

A binary supernova OB-runaway candidate inside Berkeley 97

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ABSTRACT

Aims. OB-runaway stars ejected by the binary supernova mechanism can be found near young open star clusters. In this paper, we present an OB-runaway candidate as a pre-SN binary companion to the progenitor of the pulsar PSR J2238+5903 inside the young open star cluster Berkeley 97.

Methods. We tried to find a kinematic outlier based on *Gaia* DR3 proper motions and parallaxes to be the pre-supernova binary companion to the progenitor of the pulsar. We took the spectra of two bright early B-type stars of the cluster, determined their effective temperature and surface gravity, and updated the parameters of the cluster. Through isochrone fitting of the color-magnitude diagram of the star cluster, we identified the members and determined the stellar parameters of the runaway star.

Results. Two bright members of the cluster, HD 240015 and HD 240016, are massive stars with spectral types of B0.5II and B1.5II and effective temperatures of $T_{\text{eff}} = 21\,000 \pm 1000$ K and $T_{\text{eff}} = 24\,000 \pm 2000$ K, respectively, as well as surface gravities of $\log(g[\text{cm/s}^2]) = 3.0 \pm 0.2$. We find that Berkeley 97 is a star cluster with an age of $\log(\text{age}[\text{yr}]) = 7.1$, an uncertainty of <0.1 dex, and an interstellar extinction of $A_V = 3.1 \pm 0.1$ mag. The runaway star has an effective temperature of $T_{\text{eff}} = 12\,250 \pm 1750$ K with a surface gravity of $\log(g[\text{cm/s}^2]) = 4.38 \pm 0.2$ (B8V type star). By tracing back the proper motion of the runaway star, the explosion center was found for different possible pulsar ages of 10, 20, and 26.6 kyr. The pulsar moving out from the 20 kyr position must have a space velocity of ~ 340 km s⁻¹, which is consistent with the general pulsar velocity distribution. This supports the idea that the pulsar originated from the cluster as a result of a binary supernova. Despite its young age, $\tau < 26.6$ kyr, the supernova remnant is not visible.

Key words. stars: early-type – stars: massive – stars: individual: Gaia DR3 2008384504995669248 – ISM: supernova remnants – pulsars: individual: PSR J2238+5903 – open clusters and associations: individual: Berkeley 97

1. Introduction

Around 30% of O-type stars and 5–10% of B-type stars are classified as runaways (Gies & Bolton 1986; Carretero-Castrillo et al. 2023). They show high space velocities greater than a specified velocity threshold of 25 km s⁻¹ relative to the local average. The threshold value is the intersection point of the distribution curves of low-velocity and high-velocity stars (Tetzlaff et al. 2011; Tetzlaff 2013). The formation of runaway stars is explained by two independent mechanisms: the binary supernova (SN) scenario (BSS) and the dynamical ejection scenario (DES). The BSS describes how a stellar companion of an evolved star can obtain high space velocities due to the SN of the primary that disrupts the binary system. Here, sudden mass loss of the primary star during its SN results in an unbound orbit of the secondary star, usually catapulting the star outward with its orbital velocity during the SN if the mass loss is more than half of the total system's mass before the SN (Blaauw 1961). Also, an asymmetry in the SN explosion gives a substantial kick to the neutron star (NS) (Wongwathanarat et al. 2013), which has been confirmed by the observed space velocity of the pulsars: 300–500 km s⁻¹ (Lyne & Lorimer 1994; Allakhverdiev et al. 1997; Hobbs et al. 2005; Hansen & Phinney 1997). The high average kinetic energies of NSs imply that the binary systems are likely to be disrupted by the SN regardless of the amount of the ejected mass. The lack of pulsar companions to many of the OB-runaway stars (Sayer et al. 1996), the low rate of X-ray binaries, and the high rate of isolated NSs show that binary

disruption is likely to occur in most cases (Guseinov et al. 2005).

In some cases, the compact object does not receive a significant kick and/or the majority of the total mass is stored on the secondary through conservative mass transfer; hence, the compact object remains bound to the companion star (van den Heuvel 1993). Runaway high-mass X-ray binaries such as 4U 1700–37 (Ankay et al. 2001), Vela X-1 (Kaper et al. 1997), and 4U 2206+54 (Hambaryan et al. 2022) are examples of this phenomenon.

The DES describes another creation channel for runaways inside a cluster, where many stars are ejected from their formation cluster due to gravitational instabilities during the early stages of cluster formation (Poveda et al. 1967). The most common scenario is a close encounter of a massive star ($>8 M_{\odot}$) and a bound binary or a close encounter of two bound binaries. In these cases, the close encounter will perturb the systems in such a way that both can become unbound. These then unbound stars can reach velocities similar to those of the BSS runaways since both mechanisms use orbital motions on similar scales, thus keeping a similar energy scale.

Kinematics of binary disruption due to an asymmetric SN explosion is widely discussed in Tauris & Takens (1998) while the observational efforts are concentrated on runaway–NS coupling and abundance investigations of runaway stars. Some examples of runaway–NS pairs (components are separated) are PSR 1706–16 – ζ Oph (Neuhauser et al. 2020) and PSR J0826+2637 – HIP 13962 (Tetzlaff et al. 2014). Based on their motion in space, the pulsars and the corresponding runaway stars were traced back in time using 3D Monte Carlo

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simulations. They were found at the same position and at the same time inside a young open cluster ($\log[\text{age}(\text{yr})] \lesssim 7.7$) hosting massive stars. The main uncertainties here lie in the unknown radial velocities (RVs) and the distance uncertainties of the NSs, so Monte Carlo simulations were done accounting for typical NS velocities and all other measurement uncertainties. The trace-back through the Galactic potential is sufficiently reliable for some ten million years. In the case of ζ Oph and PSR 1706, the time of the close approach (the SN) could be constrained to 1.78 ± 0.21 Myr and its distance to 107 ± 4 pc, and this position is consistent with an interstellar medium (ISM) cavity (Neuhäuser et al. 2020).

OB-type stars evolve fast, so they are guaranteed to be young ($\lesssim 300$ Myr) and fewer in number. This reduces the uncertainties when associating them with a cluster. Additionally, they are luminous ($> 40 L_{\odot}$), making them a good target for astrometry and follow-up spectroscopy at larger distances. Also, massive progenitor stars tend to have massive or intermediate mass companions (Pinsonneault & Stanek 2006); hence, the runaway stars are expected to be mostly O- and B-type stars.

Through a systematic search for OB-runaway stars inside the SN remnants (SNRs), the OB-runaway star HD 37424 inside SNR S 147 was proven to have been ejected by the binary disruption due to the SN of the progenitor of S 147 and the pulsar PSR J0538+2817. A kinematic study has shown that the OB-runaway star and the pulsar were once at the same position in space, close to the geometric center of the SNR, at the same time, 30 ± 4 kyr (Dinçel et al. 2015). On the other hand, the OB-runaway search inside 12 other SNRs yielded an absence of strong OB-runaway candidates in these SNRs (Dinçel et al. 2024).

An alternative search area for BSS OB-runaways is open clusters. Independent of their flight trajectory coinciding with that of an NS, BSS runaways ejected from the cluster can be distinguished from DES runaways by their ejection time. The DES mechanism is mostly efficient at the early stages of an open cluster. Star clusters older than 3 Myr will have fully gone through their phase of frequent dynamical ejections (Oh & Kroupa 2016). Therefore, an ejection of an OB-type star at a point later than this age can be explained by BSS rather than DES. In Bhat et al. (2022), a BSS origin was suggested for several well-studied OB-runaways.

In this paper, we report the detection of an OB-runaway candidate ejected from the open star cluster Berkeley 97 within the last 26.6 kyr due to the SN of the progenitor star of PSR J0538+2817. The non-detection of an SNR from a core-collapse origin, after a relatively short time period, will be useful for understanding the SNR evolution.

2. Berkeley 97 and PSR J2238+5903

Based on the information from the updated parameters of 1743 Open Clusters catalog (Dias et al. 2021), Berkeley 97 is centered on the position $\alpha = 22^{\text{h}}39^{\text{m}}23.98^{\text{s}}$, $\delta = +59^{\circ}00'16.6''$, having an angular diameter of 5 arcmin. The distance and the extinction toward the cluster are $d = 2485 \pm 110$ pc and $A_V = 2.539 \pm 0.04$ mag, respectively. The age is $\log(\text{age}[\text{yr}]) = 7.589 \pm 0.381$, with a metallicity of $[\text{Fe}/\text{H}] = -0.1 \pm 0.026$. The mean proper motion values of the cluster are $\mu_{\alpha}^* = -2.697 \pm 0.176$ mas yr $^{-1}$ and $\mu_{\delta} = -1.829 \pm 0.144$ mas yr $^{-1}$. No RV measurement was previously mentioned for the cluster. The brightest members of Berkeley 97 are the two B-type stars HD 240015 and HD 240016 (Cannon 1928).

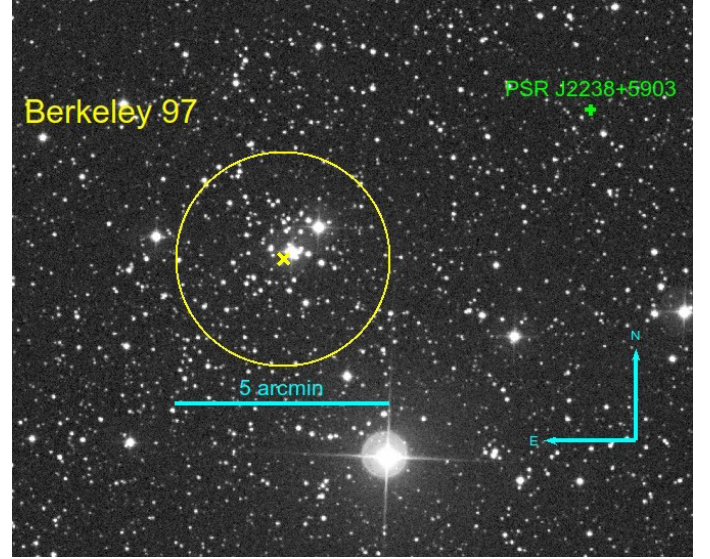


Fig. 1. Space Telescope Science Institute 2nd Digitized Sky Survey's red image of the open cluster Berkeley 97 (yellow circle) and PSR J2238+5903 (green cross) 7.9 arcmin separated from the center of the open cluster (yellow cross).

The radio-quiet γ -ray pulsar PSR J2238+5903 is located at $\alpha = 22^{\text{h}}38^{\text{m}}28.09^{\text{s}}$, $\delta = +59^{\circ}03^{\text{m}}43.3^{\text{s}}$ (Abdo et al. 2009), 7.9 arcmin (~ 5.7 pc at a distance of 2485 pc) separated from Berkeley 97 (Fig. 1). The spin period and period derivatives of the pulsar are $P = 162.7$ ms and $\dot{P} = 9.7034 \times 10^{-14}$ ss $^{-1}$, respectively (Ray et al. 2011). The spin-down age is $\tau = 26.6$ kyr. The pulsar has a typical dipole magnetic field strength of $B = 4.02 \times 10^{12}$ G, deduced from the $P\dot{P}$ by the relation

$$\frac{B}{\text{Gauss}} = 3.2 \times 10^{19} \sqrt{\frac{P\dot{P}}{s}}. \quad (1)$$

The distance to the pulsar is suggested as $d = 2.83$ kpc in the Australia Telescope National Facility (ATNF) Pulsar Catalog¹ based on measurements of absorption by neutral hydrogen combined with a model for differential rotation of the Galaxy. The neutral hydrogen column density determined from γ -ray observations is $N_{\text{H}} = 6.38 \pm 0.04 \times 10^{21}$ cm $^{-2}$ (Abdo et al. 2013). Using the relation $N_{\text{H}} (\text{cm}^{-2}) = (2.21 \pm 0.09) \times 10^{21} A_V (\text{mag})$ (Güver & Özel 2009), the extinction toward the pulsar is then $A_V = 2.89 \pm 0.14$ mag.

Pulsars constantly radiate their rotational energy and spin down. Their age can be estimated from the relation

$$t = \frac{P}{(n-1)\dot{P}} \left(1 - \left(\frac{P_0}{P} \right)^{(n-1)} \right), \quad (2)$$

where P_0 is the initial spin period and n is the magnetic breaking index. Considering $P \gg P_0$ and adopting the breaking index, the theoretical value of $n = 3$, the characteristic age of the pulsar is calculated as $\tau = P/2\dot{P}$. This value is somewhat larger than the real age, as the pulsars have a small but non-zero P_0 . For example, the characteristic age of the Crab Pulsar is 1260 yr (Lyne et al. 2015), while the real age is 970 yr, found from the historical records (Stephenson & Green 2003). Another good example is PSR J0538+2817, having a characteristic age of ~ 620 kyr and a real age of 30 ± 4 kyr, measured by calculating

¹ <http://www.atnf.csiro.au/research/pulsar/psrcat/>

Table 1. Geometrical distances, proper motions, parallaxes, G -band brightnesses, and $G_{\text{BP}}-G_{\text{RP}}$ color indices of the 23 members of Berkeley 97.

<i>Gaia</i> DR3 source	r_{geo} (pc)	π (mas)	μ_{α} (mas yr $^{-1}$)	μ_{δ} (mas yr $^{-1}$)	G (mag)	$G_{\text{BP}}-G_{\text{RP}}$ (mag)
2008383233685344512	2713 $^{+406}_{-316}$	0.3577 $\pm$ 0.0343	-2.721 $\pm$ 0.035	-1.895 $\pm$ 0.034	16.096 $\pm$ 0.003	1.207 $\pm$ 0.009
2008383302396651264	2738 $^{+309}_{-263}$	0.3387 $\pm$ 0.0322	-2.703 $\pm$ 0.031	-1.952 $\pm$ 0.034	15.480 $\pm$ 0.003	1.118 $\pm$ 0.026
2008383302396655488	2630 $^{+310}_{-237}$	0.3652 $\pm$ 0.0363	-2.873 $\pm$ 0.038	-2.301 $\pm$ 0.038	9.474 $\pm$ 0.003	0.938 $\pm$ 0.007
2008383302404810880	2961 $^{+233}_{-285}$	0.3244 $\pm$ 0.0296	-2.726 $\pm$ 0.031	-1.956 $\pm$ 0.029	15.755 $\pm$ 0.003	1.137 $\pm$ 0.011
2008383302404812544	2605 $^{+115}_{-138}$	0.3569 $\pm$ 0.0163	-2.626 $\pm$ 0.018	-1.913 $\pm$ 0.017	14.199 $\pm$ 0.003	1.058 $\pm$ 0.008
2008383302404816640	2635 $^{+169}_{-175}$	0.3503 $\pm$ 0.0211	-2.724 $\pm$ 0.022	-1.902 $\pm$ 0.021	15.112 $\pm$ 0.003	1.133 $\pm$ 0.007
2008384436276195712	2622 $^{+166}_{-149}$	0.3597 $\pm$ 0.0201	-2.750 $\pm$ 0.021	-1.896 $\pm$ 0.020	15.037 $\pm$ 0.003	1.065 $\pm$ 0.007
2008384706850332672	2628 $^{+193}_{-181}$	0.3584 $\pm$ 0.0261	-2.643 $\pm$ 0.027	-1.912 $\pm$ 0.025	15.589 $\pm$ 0.003	1.296 $\pm$ 0.013
2008384711154095872	2863 $^{+174}_{-140}$	0.3242 $\pm$ 0.0214	-2.801 $\pm$ 0.022	-1.795 $\pm$ 0.021	15.208 $\pm$ 0.003	1.202 $\pm$ 0.007
2008384711154096256	2835 $^{+210}_{-198}$	0.3209 $\pm$ 0.0266	-2.812 $\pm$ 0.027	-1.916 $\pm$ 0.025	15.564 $\pm$ 0.003	1.125 $\pm$ 0.008
2008384779873564032	2623 $^{+96}_{-121}$	0.3563 $\pm$ 0.0168	-2.780 $\pm$ 0.017	-1.834 $\pm$ 0.016	14.491 $\pm$ 0.003	1.049 $\pm$ 0.007
2008384814233517312	2824 $^{+155}_{-127}$	0.3254 $\pm$ 0.0178	-2.517 $\pm$ 0.018	-1.719 $\pm$ 0.018	14.664 $\pm$ 0.003	1.043 $\pm$ 0.007
2008430203449108224	2525 $^{+67}_{-65}$	0.3648 $\pm$ 0.0114	-2.953 $\pm$ 0.012	-1.724 $\pm$ 0.012	13.262 $\pm$ 0.003	0.962 $\pm$ 0.007
2008430233501492608	2820 $^{+134}_{-109}$	0.3264 $\pm$ 0.0143	-2.683 $\pm$ 0.015	-1.821 $\pm$ 0.015	13.733 $\pm$ 0.003	1.051 $\pm$ 0.007
2008430237808841600	2658 $^{+77}_{-70}$	0.3583 $\pm$ 0.0125	-2.747 $\pm$ 0.013	-1.911 $\pm$ 0.013	9.840 $\pm$ 0.003	0.869 $\pm$ 0.007
2008430237808844672	2872 $^{+209}_{-151}$	0.3277 $\pm$ 0.0209	-2.749 $\pm$ 0.022	-1.859 $\pm$ 0.021	15.123 $\pm$ 0.003	1.072 $\pm$ 0.007
2008430237808846464	2872 $^{+235}_{-208}$	0.3298 $\pm$ 0.0256	-2.686 $\pm$ 0.026	-1.932 $\pm$ 0.025	15.255 $\pm$ 0.003	1.167 $\pm$ 0.008
2008430237808846848	2941 $^{+211}_{-192}$	0.3148 $\pm$ 0.0206	-2.573 $\pm$ 0.021	-1.897 $\pm$ 0.020	14.821 $\pm$ 0.003	1.048 $\pm$ 0.008
2008431715277595264	2965 $^{+192}_{-181}$	0.3091 $\pm$ 0.0223	-2.789 $\pm$ 0.023	-1.990 $\pm$ 0.023	15.223 $\pm$ 0.003	1.073 $\pm$ 0.008
2008431715277915264	2398 $^{+187}_{-148}$	0.3906 $\pm$ 0.0312	-3.001 $\pm$ 0.033	-1.763 $\pm$ 0.032	15.857 $\pm$ 0.003	1.163 $\pm$ 0.007
2008431749637658624	2907 $^{+224}_{-167}$	0.3162 $\pm$ 0.0213	-2.950 $\pm$ 0.022	-2.324 $\pm$ 0.022	15.019 $\pm$ 0.003	1.321 $\pm$ 0.007
2008384504995669248	2620 $^{+139}_{-159}$	0.3560 $\pm$ 0.0241	-0.379 $\pm$ 0.025	-1.352 $\pm$ 0.024	15.384 $\pm$ 0.003	1.182 $\pm$ 0.008
2008383233685346560	2484 $^{+155}_{-134}$	0.3713 $\pm$ 0.0289	-1.922 $\pm$ 0.028	-1.497 $\pm$ 0.028	15.643 $\pm$ 0.003	2.168 $\pm$ 0.010

the flight time and confirmed by the pre-SN binary companion's motion (Dinçel et al. 2015). They are both linked to SNRs. However, PSR J2238+5903 is not linked to any SNR despite its very young age. Also, the proper motion of the pulsar is unknown.

As the cluster catalog in Dias et al. (2021) is based on the *Gaia* DR2 catalog, we re-selected the members of the cluster and fit an isochrone on the color-magnitude diagram (CMD) based on *Gaia* DR3 data (Gaia Collaboration 2016, 2023). The parallax of HD 240016 and HD 240015 are $\varpi = 0.3652 \pm 0.0363$ and 0.3583 ± 0.0125 mas, respectively. Thus, we selected the sources having parallax values between 0.3 and 0.4 mas detected on a significance larger than ten within 2.5 arcmin from the cluster center, and we found 25 such stars. The star *Gaia* DR3 2008383233685346560 lies significantly out of the isochrone in the CMD. Hence, we excluded this star from the membership. The average proper motion values of the 23 members are $\mu_{\alpha}^* = -2.753 \pm 0.121$ mas yr $^{-1}$ and $\mu_{\delta} = -1.915 \pm 0.151$ mas yr $^{-1}$, where the errors are the standard deviations, which corresponds to only 1.5 and 1.9 km s $^{-1}$, respectively, and shows that they exhibit a common proper motion (Table 1). One star, *Gaia* DR3 2008384504995669248, has a significantly different proper motion: $\mu_{\alpha}^* = -0.379 \pm 0.025$, $\mu_{\delta} = -1.352 \pm 0.024$ mas yr $^{-1}$.

The geometrical distances of the potential members were retrieved from Bailer-Jones et al. (2021). The average of these distances is $r_{\text{geo}} = 2733$ pc, with a standard deviation of 163 pc, which is consistent with the average upper and lower errors of individual measurements, 160 and 170 pc, respectively.

The CMD – G versus ($G_{\text{BP}}-G_{\text{RP}}$) – of the potential members and the kinematical outlier was set and fit by theoretical isochrones.

We generated the isochrone tables involving stellar parameters as a function of the initial masses for a metallicity of $[\text{Fe}/\text{H}] = -0.1$ with the CMD 3.7² website, using the “Parsec 1.2S” stellar evolutionary tracks (Chen et al. 2015) with bolometric corrections from Girardi et al. (2008), the extinction curve from Cardelli et al. (1989) and O'Donnell (1994), and with an extinction law $R_V = 3.1$ (Fig. 2). We used the canonical two-part power-law initial mass function from Kroupa (2001, 2002).

To obtain a more precise and accurate cluster age, we observed the bright members of the cluster HD 240015 and HD 240016. These stars satisfy the kinematical and distance criteria and are not expected to be runaway stars.

3. Observations

We took the spectra of the bright members HD 240015 and HD 240016 in several observing epochs by using the Fibre Linked Échelle Astronomical Spectrograph (FLECHAS) (Mugrauer et al. 2014) on the 90-cm Schmidt telescope at the University Observatory Jena (Table 2). FLECHAS provides a resolving power of $R \sim 9200$ and a wavelength range of 3900–8100 Å. We took the spectra with 2×2 pixel binning, which reduces the resolving power to $R \sim 7000$. For optimal calibration, three arc (Th-Ar lamp) and flatfield images (Tungsten lamp), each with a detector integration time (DIT) of 1.5 s, were always taken immediately before the science exposures. The charge-coupled device of FLECHAS was always operated at

² http://stev.oapd.inaf.it/cgi-bin/cmd_3.7

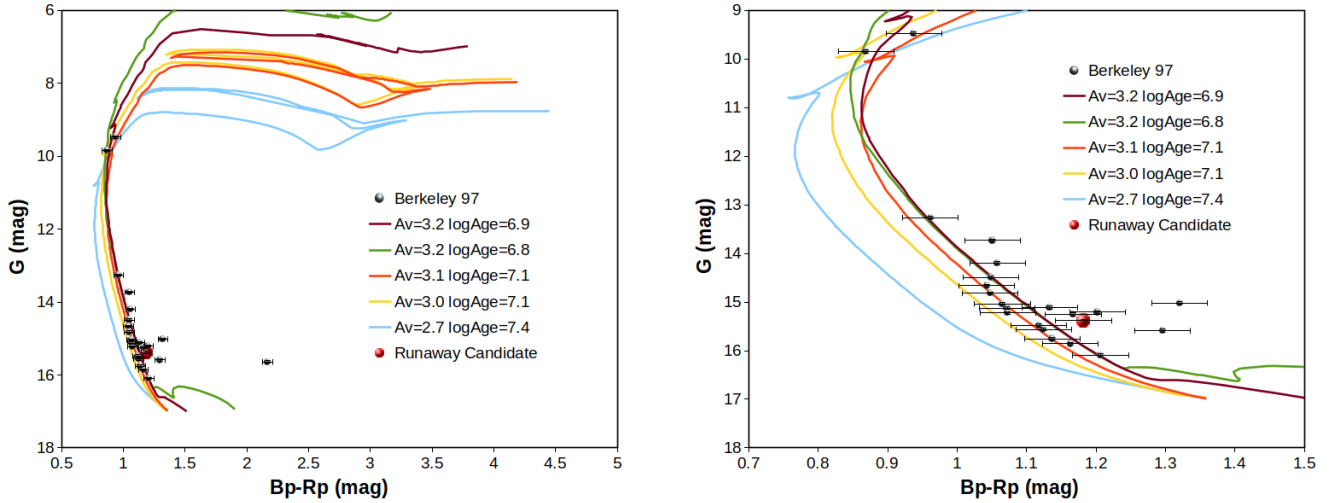


Fig. 2. CMD – G vs. $(G_{BP} - G_{RP})$ – Berkeley 97 potential members brighter than 17 mag in G -band. *Left:* CMD – G vs. $(G_{BP} - G_{RP})$ – of Berkeley 97. Unlike how it is mentioned in the literature, the isochrones fitting of the CMD are of $\log(\text{age}[\text{yr}]) = 6.8\text{--}7.1$ for extinction values between and $A_V = 3.0\text{--}3.2$ mag. For $\log(\text{age}[\text{yr}]) = 7.1$, the isochrone represents hypothetical stars with masses of $M = 1.8\text{--}16 M_\odot$. One star with a color index value larger than $G_{BP} - G_{RP} > 2.0$ mag is unlikely a member. *Right:* Close-up of the same CMD on the left. The brightest stars are HD 240016 and HD 240015 consecutively. The runaway candidate is shown as a red point. A typical 0.02 mag photometric error for each target is assigned to represent the uncertainty in the theoretical isochrones. The errors along the y -axis are smaller than the labels.

Table 2. Dates of the observation of each star together with the signal-to-noise ratio obtained around the $H\beta$ $\lambda 4860$ line.

Stars	Date	S/N	Exp. time
HD 240015	Sep. 30, 2022	24	1200 s
HD 240015	Aug. 18, 2023	30	2400 s
HD 240015	Sep. 07, 2023	26	2400 s
HD 240016	Sep. 30, 2022	30	1200 s
HD 240016	Mar. 11, 2023	28	2400 s
HD 240016	Aug. 20, 2023	35	2400 s
HD 240016	Aug. 23, 2023	35	2400 s
HD 240016	Sep. 07, 2023	40	2400 s

a cooling temperature of -30°C . We took a set of three dark frames for each DIT used for the arc, flatfield, and science exposures and median combined them for efficient cosmic ray removal. Each spectrum and dark frame was divided into three frames in order to remove cosmic rays.

We reduced the data obtained in the IRAF environment (Tody 1986). Dark frames were combined into master darks of all the used integration times and were then subtracted from the science, flat, and arc frames. We combined the three science frames with average sigma clipping rejection in order to remove cosmic rays. We extracted the flat and then the arc and the science frames by tracing each echelle aperture of the flat frame and then the science frame was divided by the flat frame. We identified the emission lines of the extracted arc spectrum and wavelength calibrated the science. After the wavelength calibration, the science was normalized. Finally, spectra in all the apertures were trimmed and combined to have one single spectrum.

We compared the spectra of HD 240015 and HD 240016 with the synthetic spectra, which were calculated from the Potsdam Wolf-Rayet/OB-star model atmospheres (Fig. 3)³. The

spectra were calculated for a micro-turbulence velocity of $v_{\text{turb}} = 7 \text{ km s}^{-1}$ and solar metallicity, with a grid resolution of 1000 K in temperature and 0.2 dex for the surface gravity, $\log(g)$.

We applied boxcar smoothing to the synthetic spectra until the H intensity was equalized with that of the observed spectrum. After a visual comparison of the $H\beta$ wings ($4844\text{--}4874 \text{ \AA}$), we chose the possible $\log(g)$ values as $\log(g[\text{cm/s}^2]) = 2.6\text{--}3.2$. Then, we cross correlated the observed spectra with template spectra from 15 000–28 000 K temperatures, each separated into three $\log(g)$ values, 2.8, 3.0, and 3.2 with the fxcor (Fourier cross-correlation) task IRAF. We selected the spectra with the largest correlation height (Fig. 4) for a detailed visual inspection. We also measured the RVs of the stars in each observation epoch by Fourier cross-correlation in IRAF, with the best-fitting model spectra used as a template after the spectra were shifted in the wavelength space for the heliocentric RV.

We measured the Doppler shift of the ISM lines on the stellar spectra, Na I-D1 and Na I-D2 by Gaussian fitting. The average heliocentric RV of interstellar Na I-D1 and Na I-D2 lines of HD 240015 and HD 240016 are $RV_{\text{Na}} = -25.1 \pm 0.7 \text{ km s}^{-1}$ and $RV_{\text{Na}} = -21.8 \pm 0.6 \text{ km s}^{-1}$, respectively. These values are considerably less than the measured heliocentric RV of the stars (Table 3). The RV variation in ISM lines might be due to the S/N and dispersion quality of the data.

The RVs measured for HD 240015 are consistent with each other within the errors. The weighted mean velocity is -47.5 km s^{-1} , with an error of 4.8 km s^{-1} , and the standard deviation is 4.2 km s^{-1} . The weighted mean velocity of HD 240016 is the same, $-47.5 \pm 3.0 \text{ km s}^{-1}$. However, the standard deviation of the measured velocities is high, 10.2 km s^{-1} . They vary between -37 and -59 km s^{-1} , implying the target is a spectroscopic binary. More observations are needed to constrain its orbital elements, but the binary parameters of this star are out of the scope of this work; hence, further observations were not needed. As there is no RV measurement for Berkeley 97 in the literature, -47.5 km s^{-1} can set a reference value for the RV of the OB-runaway candidate when it is determined with future observations.

³ <https://www.astro.physik.uni-potsdam.de/~wrh/PoWR/powrgrid1.php>

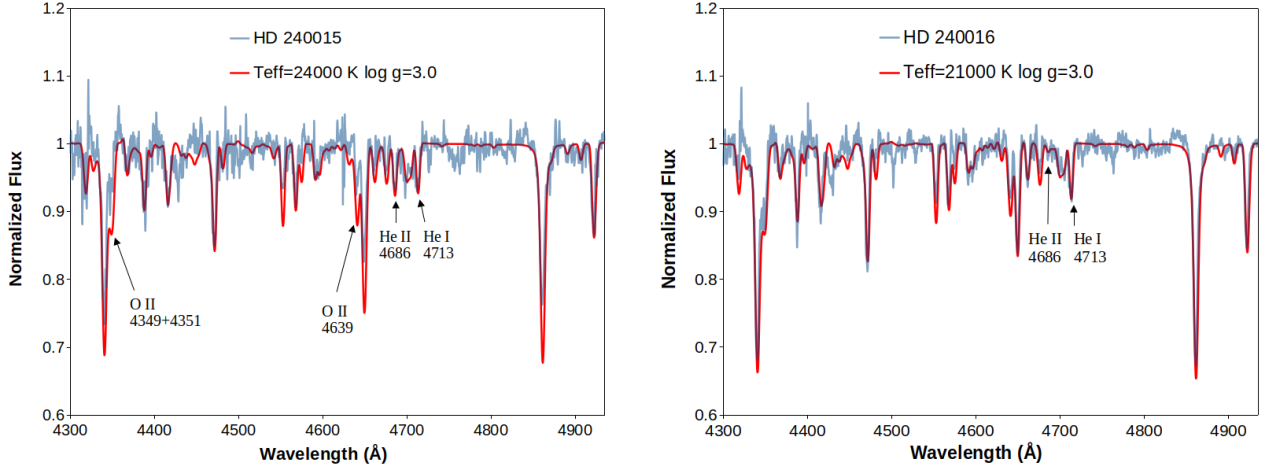


Fig. 3. Spectra of HD 240016 and HD 240015 with best-fitting model spectra overlayed.

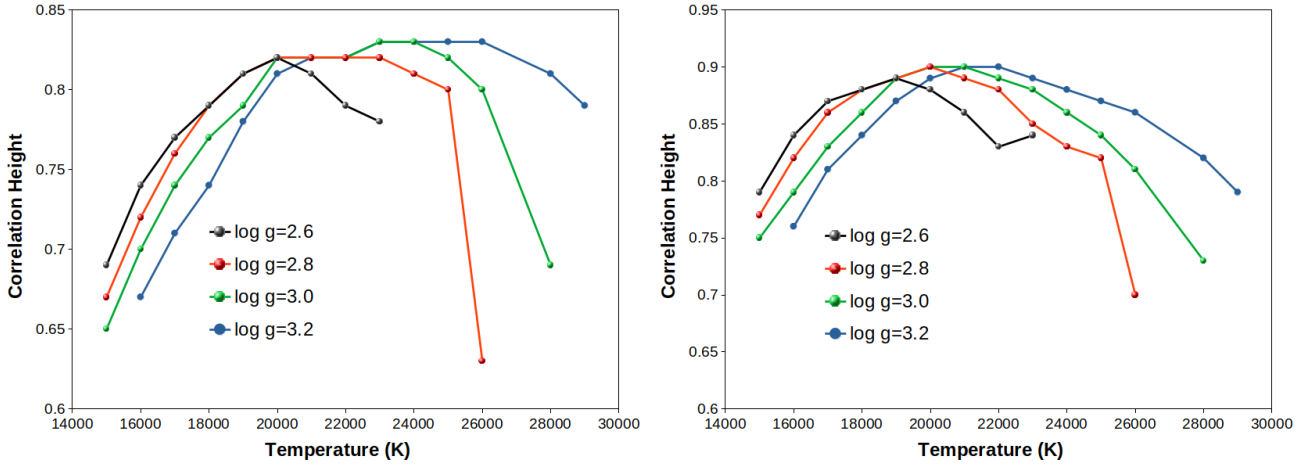


Fig. 4. Cross-correlation heights of the stars HD 240015 and HD 240016 with the template spectra for four different $\log(g)$ values between 2.6–3.2 dex.

Table 3. Heliocentric RVs measured for stars and interstellar Na I-D1 and-D2 lines toward the stars.

Date	RV _{Helio}	Na I-D1	Na I-D2
HD 240015			
Sep. 30, 2022	-51.7 ± 7.7	-26.2	-25.6
Aug. 18, 2023	-46.4 ± 7.7	-24.6	-23.8
Sep. 07, 2023	-43.5 ± 10.1	-26.1	-24.3
HD 240016			
Sep. 30, 2022	-57.5 ± 6.2	-23.7	-20.8
Mar. 11, 2023	-37.4 ± 9.2	-25.5	-22.0
Aug. 20, 2023	-43.6 ± 7.4	-22.1	-21.0
Aug. 23, 2023	-58.7 ± 6.9	-22.8	-21.3
Sep. 07, 2023	-38.9 ± 5.3	-23.2	-20.8

Notes. Values are in kilometer per second. The Gaussian full width half maximum of the sodium lines is about 1.2 Å.

The star HD 240016 shows no significant He II λ 4686 but a relatively strong Si III $\lambda\lambda$ 4552-4568-4575. He II λ 4686 appears at $T_{\text{eff}} = 22\,000$ K with $\log(g[\text{cm/s}^2]) = 3.0$. So, the star should have a temperature smaller than $T_{\text{eff}} < 22\,000$ K. On the other hand, the star shows stronger O II λ 4640 and λ 4650 (blend

Table 4. Measured parameters of the observed stars with the spectral types adopted in this work and the most precise spectral types available in the literature.

Stars	T_{eff} (K)	$\log(g)$	SpT (tw)	SpT
HD 240015	$24\,000 \pm 2000$	3.0 ± 0.2	B0.5II	Be
HD 240016	$21\,000 \pm 1000$	3.0 ± 0.2	B1.5II	B

Notes. The spectral types of the stars determined in this work (tw) are given in the fourth column. We adopted the spectral types following [Hohle et al. \(2010\)](#), and the literature spectral types are from [Chick et al. \(2020\)](#).

+ C III) lines compared to the $T_{\text{eff}} = 18\,000$ K model with $\log(g[\text{cm/s}^2]) = 2.8$ –3.0 as well as a weaker Mg II λ 4481. Unlike HD 240016, HD 240015 shows a significant He II λ 4686 line whose strength equals that of He I λ 4713, implying a temperature of around $T_{\text{eff}} = 24\,000$ K. We note that the O II λ 4640 and O II λ 4349+4351 lines are weaker than the model spectrum, implying a higher or lower temperature. However, the major temperature indicator for this temperature range is the He II λ 4686. The emission in the hydrogen lines and lower S/N increase the uncertainty in the stellar parameters of HD 240015. The temperature and $\log(g)$ values of the stars are given in Table 4.

Table 5. Derived and observed parameters of the OB-runaway candidate.

T_{eff} (K)	$\log(g)$	M ($M_{\odot}$)	L ($L_{\odot}$)	v_{pec} km s $^{-1}$	SpT	G (mag)	$G_{\text{BP}}-G_{\text{RP}}$
$12\,250 \pm 1750$	4.38 ± 0.02	2.85 ± 0.65	1.8 ± 0.4	29.6 ± 3.0	$B8 \pm 1V$	15.38 ± 0.003	1.18 ± 0.008

Notes. Effective temperature, surface gravity, mass, and luminosity were derived from the CMD of Berkeley 97. The peculiar transverse velocity of the stars was calculated using their *Gaia* DR3 proper motion and parallax. Their apparent G -band brightness and $G_{\text{BP}}-G_{\text{RP}}$ color-index is listed in the *Gaia* DR3.

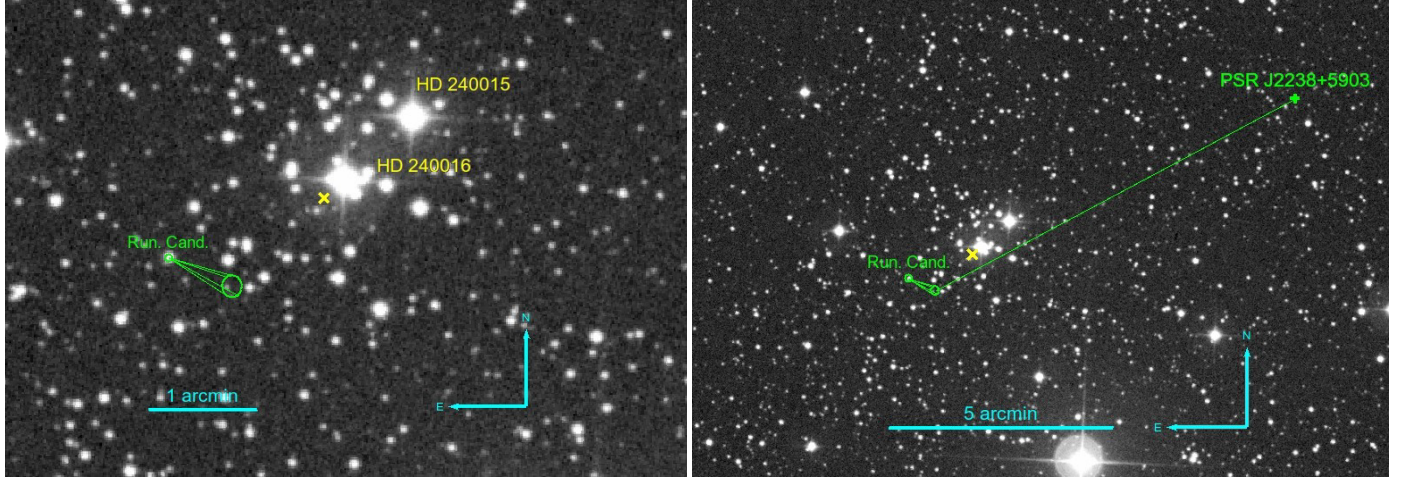


Fig. 5. Possible explosion center and pulsar's flight trajectory. *Left:* Tracing back of the runaway candidate (green lines) for 20 kyr. The explosion center is within the cluster. *Right:* Hypothetical flight trajectory (Euclidian) of the pulsar for the same time span. The pulsar velocity, in this case, is ~ 340 km s $^{-1}$.

4. Results

The bright cluster members HD 240015 and HD 240016 are B0.5II and B1.5II type stars, confirming that the age of the cluster is $\log(\text{age}[\text{yr}]) = 7.1$, with an uncertainty smaller than 0.1, and the extinction is $A_V = 3.1 \pm 0.1$ mag, for a metallicity of $[\text{Fe}/\text{H}] = -0.1$ (Fig. 2). Based on the theoretical isochrones, both stars have a mass of $M = 15.6^{+2.8}_{-2.3} M_{\odot}$.

The star *Gaia* DR3 2008384504995669248, the kinematic outlier in the cluster, has a proper motion of $\mu_{\alpha}^* = -0.379 \pm 0.025$ $\mu\text{s} = -1.352 \pm 0.024$ mas yr $^{-1}$. The geometrical distance of the star is $r_{\text{geo}} = 2620^{+139}_{-159}$ pc (Bailer-Jones et al. 2021), consistent with the cluster distance.

The proper motion of the star relative to the cluster average is $\mu_{\alpha}^* = 2.374 \pm 0.146$ $\mu\text{s} = 0.563 \pm 0.175$ mas yr $^{-1}$, and the corresponding transverse velocity is $v_{\text{trans}} = 30.1^{+4.3}_{-3.7}$ km s $^{-1}$, which is above the runaway star velocity limit. Therefore, it is a strong runaway candidate. We derived the atmospheric parameters (Table 5) from the isochrone fit to the CMD of the cluster. The position of the star in the CMD does not exactly lie on the isochrone, which might be natural for relatively faint targets. It might also be exposed to a locally enhanced extinction due to a foreground cloudlet. The mass, and hence all the other corresponding parameters of the isochrone at the $G_{\text{BP}}-G_{\text{RP}}$ value of the star, was taken as the lower limit, $M = 2.2 M_{\odot}$, while the same at the G -band magnitude was taken as the upper limit of the mass, $M = 3.5 M_{\odot}$. Hence, the star is predicted to be a main-sequence late B-type star.

Gaia DR3 2008384504995669248 can be the pre-SN binary component to the progenitor of the pulsar. Hence, the flight trajectories of both objects must coincide at the same position. However, the pulsar proper motion is unknown. Yet, if a hypothetical trajectory of the pulsar yields a reasonable pulsar space

velocity, then the link between the pulsar and the runaway is highly likely.

We found the explosion center by tracing back the peculiar proper motion of the runaway star (Fig. 5), which is the relative proper motion with regard to the cluster. The flight time is uncertain but limited to $\tau \sim 26.6$ kyr, as the characteristic age of the pulsar generally sets an upper limit for its real age. The pulsar velocity is calculated by the distance taken by the pulsar, from the explosion center, divided by the exercised flight time. The runaway tracing back for 20 kyr (considered pulsar age/flight time) gives a pulsar velocity of $v_{\text{sp}} \sim 340$ km s $^{-1}$, which is a typical value for the space velocity of a pulsar (Lyne & Lorimer 1994). Flight times as low as 10 kyr yield a velocity of $v_{\text{sp}} \sim 650$ km s $^{-1}$, which is more unlikely. The lowest possible velocity is 246 km s $^{-1}$, calculated for 26.6 kyr. Therefore, the kinematic age of the pulsar should be about 20 kyr. Thus, the SN should have occurred about 20 kyr ago. Furthermore, for such high kick velocities, binary disruption is likely.

Although a proper motion measurement is not possible for the pulsar with the existing data, we sketched all of the positions available in the literature with the epoch of observations on the X-ray image (Fig. 6). The γ -ray detections have substantial positional uncertainties of several arcminutes. There are four relatively precise detections: two from γ -ray timing studies, one from an X-ray point source, and one from an IR source in the K -band (Table 6). The theoretical proper motion of the pulsar for an age of 20 kyr is only ~ 27 mas yr $^{-1}$ with a parallactic angle of $\sim 298^\circ$, while the positional uncertainties are still large: ~ 1 arcsec. Also, the positional uncertainties determined by the first γ -ray timing (MJD = 54 800) are probably underestimated because the position is largely (several arcseconds) separated from the other positions. Also, γ -ray positions are always less precise compared to X-ray positions. On the other hand, the

Table 6. Possible positions of the pulsar in the literature.

MJD (day)	Instrument	RA (deg)	Error (arcsec)	Dec (deg)	Error (arcsec)	Ref.
54 322	UKIDSS WFC	339.6167070	0.6	+59.061823000	0.6	(1)
54 800	Fermi LAT	339.6177917	0.6	+59.061333300	0.4	(2)
55 555	Fermi LAT	339.6170375	2.8	+59.062047222	1.46	(3)
56 038.411	Chandra ACIS	339.6163700	1.0	+59.061950000	1.0	(4)

Notes. The modified Julian date (MJD) of observations, the telescopes and instruments used, and equatorial coordinates with their uncertainties are given, respectively.

(1) Lucas et al. (2008); (2) Ray et al. (2011); (3) Kerr et al. (2015); (4) Wang et al. (2016).

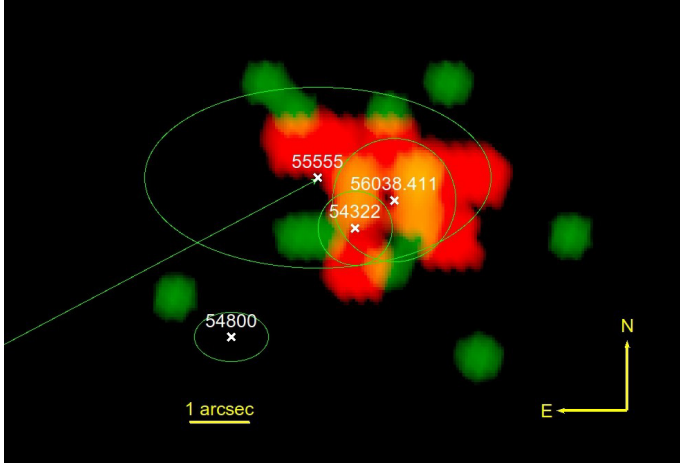


Fig. 6. Centre de Données astronomiques de Strasbourg (CDS) Hierarchical Progressive Survey (HiPS) color composite image of the region around the pulsar, retrieved from Aladin Sky Atlas. Red represents the soft X-ray (0.5–1.2 keV) data taken by Chandra ACIS, while green is the medium band (1.2–2.0 keV) of the same. The source seen in the image is most probably the X-ray counterpart of PSR J2238+5903. The point sources mentioned in Table 6 are shown with a white X with the corresponding MJDs and positional error ellipses. The green vector shows the direction of motion if the pulsar originated from the position we found using the OB-runaway proper motion.

parallactic angle between the IR and the X-ray sources (MJDs; 54 322 and 56 038.411) is $\sim 305^\circ$, consistent with our expectation. Future X-ray and IR observations might be helpful to at least see the direction of motion. Also, an independent study should verify that these two sources are the X-ray and IR counterparts of the pulsar.

We also searched for an optical counterpart using the *Gaia* DR3 catalog within 20 arcseconds from the pulsar. Yet we did not find any optical source with a significantly high proper motion, namely, $>8 \text{ mas yr}^{-1}$ ($\sim 100 \text{ km s}^{-1}$).

Based on the isochrones (Fig. 2) and using the initial mass function from Kroupa (2001, 2002), the mass of the OB-runaway candidate is $M \sim 3 M_\odot$, while the maximum mass among the members of the cluster is $M \sim 16 M_\odot$. Hence, the progenitor zero-age main-sequence mass should be close to this value: $M_{\text{progenitor}} \sim 16 M_\odot$. Assuming a circular orbit, we reconstructed the hypothetical pre-SN binary system for two different orbital velocities assumed for the secondary (Table 7). The first velocity is the 2D peculiar transverse velocity of the runaway star (the pre-SN secondary), 30 km s^{-1} , while the other one is a hypothetical 3D peculiar velocity of the runaway, 42 km s^{-1} , calculated by assuming the star has the same peculiar velocity in the radial direction as the transverse velocity. We note that the 2D pecu-

Table 7. Calculated parameters of the pre-SN binary for two different peculiar velocities of 30 (top) and 42 (bottom) km s^{-1} .

Configur.	Sep. ($R_\odot$)	RL radius ($R_\odot$)	Period (days)
3 & 16 $M_\odot$	2839	1494	4046
3 & 10 $M_\odot$	1621	787	2110
3 & 5 $M_\odot$	658	279	697
3 & 16 $M_\odot$	1448	762	1474
3 & 10 $M_\odot$	826	401	769
3 & 5 $M_\odot$	336	142	254

Notes. The binary separation, the Roche-Lobe radius, and the period for different configurations are given, respectively.

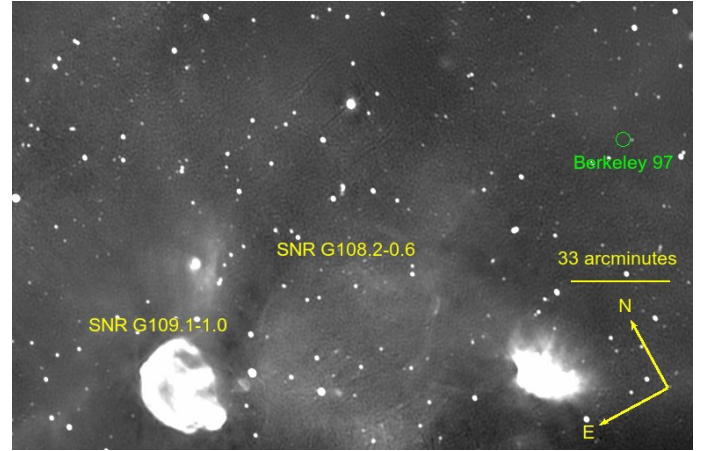


Fig. 7. CGPS 1420 MHz image of the region. No shell structure of an SNR is detectable, while the shells of the bright SNR G109.1–1.0 and a faint SNR G108.2–0.6 can be clearly detected. A green circle shows Berkeley 97. The bar is 33 arcmin (26 pc) long.

liar transverse velocity of the runaway star is the lower limit of the 3D peculiar velocity. Also, the RV can surely be even larger than the assumed value. Considering the possible mass loss during the post-main sequence evolution (van den Heuvel 1976; Taam & Sandquist 2000; Zapartas et al. 2017), we calculated the parameters for three different pre-SN progenitor masses 5, 10, and $16 M_\odot$.

The Roche lobe radius $762 R_\odot$ for 42 km s^{-1} implies that the system might have been an interacting binary at the supergiant phase of the primary (van den Heuvel 1993; Woosley et al. 1995), as the massive stars can expand beyond this size, as in the star VY CMa, $1420 R_\odot$ (Witkowski et al. 2012). Thus, they can fill their Roche lobe and accrete matter onto their companion.

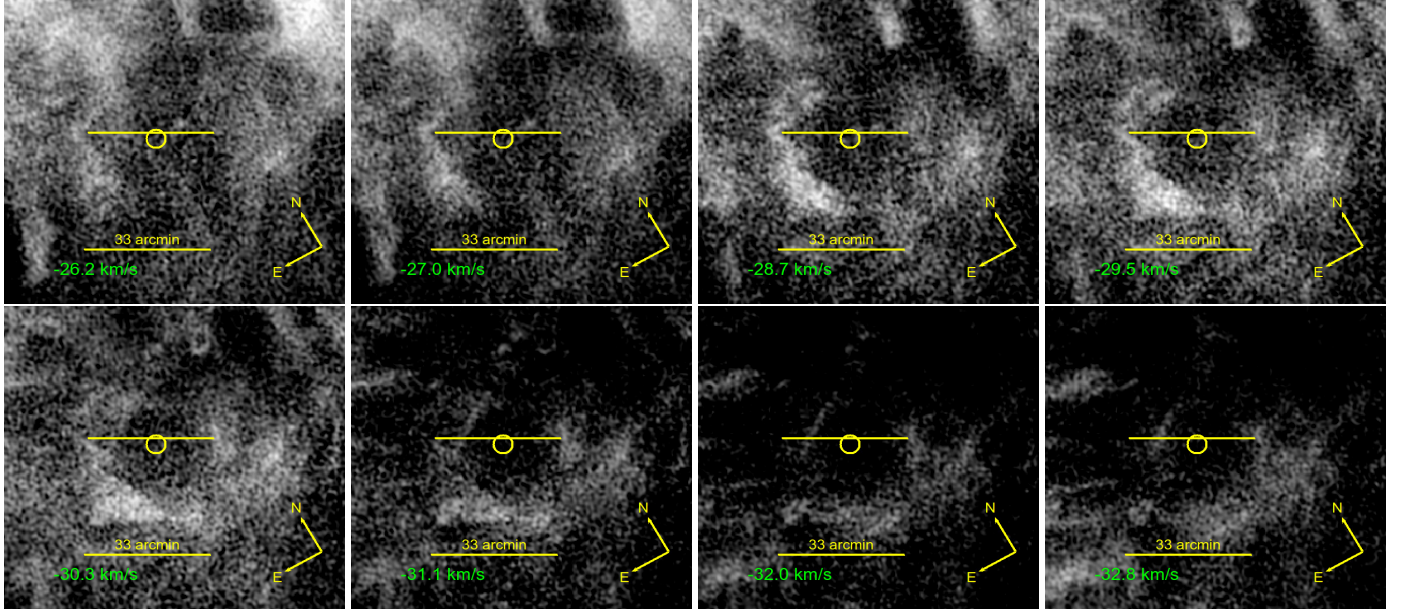


Fig. 8. CGPS 21-cm H I images of Berkeley 97 and surroundings. There was no sign of an SNR in any wavebands; however, a void is present at $v_{\text{LSR}} = -29 \pm 2 \text{ km s}^{-1}$. The local standard of rest velocities (v_{LSR}) are given in each image. The green circle shows Berkeley 97. The bar is 33 arcmin (26 pc) long.

However, for 30 km s^{-1} , the minimum velocity of the runaway, the system is likely to be detached (Table 7).

5. Discussion

A characteristic age of $\tau = 26.6 \text{ kyr}$ implies that an SNR related to the pulsar should still be visible. An SNR at this age should either show a radio shell through non-thermal synchrotron radiation of accelerated electrons, possibly with a hot X-ray shell, or optical emission of recombining H atoms and forbidden transitions from various atoms. However, no SNR is mentioned in the literature that can be related to the pulsar. We checked archival images taken in the radio, optical, and X-ray spectral range toward the pulsar and the cluster to find a shell or pulsar wind nebula (PWN) structure. However, no sign of an SNR shell or a PWN was found in the Canadian Galactic Plane Survey (CGPS) 1420 MHz (Fig. 7), the Space Telescope Science Institute 2_{nd} Digitized Sky Survey's red images, or the ROSAT X-ray images.

Considering the typical SNR dissipation time of 100 kyr, one expects to find 2000 SNRs with a galactic SN rate of two SN per century within the Milky Way (Tammann et al. 1994). However, observations have shown evidence of only 300 SNRs, which is inconsistent with the expected number of SNe (Green 2009). One reason might be that some SNe do not produce a visible SNR due to the low density of the ambient medium. The SNR is not able to sweep up enough interstellar material and thus cannot enter a Sedov or radiative phase for a long time. Such bubbles can form around the young open clusters and OB associations through strong winds or the SNe of massive stars. Another possibility is that the SNR interacts with dense molecular clouds, and the shock wave loses its entire energy and merges with the ISM much sooner than expected. A good example is SNR CTB 109, whose shock wave dissipated on the western side where it had an interaction with a giant molecular cloud (Sasaki et al. 2006). The lower the explosion energy, the lower the cloud density required for such dispersion.

We checked the 21 cm-H I images from CGPS extending from 0 to -80 km s^{-1} local standard of rest (LSR) velocities to

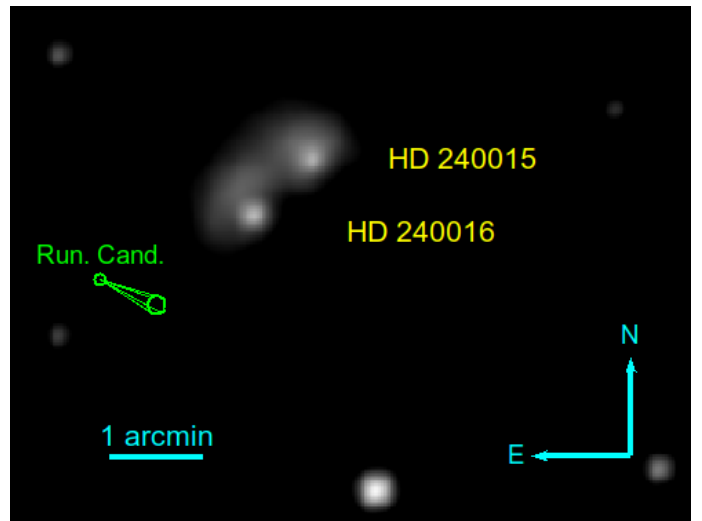


Fig. 9. WISE W4 image of the cluster. The bow shock features are clearly seen around the massive stars of the cluster. The explosion center is the larger green circle.

find a bubble inside H I clouds resulting from the ionization of hydrogen due to the hot SNR or the strong winds and UV radiation from the massive stars of Berkeley 97. The cluster is surrounded by a void at $v_{\text{LSR}} = -29 \pm 2 \text{ km s}^{-1}$ (Fig. 8). The void has an angular diameter of $\sim 33 \text{ arcmin}$, which translates to a physical diameter of 26 pc at a distance of 2.7 kpc. The diameter is consistent with the diameter of an evolved SNR.

The tracing back of the pulsar to the runaway star implies a kinematical age of 20 kyr. Considering the case of an extended free expansion phase, the SNR blast wave moves freely at a constant high velocity, such as 5000 km s^{-1} (shock velocity from a core-collapse of a massive star). In 20 kyr, it expands up to a radius of about 100 pc, which is incomparably larger than the void radius of $\sim 13 \text{ pc}$. The SNR must expand very slowly ($\sim 1250 \text{ km s}^{-1}$) in this void for only 10 kyr, which dictates a

high pulsar space velocity of $\sim 650 \text{ km s}^{-1}$. The SNR is likely to have already interacted with the ambient medium. Therefore, the possible explanation is that the SNR has already merged with the ISM and faded away. This might be explained by a low SN explosion energy, as in the case of the Crab Nebula ($\sim 10^{50}$ erg) (Yang & Chevalier 2015). The SNR evolved slowly in a relatively hot medium with a high speed of sound so that the expansion velocity became subsonic at an early age. In either case, the explosion energy should be very low. A third option can be that the cluster is not related to the H I clouds, and the ejecta expands freely for longer distances.

The massive members of Berkeley 97, HD 240015 and HD 240016, are definitely not runaway stars, yet they show bow-shock features in the IR (Chick et al. 2020). However, considering the age of the cluster, $10^{7.1}$ (12.59 Myr), the star formation must be mostly completed, and the dust around the cluster should have been dispersed by the strong UV radiation, winds and SNe of the massive members.

Dust is mainly formed by AGB stars, SNRs, and PWNe. Therefore, the dissipated SNR or the wind nebula that the pulsar once had might be an agent that produces the dust heated by the bow shocks today. The bow shock direction does not point toward the explosion center (Fig. 9). Hence, it is not expanding from the center. Although the dynamics are not clearly understood, one can speculate that some part of the dust is dragged inward by the reverse shock and interacts with the massive stars' magnetosphere. A spectrum of the IR emission can reveal if the dust has SN content (e.g., enrichment in α -process elements).

On the other hand, the generation of the bow shock by two non-runaway stars can be explained by the fact that the whole cluster has a peculiar space velocity. In the direction of $l = 110^\circ$, at around 2.7 kpc, local bodies can have a wide range of velocities between -35 and -55 km s^{-1} due to the Perseus arm density shock wave (Foster & MacWilliams 2006). Such an explanation can be valid in this case, the cluster penetrates to a low-velocity region and shows a relative RV of $\sim -22 \text{ km s}^{-1}$, which is the difference between the RV of HD 240015 and the average ISM lines.

6. Summary

Through careful member selection using *Gaia* DR3 data and spectroscopic confirmation of its bright members, we find that Berkeley 97 is a young open cluster at an age of $\log(\text{age}[\text{yr}]) = 7.1$ with an uncertainty of <0.1 dex. The extinction toward the cluster is $A_V = 3.1 \pm 0.1$ mag.

The origin of the γ -ray pulsar PSR J2238+5903 is likely to be the cluster. The hypothetical space velocities calculated for the pulsar in case of ejection from the cluster are consistent with the typical space velocities of pulsars in general.

The star *Gaia* DR3 2008384504995669248 can be the pre-SN companion to the progenitor of the pulsar. It is a late B-type runaway star (B8V) with a 2D peculiar transverse velocity of $\sim 30 \text{ km s}^{-1}$.

The SNR should have been detectable for a maximum age of 26.6 kyr. However, it does not manifest itself at any wavelength. The explosion energy of the SNR must have been very low, and the shock wave either has already dissipated and merged into the ISM or is very slowly expanding into the low-density ambient medium.

The massive members HD 240015 and HD 240016 show bow-shock features in mid-IR, although they are not runaway stars. The relic dust from the star formation should have already been dispersed by the cluster; therefore, it might have been pro-

duced by SN or the PWN recently. However, it is also possible that the cluster penetrates a lower velocity region on the edge of the Parseus arm density wave.

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