-hand panel); Cep OB1 association members are shown in the right-hand panel, they can be considered as the most probable birth counterparts of 4U 2206+54/BD+532790.

different models and estimates the parameters of the most probable model. In the simple model, the difference between the measured radial velocities – $RV_{\rm obs}(t_i)$ and the model predicted ones – $RV_{\rm model}(t_i)$ at the epoch of t_i (for details, see Gregory 2007) can be represented as a Gaussian distribution with standard deviation of $\epsilon(t_i)$:

$$RV_{\rm obs} - RV_{\rm model} = \epsilon, \qquad (2)$$

where ϵ ($\epsilon^2 = \sigma^2 + s^2$) includes reported measurement errors – $\sigma(t_i)$ and unknown uncertainties – s (e.g. any real signal in the data) that cannot be explained by the model prediction.

The best-fitting orbital parameters are listed in Table 3. Note that the values of the fitted parameters and their uncertainties correspond to the mean values and standard deviations of the peak, mean, mode, and median of the reported posterior probability densities (for details, see Gregory 2005, 2007). In Fig. 4 are plotted the orbital phase folded radial velocity curve, the best-fitting solution with model uncertainties, and the residuals of the fit.[2] The systemic

[2]The RV plot, presented in Stoyanov et al. (2014), is inconsistent with the orbital elements (e.g. ω), derived by the authors.

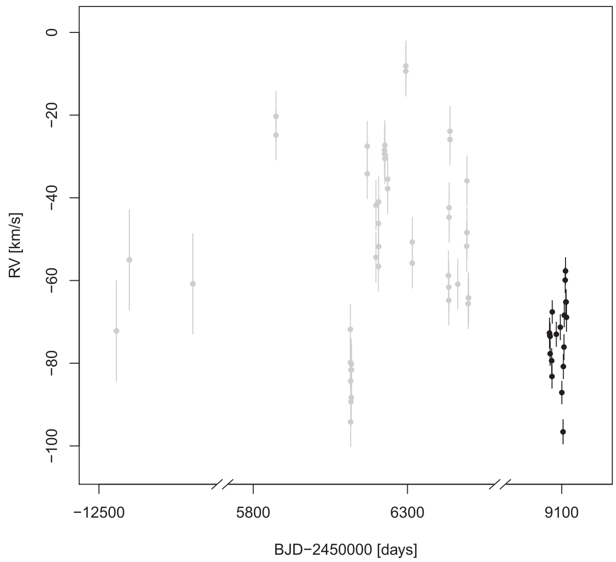

Figure 3. The RV measurements of BD+532790 from the literature (Abt & Bautz 1963; Stoyanov et al. 2014) are shown as grey filled circles and those derived from our FLECHAS observations with black filled circles, respectively. The standard deviations are illustrated as error bars.

Table 2. The RVs of BD+532790 for all observing epochs, as determined in our spectroscopic monitoring project together with the reached *SNR*, measured in the wavelength range between 5820 and 5850 Å.

BJD-2450000	RV (km s^{-1})	SNR
9060.44067	− 72.7 ± 3.6	53
9061.45550	− 73.3 ± 3.1	60
9062.43062	− 73.5 ± 2.9	71
9062.51123	− 77.7 ± 2.8	75
9067.48182	− 79.4 ± 2.9	73
9068.42210	− 83.2 ± 2.8	62
9069.38899	− 67.6 ± 2.7	69
9082.47820	− 73.0 ± 2.9	61
9095.48532	− 71.3 ± 3.0	67
9100.38390	− 87.1 ± 2.7	65
9104.34670	− 96.6 ± 2.9	63
9105.34096	− 80.8 ± 2.9	87
9107.35124	− 76.1 ± 3.0	62
9108.34312	− 68.4 ± 2.8	71
9111.33612	− 59.9 ± 3.0	65
9112.33579	− 57.7 ± 3.2	61
9113.32245	− 65.2 ± 3.0	60
9114.32943	− 65.2 ± 2.9	64
9115.47070	− 68.9 ± 3.4	70
	<RV> ± SD	<SNR>
	− 73.6 ± 9.4	66

Table 3. Orbital parameters of 4U 2206+54.

Parameter	Value
Fitted parameters	
P (d)	9.55346 ± 0.001
T_p (d)	2456 227.873 ± 0.004
e	0.74 ± 0.13
ω (deg)	48.3 ± 4.5
γ (km s^{-1})	− 61.50 ± 1.55
K_1 (km s^{-1})	32.88 ± 6.29
s (km s^{-1})	11.83 ± 2.92
Derived parameters	
$a_1 \sin i$ (10^6 km)	3.00 ± 0.36
$f(m_1, m_2)$ (M$_\odot$)	0.0115 ± 0.004
Other quantities	
χ^2	315.8
N_obs (primary)	65
Time span (d)	21 558.971
rms (km s^{-1})	13.60

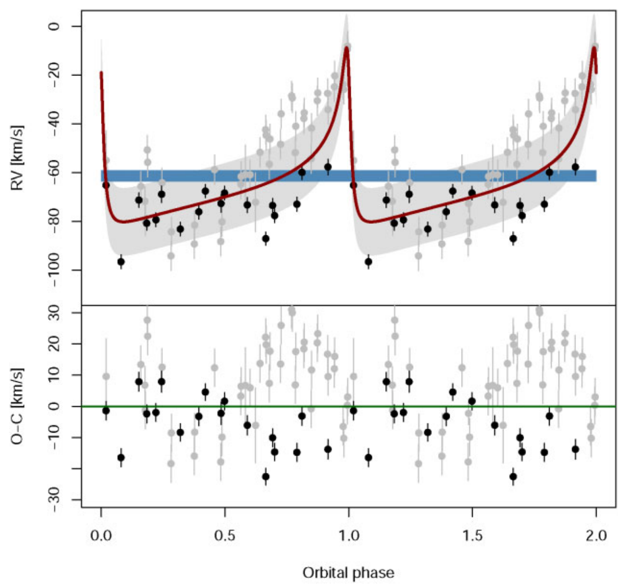

Figure 4. The fitted binary star model (Gregory 2005, 2013; Dumusque et al. 2017) and residuals of radial velocities of BD+532790 were taken from the literature (Abt & Bautz 1963; Stoyanov et al. 2014) and derived from our observations. The red line depicts the most probable radial velocity at orbital phase predicted by the fitted binary model. The grey area corresponds to the predicted uncertainties. The blue band shows the systemic velocity and its uncertainty. Lower panel: Residuals of the observed and model-predicted radial velocities (for details, see text). The RV measurements are shown with filled circles as in Fig. 3.

velocity $\gamma = -61.5 \pm 1.55\,\mathrm{km\,s^{-1}}$ together with other astrometric parameters presented in *Gaia EDR3* is intended to serve as an input to retrace its orbits back in time to investigate the probable birthplace and kinematic age of HMXB 4U 2206+54. However, statistically significant lack of the good fit (the reduced chi-square $\gtrsim 5$, see, Table 3) with a simple Keplerian orbit and relatively larger value of the parameter s indicates the presence of either an unknown signal (e.g. irregular/unstable variation of the atmospheric layers, mass transfer or rotation, presence of an accretion/decretion disc, etc.) in the data or small sample size with larger errors or applied model simplicity. Therefore, 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 $V_{sys} \equiv \gamma = -61.5\,\mathrm{km\,s^{-1}}$ with standard deviation of $SD_{\mathrm{V_{sys}}} = 15.0\,\mathrm{km\,s^{-1}}$.

2.2 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+532790, 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, disc, 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 (Palous, Jungwiert & Kopecky 1993; Fernández, Figueras & Torra 2008; Bajkova & Bobylev 2019).

In order to take account of the uncertainties in the astrometric parameters of the star and associations, 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 (Mel'nik & Dambis 2017; Soubiran et al. 2018; Cantat-Gaudin et al. 2020; Melnik & Dambis 2020) or the astrometric parameters of the individual member star (Gaia Collaboration et al. 2018; Gaia Collaboration 2020). Such a procedure is superior to the individual, independent random drawing of each parameter that ignores their mutual dependence and results in 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., Section 3).

For numerical integration, we utilize 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 $\tau = 2.0 \pm 0.5$ Myr). Most recently, van der Meij et al. (2021) confirmed that the high-mass X-ray binary HD153919/4U 1700-37 originates from NGC 6231, the nucleus of the OB association Sco OB1, with its kinematic age of 2.2 Myr, based on the *Gaia DR2* proper motions and parallaxes. 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 ($\tau = 2.33 \pm 0.05$ Myr).

3 RESULTS

Our trace back motion study of 4U 2206+54 and its possible parental stellar groups (see, Section 2) revealed that only the association Cep OB1 can be considered as a candidate. The astrometric and kinematic parameters of its centroid were determined by member stars (Mel'nik & Dambis 2017; 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 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. 2), suggesting that it may include a chain of OB associations (Mel'nik & Dambis 2017; Melnik & Dambis 2020) or cores of different ages (see, Section 4), we performed also a trace back motion study of 4U 2206+54 and each member star to identify the most probable common birthplace inside of the Cep OB1 association. Note that from 58 member stars (Mel'nik & Dambis 2017) of Cep OB1, 46 have an entry in *Gaia EDR3* and only 23 have radial velocity measurements. It turned out that only two member stars, HD 235673 and BD+532820, with spectral types of O6.5V and B0V, respectively, show a significant number of close passages with BD+532790. Namely, from 1 million Monte Carlo simulations 1234 (0.12 per cent) and 52936 (5.3 per cent) 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. 6) and a significant number of them, namely 692 (∼56 per cent) and 36 929 (∼70 per cent), are concentrated within relatively narrow time intervals $\delta t = 2.8$ (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+532820 or 4U 2206+54–HD 235673) in reality were at the same place at the same time, we created virtual pairs inside Cep OB1 association at the positions corresponding to BD+532820 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 per cent 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) per cent and 0.29 (0.21–0.33) per cent of cases from of 1 million runs corresponding to the pairs 4U 2206+54–BD+532820 and 4U 2206+54–HD 235673, respectively. Shortly, these fractions can be considered as lower thresholds in favour of the hypothesis that a pair of HMXB and member star of 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 neighbouring stars of 4U 2206+54/BD+532790 within 10 arcmin extracted from *Gaia EDR3* and calculated traced back orbits and compared them with the real trajectories of BD+532820 and HD 235673. It turned out that for such a 'random' 4U 2206+54 in one million trials only eight and two cases are successful (i.e. separation not exceeding 15 pc) with BD+532820 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 per cent confidence interval under the assumption of binomial distribution, we expect close meetings within 15 pc in 0.0008 (0.0003–0.001) per cent and 0.0002 (0.00 002–0.0007) per cent of successful cases even with this conservative randomization.

Thus, statistically, the vicinity of both member stars (BD+532820 and HD 235673) of 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+532820 can be considered as more probable one than the one of HD 235673 (see, further Section 4).

In Fig. 5, the past 3D trajectories are displayed for the member star BD+532820 of Cep OB1 and for BD+532790 itself. The analysis of separations and corresponding times (see Fig. 6) shows that BD+532790 and BD+532820, in reality, were both inside of the same volume (sphere with a radius of ∼15 pc) $\tau = 2.8 \pm 0.4$ Myr ago. We observe a similar picture for the neighbouring stars of BD+532820 in the projection on the sky, i.e. purely using their position, distance, and proper motions (see Fig. 5, right-hand panel).

Fig. 6 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 also studied the trace back motion of the pair (4U 2206+54–BD+532820) with a number of input systemic radial velocities corresponding to the observed mean radial velocity values and standard deviations with different instruments (see, Table 4). 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.

It turned out that all of these cases confirmed our previous result, i.e. very similar kinematic age of the 4U 2206 and a statistically significant success rate.

4 DISCUSSION

Based on the parameters of BD+532790 provided by *Gaia EDR3*, we calculated its absolute magnitude $M_V = -4.44 \pm 0.70$ mag ($V = 9.84 \pm 0.2$ mag, $B = 10.11 \pm 0.1 9$ mag, $d = 3135.8 \pm 91.7$ pc, $A_v = 1.8 \pm 0.70$ 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 $\mathcal{M}= 23.5^{+14.5}_{-8.0}$ $M_\odot$ using the luminosity-mass relation for main-sequence stars selected from the components of detached eclipsing spectroscopic binaries in the solar neighbourhood [Eker et al. 2018, $\log \mathcal{L} = (2.726 \pm 0.203) \times \log \mathcal{M} + (1.237 \pm 0.228)$]. Note, the estimate of spectroscopic mass $\mathcal{M}=27^{+67}_{-23}$ $M_\odot$(Hainich et al. 2020) of BD+532790 exhibits 35 per cent larger than its evolution mass, i.e. the mass of an object that has evolved like a single star and exhibits the current stellar and wind parameters. However, in general, there is good agreement between spectroscopic and evolutionary masses of single stars within the one sigma error bars (see, e.g. Nieva & Przybilla 2014).

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 (Meynet & Maeder 2003; Weidner & Vink 2010; Ekström et al. 2012). 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 at a distance of 3470 pc. According to Massey, Johnson & Degioia-Eastwood (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 $M_\odot$ stars (Massey et al. 1995).

Based on the *Gaia* data, Mel'nik & Dambis (2017) and Melnik & Dambis (2020) studied the kinematics of OB-associations with the use of the Tycho-Gaia Astrometric Solution (TGAS) and *Gaia DR2* and listed 58 member stars of the Cep OB1 association, having luminosity classes in the range of I to V, with spectral types of O5-M4, out of which 37 have O-B2 classes, three red and two evolved A class supergiant stars. On the other hand, Kharchenko et al. (2005a) and Kharchenko et al. (2005b) identified three ionising star clusters related to the Cep OB1 association: NGC 7380, IC 1442, and MWSC 3632. In addition Mel'nik & Dambis (2017) and Melnik & Dambis (2020) included six stars of NGC 7235 (9.3 Myr old, Cantat-Gaudin et al. 2020) with spectral types of B0-B2 in the list of bona-fide member stars of the Cep OB1 association. Moreover, according to the most recent catalogues of stellar groups (Soubiran et al. 2018; Cantat-Gaudin et al. 2020) in the region of Cep OB1 there are more groups in the age range of 4–10 Myr (see, Fig. 2).

In order to obtain more constraints on the age of the Cep OB1 association or its subgroups, we performed a membership analysis of the above-mentioned bona-fide member stars. First of all, we used *Gaia* EDR3 astrometric data and utilized the UPMASK (Unsupervised Photometric Membership Assignment in Stellar Clusters; Krone-Martins & Moitinho 2014) method to calculate membership probabilities of the observed stars. The application of this method to 46 *Gaia* EDR3 stars showed that a overwhelming majority (∼ 85 per cent) of them a have membership probability ≥0.5, i.e. they have a common origin in a 5D astrometric space (α, δ, ϖ/distance, $\mu_\alpha \cos\delta$, μ_δ) in comparison to the field stars which are spatially randomly distributed objects of different origins.

We obtained similar results by making use of non-parametric (e.g. Clusterix 2.0; Balaguer-Núñez et al. 2020) and parametric (e.g. BANYAN-Sigma Gagné et al. 2018) methods, where Cartesian 3D (XYZ) positions, kinematic and photometric parameters of these *Gaia EDR3* stars were also used as input parameters.

We estimated the lower limit of the age of the Cep OB1 association to be ∼4 Myr from its turn-off point (HD 235673 $M_V \approx -5.5$, HD 215835 $M_V \approx -6.5$) in the unreddened absolute visual magnitude–colour diagram as a coeval star-forming region.

In addition, to update this age inferred from the above-mentioned approach (i.e. stellar evolution models), we also tried to assess the kinematic age of the Cep OB1 association as a whole expanding stellar system. We analysed how the mean, median, or mode of the distribution of mutual distances of the member stars changes with time. We performed this by tracing back the orbits of the individual member stars of the Cep OB1 to determine when they were closest together. We find that the average distance between the members remains roughly constant for ∼10–15 Myr. Thus, our empirical approach to estimate the kinematic age of an expanding (as a whole) stellar system by the analysis of the distribution of mutual distances of bona-fide member stars in the past (see, e.g. Booth, del Burgo & Hambaryan 2021), does not show a global minimum, suggesting also on a possible non-coeval star formation in this extended Cep OB1 association as a complex star-forming region unlike to a compact ones (see, e.g. Shevchenko et al. 1991).

Thus, the estimated ages of 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, Section 3). 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 $M_\odot$ and a 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 Cep OB1 association with its brightest member BD+532820.

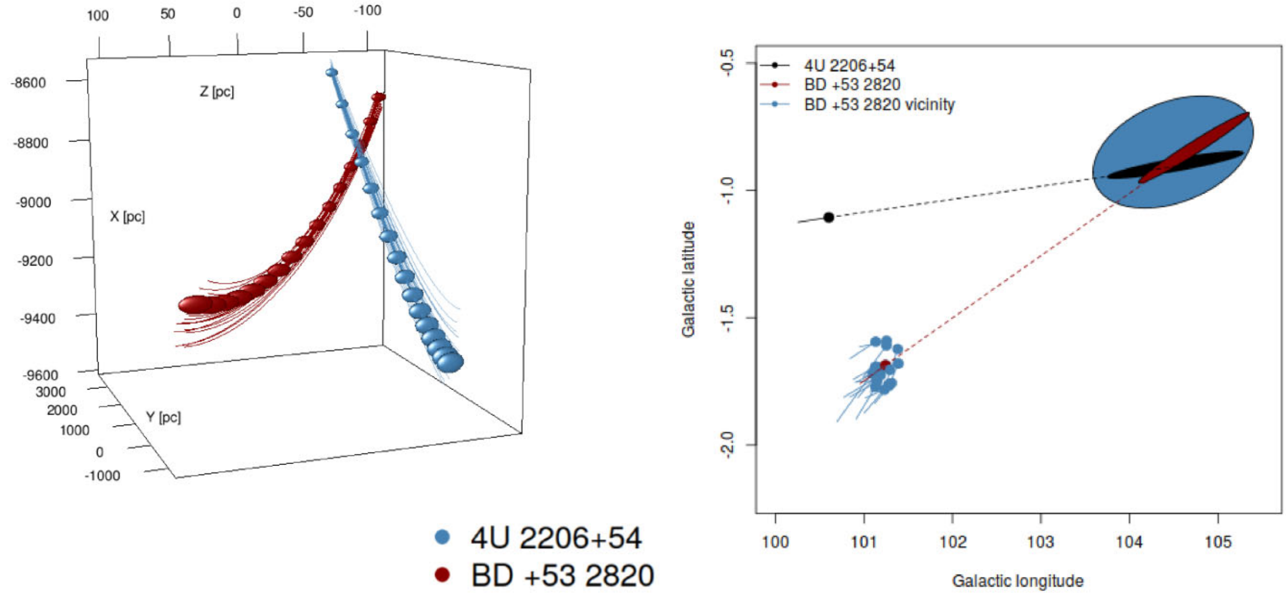

Figure 5. Left-hand panel: The 3D trajectories of 4U 2206+54/BD+532790 and BD+532820 ≡ Gaia EDR3 2005418950349782272, a member of Cep OB1 association, in Galactocentric Cartesian coordinates in the past. Right-hand panel: The positions and proper motions of 4U 2206+54/BD+532790 and subgroup of stars in Cep OB1 association with its brightest star, BD+532820, in Galactic coordinates. With filled colours of ellipses, the most probable positions of corresponding stars at 2.4–3.2 Myr ago are indicated.

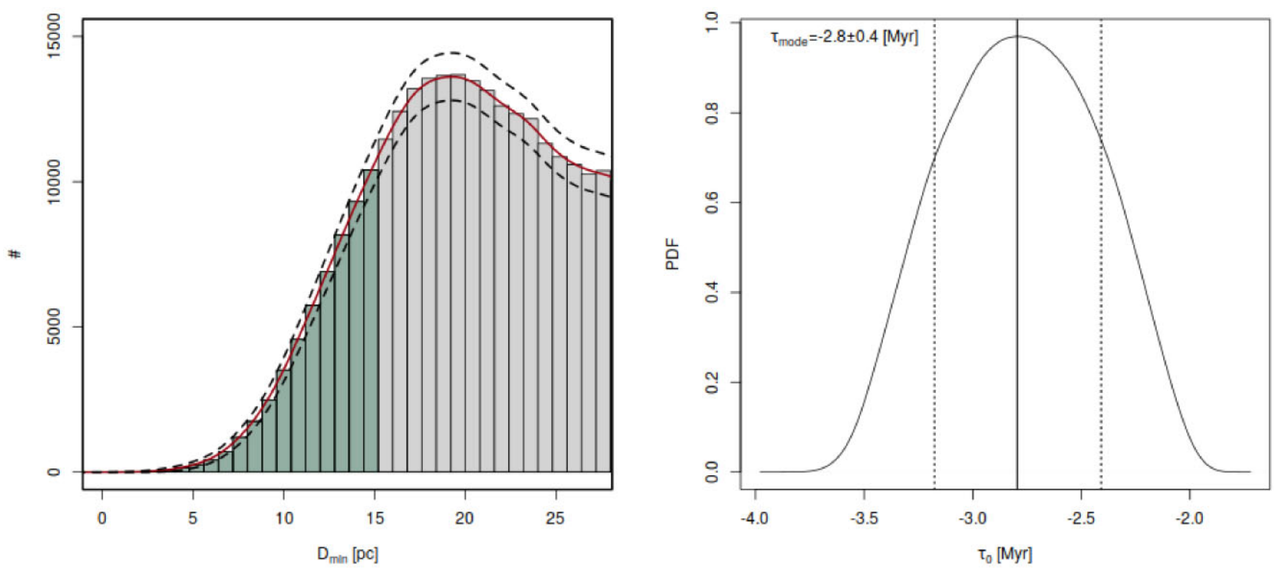

Figure 6. Distributions of minimum separations (D_{min}) and corresponding flight times (τ_0) of the closest stellar passage of 4U 2206+53 and BD+532820 ($\leq$15 pc separation, rated as success, marked as filled green area) according to the trace back motion study of them in the Galaxy. The red curve with enveloping dashed curves shows the fit of expected distribution of minimum separations for the 3D case [equation (A3) in Appendix, Hoogerwerf et al. 2001]. The highest posterior density (HPD) interval, 68 per cent 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).

An application of the UPMASK method to the stars extracted from *G*aia EDR3 around the brightest member star BD+532820 in the circle within a radius of 10 arcmin revealed 22 other stars which can be considered as members of this subgroup. Unfortunately, all of them are too faint and there is no information about their pre-main-sequence nature (e.g. detailed spectral analysis, X-ray observations) in the astronomical literature. Only two young stellar candidate objects have distances not exceeding 500 pc from the Sun. Nevertheless, based on their location the CMD diagram (assuming similar interstellar absorption $A_V \sim 1.2$ as the brightest member BD+532820, $M_V = -3.5 \pm 0.5$, $\mathcal{M}= 17.5^{+10.5}_{-5.0}\,\mathrm{M}_{\odot}$) showed that the age of the subgroup can be estimated to be $\sim$ 7–10 Myr. We obtained similar constraints by using isochrones from the Geneva stellar models (Ekström et al. 2012).

Table 4. The input systemic radial velocity parameters (weighted mean and standard deviation) for the trace back motion study of 4U 2206+54 and its success rate, hence the most probable flight time to the subgroup of stars (i.e. birth counterpart) of the Cep OB1 association with its brightest member star BD+532820.

Number of RVs	RV_{mean} ($km\,s^{-1}$)	RV_{SD} ($km\,s^{-1}$)	Success rate(%)	τ_0 (Myr)	Rem
3	−62.7	8.8	4.4	$-2.7^{+0.3}_{-0.5}$	1
43	−50.6	22.5	3.8	$-2.8^{+0.4}_{-0.1}$	2
19	−73.6	9.4	4.2	$-2.8^{+0.4}_{-0.4}$	3
65	−65.7	18.9	3.9	$-2.7^{+0.2}_{-0.5}$	4
65	−66.6	8.7	4.3	$-2.7^{+0.3}_{-0.4}$	5

Notes. [1]Abt & Bautz (1963)
[2]Stoyanov et al. (2014)
[3]This work
[4]Abt & Bautz (1963), Stoyanov et al. (2014,) and this work
[5]Weighted average of the mean values of the radial velocities measured by the different RV montoring surveys (instruments).

Having estimates of the age range of Cep OB1, the conservative lifetime of the donor star of the HMXB BD+532790 and the flight time to the probable birthplace, 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) and Meynet & Maeder (2003) to be $\mathcal{M}_{\rm initial} \sim 32$–$60\,{\rm M}_\odot$.

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.

If we consider a circular pre-SN orbit, when the progenitor explodes in a symmetric SN, an amount of mass is ejected instantaneously. Ignoring the effects of the impact of the ejected shell on the companion star and assuming that there is no mass loss or mass transfer during the circularization of the orbit by the tidal force, the orbital period of the re-circularized orbit is (Nelemans, Tauris & van den Heuvel 1999):

$$P_{\rm re-circ} = P_{\rm postSN}\left(1 - e^2_{\rm postSN}\right)^{3/2}, \quad (3)$$

where $P_{\rm postSN}$ and $e_{\rm postSN}$ are the post-SN orbital period and eccentricity, respectively. Using $P_{\rm postSN} = 9.56 \pm 0.001$ d and $e_{\rm postSN} = 0.74 \pm 0.13$, we estimated $P_{\rm re-circ} = 2.9 \pm 1.8$ d.

From the conservation of momentum and Kepler's third law, the runaway velocity ϑ can be estimated as:

$$\vartheta = (2\pi G)^{1/3}\,\Delta\mathcal{M}\,\mathcal{M}_1\,P^{-1/3}_{\rm re-circ}\,(\mathcal{M}_1 + \mathcal{M}_2)^{-5/3}, \quad (4)$$

where $\mathcal{M}_1$ and $\mathcal{M}_2$ are the masses of the present-day donor star (primary) and compact object (secondary), respectively. $\Delta\mathcal{M}$ denotes the mass of the ejected material during the SN event, which can be estimated using the relative velocity of 4U 2206+54/BD+532790 with respect to BD+532820.

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 $\vartheta \equiv V_{\rm relative} = 92.6^{+14.6}_{-16.2}\,{\rm km\,s^{-1}}$ with respect to BD+532790 or its vicinity stars and hence, $\Delta\mathcal{M} = 5.6^{+3.6}_{-2.2}\,{\rm M}_\odot$ for the neutron star of mass $\mathcal{M}_2 = 1.4\,{\rm M}_\odot$. Note that the estimate of $\Delta\mathcal{M}$ is not changing significantly depending on the mass of a neutron star (1.2–2.2 $\rm M_\odot$) and/or period of the re-circularized orbit [i.e. the post-SN eccentricity ≈ 0, at most by a factor of 1.5, cf., equation (4)]. Thus, at the moment of the SN instantaneous explosion, the collapsing core would have a mass of $7.0^{+4.2}_{-2.6}\,{\rm M}_\odot$, which explodes as an 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 (equation A14 in Appendix, Hurley, Tout & Pols 2002) ∼ 200–350 $\rm km\,s^{-1}$ 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+532790, mass of the ejected material $\Delta\mathcal{M}$, orbital velocity (465–530 $\rm km\,s^{-1}$) of the binary at the moment of explosion, and post–SN runaway systemic velocity ($\rm V_{relative}$) 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 ($\gtrsim 32\,{\rm M}_\odot$) of a star that will explode as an SN with helium core mass $\mathcal{M}_{\rm He} \geq 13.4\,{\rm M}_\odot$ and $\mathcal{M}_{\rm lost} \geq 6.4\,{\rm M}_\odot$ (the fraction of mass lost ∼0.2 van den Heuvel et al. 2000).

5 CONCLUSIONS

We presented the following study and results:

(i) We found that the member star of Cep OB1 association BD+532820 (spectral type B0 and luminosity class IV) and runaway HMXB 4U 2206+54/BD+532790 pair satisfy 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, an 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+532790, we obtained a runaway velocity of 75–100 $\rm km\,s^{-1}$ at the moment of SN explosion. Our conclusions hold for a wide range of radial velocity of BD+532820 of 23 ± 16 $\rm km\,s^{-1}$.

(ii) Given current orbital parameters of the HMXB 4U 2206+54/BD+532790 and using approaches described by van den Heuvel et al. (2000), Nelemans et al. (1999), Tauris & Takens (1998), Hurley et al. (2002) and Postnov & Yungelson (2014), we estimated a number of parameters of the progenitor binary system, i.e. mass of the SN progenitor: $\gtrsim 32\,{\rm M}_\odot$ ($\mathcal{M}_{\rm He} \geq 13.4\,{\rm M}_\odot$, $\mathcal{M}_{\rm lost} \geq 6.4\,{\rm M}_\odot$), mass of the ejected SN shell $\Delta\mathcal{M} \gtrsim 5\,{\rm M}_\odot$, required minimum kick velocity of the produced neutron star $\rm v_{kick}$ ∼200–350 $\rm km\,s^{-1}$.

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DATA AVAILABILITY

The data underlying this article are available either in the article or from the Gaia Archive at https://gea.esac.esa.int/archive/. Data resulting from this work will be made available upon reasonable request.

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