Discovery of an OB runaway star inside SNR S147

B. Dincel, R. Neuhäuser, S. K. Yerli, A. Ankay, N. Tetzlaff, G. Torres and M. Mugrauer

1 Astrophysikalisches Institut und Universitäts-Sternwarte Jena, D-07745 Jena, Germany
2 Department of Physics, Orta Doğru Teknik Üniversitesi, 06531 Ankara, Turkey
3 Department of Physics, Boğaziçi University, 34324 Istanbul, Turkey
4 Harvard–Smithsonian Center for Astrophysics, 60 Garden St, Mail Stop 20, Cambridge, MA 02138, USA

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ABSTRACT
We present first results of a long-term study: Searching for OB-type runaway stars inside supernova remnants (SNRs). We identified spectral types and measured radial velocities by optical spectroscopic observations and we found an early type runaway star inside SNR S147. HD 37424 is a B0.5V-type star with a peculiar velocity of $74 \pm 8$ km s$^{-1}$. Tracing back the past trajectories via Monte Carlo simulations, we found that HD 37424 was located at the same position as the central compact object, PSR J0538+2817, 30 $\pm$ 4 kyr ago. This position is only $\sim$4 arcmin away from the geometrical centre of the SNR. So, we suggest that HD 37424 was the pre-supernova binary companion to the progenitor of the pulsar and the SNR. We found a distance of $1333^{+103}_{-112}$ pc to the SNR. The zero-age main sequence progenitor mass should be greater than 13 M$_\odot$. The age is $30 \pm 4$ kyr and the total visual absorption towards the centre is $1.28 \pm 0.06$ mag. For different progenitor masses, we calculated the pre-supernova binary parameters. The Roche lobe radii suggest that it was an interacting binary in the late stages of the progenitor.

Key words: stars: early type – stars: individual: HD37424 – pulsars: individual: PSR J0538+2817 – ISM: individual objects: SNR G180.0-1.7 (S147) – ISM: supernova remnants.

1 INTRODUCTION
High space velocities of OB runaway stars are explained by two independent mechanisms: dynamical ejection due to gravitational interactions of massive stars in cluster cores (Poveda, Ruiz & Allen 1967) and binary disruption as a result of a supernova (SN) explosion of the initially more massive component (Blaauw 1961). Both scenarios are viable, but whether one of the mechanisms is dominant is still uncertain. According to the virial theorem, through a symmetric SN explosion in a binary system, if more than half of the total mass of the system is released, then the new born neutron star (or black hole) and the non-degenerate component are no more gravitationally bound (Blaauw 1961). However, the energy stored in the orbit, in most cases, is not sufficient to produce the neutron star (NS) kick velocities that are typically in the range of 300–500 km s$^{-1}$ (Lyne & Lorimer 1994; Allakhverdiev et al. 1997; Hansen & Phinney 1997; Hobbs et al. 2005). The asymmetry in SN explosions is responsible for such high velocities (Wongwathanarat, Janka & Müller 2013). Therefore, there are no pulsar companions to many of the OB runaway stars (Sayer, Nice & Kaspi 1996). 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). The runaway high-mass X-ray binaries like 4U1700-37 (Ankay et al. 2001) and Vela X–1 (Kaper et al. 1997) are such examples. Yet, the low rate of X-ray binaries and the high rate of isolated NSs by taking into consideration the selection effects, the binary disruption is likely to occur in most cases (Guseinov, Ankay & Tagieva 2005, hereafter G05). The kinematics of the binary disruption due to an asymmetric SN explosion is widely discussed in Tauris & Takens (1998). However, a sample of observationally confirmed OB runaway–NS couples is needed for a better understanding of the problem.

The importance of searching for OB runaways inside supernova remnants (SNRs) was first mentioned in van den Bergh (1980). However, the kinematical study of known OB stars inside SNRs was concluded with a lack of OB runaways due to the poor sample of SNRs and OB stars. Still, there is no known O- or B-type runaway star that can be directly linked to an SNR given in the literature.

In G05, the outcome of exploring runaway pairs from binary SN disruption is broadly discussed. First, identifying the explosion centres more precisely will be useful for determining the velocities of young NSs of which proper motion (pm) measurements have high uncertainties. Thus, thekick that is gained by the NS due to the asymmetry of the SN can be determined more precisely. Secondly,
the distance to the remnant can be measured more accurately by studying the runaway star, as it cannot move far away from the explosion centre in the observational lifetime of the SNR. Finally, possible effects of a close binary system on the asymmetry of the SNr can also be examined. Additionally, it would be a direct evidence of the binary SN scenario (BSS).

The observational efforts are concentrated on runaway–NS coupling and abundance investigations of runaway stars. Some examples of the runaway–NS pairs (components are separated) are PSR B1929+10 – ζ Oph (Hoogerwerf, de Bruijne & de Zeeuw 2001; Bobylev 2008; Tetzlaff et al. 2010), PSR J0630–2834 – HIP 47155 (Tetzlaff et al. 2013) and PSR J0826+2637 – HIP 13962 (Tetzlaff et al. 2014). Based on their motions in space, the pulsars and the corresponding runaway stars were traced back in time by using 3D Monte Carlo simulations. They were found at the same position and the same time inside a young open cluster. The PSR J0630–2834 – HIP 47155 pair is thought to be ejected from very old SNR Antlia.

There are considerable uncertainties in these cases as the SN events took place more than 10^7 yr ago. The separation between the objects is very large and the SNR has faded away long ago and/or the components are outside of the SNR (the Antlia case). Other important observational evidence is the enhancement of α-process elements in the hypervelocity star HD 271791. The star is proposed to be ejected from a massive close binary system due to an SN that enriches its photosphere in elements which can be synthesized in large amounts during the evolution of the progenitor (Przybilla et al. 2008).

The method followed in our work is a direct study of possible runaway stars inside SNRs as described in G05.

Briefly, assuming that the massive binary mass ratio is greater than 1:4, OB-type star candidates are determined by a careful study of their BVJHK magnitudes obtained from the UCAC4 catalogue (Zacharias et al. 2013). The angular separation of the sources from the geometrical centres (GCs) of the remnants are within the limits of the maximum angular distance that a runaway star can have in a lifetime of an SNR. The distance moduli are calculated for all sources within this region, and the sources having extinctions and radial distances consistent with those of the SNRs are considered as ‘candidates’. Measuring the radial velocities (RV) and identifying the spectral types of these objects via spectroscopy reveal their runaway nature, their youth and the exact spatial relations with the SNRs, in other words, the genetic connections.

Although the runaway stars arising from BSS may also be late-type stars, it is time consuming to check the possible runaway nature of all the stars inside each SNR. Also, the late-type stars are too faint to observe at large distances. A star having the same age as an SN progenitor must be young. As OB-type stars evolve faster, they automatically satisfy this condition. Furthermore, high-mass stars are rare objects. An OB runaway star discovered inside an SNR can be explained by the BSS. Considering the very short observable lifetimes of SNRs and relatively short later evolution stages of stars, most probably, main-sequence stars are expected as OB runaways connected to SNRs.

The space velocity of an OB runaway star is thought to be larger than 30–40 km s\(^{-1}\) (Feast & Shuttleworth 1965; Sayer et al. 1996). A more precise value is proposed in Tetzlaff, Neuhaüser & Hohle (2011a): 28 km s\(^{-1}\) in 3D and 20 km s\(^{-1}\) in 2D. To summarize, a main-sequence OB-type star of which at least one component of the velocity vector is greater than 20 km s\(^{-1}\) is searched in selected SNRs.

The first criterion of the candidate selection is the restriction of the angular position. Most of the OB runaways have peculiar velocities lower than 80 km s\(^{-1}\) (Gies & Bolton 1986; Philip et al. 1996; Tetzlaff et al. 2011a). As the shock wave velocity of the SNRs are decelerated from roughly 10 000 km s\(^{-1}\) to several hundred km s\(^{-1}\), it is expected that the runaway star cannot exceed one tenth of the angular diameter (θ) of the related SNR. This value is somewhat relaxed to 6/θ considering the uncertainties in the GCs of the SNRs. The stars in this region are expected to be consistent with the respective SNR in terms of distance and reddening.

For this comparison, the adopted distances of SNRs given in Guseinov, Ankay & Tagieva (2003b, 2004b,c), and \(A_V\) values from Neckel, Klare & Sarcander (1980) were used. 48 SNRs within 5 kpc from the Sun were selected for investigation.

In this paper, the result of the runaway search in SNR G180.0−1.7 (S147) is given. The kinematic relation between the runaway star HD 37424 and the pulsar PSR J0538+2817 is shown, the possible host OB association is discussed, the SNR parameters are constrained and the pre-SN binary is constructed.

2 S147, PSR J0538+2817 and HD 37424

S147 is a shell-type SNR located in the Galactic anticentre direction. It is 180 arcmin in diameter with a GC at \(α = 05°39′00″, δ = +27°50′00″\) (Green 2009). It was first mentioned as an SNR candidate in Minkowski (1958). The compact object related to the SNR is radio pulsar PSR J0538+2817 (Anderson et al. 1996). In optical bands, the shell structure is well defined and dominated by filamentary emission in Hz. The emission is brighter in the north and south edges and mainly concentrated in the southern parts. Despite of its old age, it conserves the spherical symmetry except for the blowout regions in east and west (Fig. 1). The total absorption in the \(V\) band is \(A_V = 0.7 \pm 0.2\) mag (Fesen, Blair & Kirshner 1985). Radio observations reveal that the spectral index is unusually varying. The shell structure observed at radio wavelengths coincides with that in optical bands and is well defined (Fuerst & Reich 1986). But, no X-ray emission is observed from the remnant (Sauvageot, Ballet & Rothenflug 1990). Suggested distances vary from 0.6 to 1.9 kpc in various publications (Table 1). Four of the measurements are based on \(Σ−D\) relation which is useful to estimate the distance by using the surface brightness of the SNR. In Sofue, Furst & Hirth (1980) and Kundu et al. (1980), the model of Milne (1979) is used, while in Clark & Caswell (1976) and Guseinov et al. (2003a), estimations are based on their own models. The radius lower limit calculated through SNR dynamics based on the model of Chevalier (1974) sets another constraint on the SNR distance. The distance derived from the pulsar’s parallax or dispersion measure (DM) is larger than the distance suggested for the background stars of which spectra show high-velocity gas related to the SN.

The age was estimated as more than 100 kyr from the Sedov solution by using a shock velocity \(\sim 80–100\) km s\(^{-1}\) (Kundu et al. 1980; Sofue et al. 1980). This velocity was derived from the RV of the filamentary knots in Lozinskaya (1976) and Kirshner & Arnold (1979). However, the pulsar–SNR relation indicates an age of 30 ± 4 kyr (from the travel time from the GC to the present position; Kramer et al. 2003; Ng et al. 2007). For a distance of 1.3 kpc, and an angular diameter of 200 arcmin, the radius (\(R\)) of the SNR is 38 pc. Then, assuming an age of 30 kyr, the remnant is in its Sedov Phase having a blast wave velocity of 500 km s\(^{-1}\). The estimated explosion energy is between 1 and \(3 \times 10^{51}\) erg and the corresponding intercloud gas density is 0.03–1 cm\(^{-3}\) (Katsuta et al. 2012). The SNR is
expanding in a low-density medium, probably in the cavity generated by the progenitor.

The central source, PSR J0538+2817, is an extensively studied radio and X-ray pulsar located at $\alpha = 05^h38^{m}33^{s}$, $\delta = +28^\circ17'09'$.2, $\sim 28$ arcmin away from the GC towards north. The 143.16 ms period and $3.67 \times 10^{-13}$ s$^{-1}$ period derivative (Anderson et al. 1996) imply a characteristic age of $\sim 620$ kyr which is $\sim 20$ times larger than its kinematic age of 30 kyr. This discrepancy is explained by either a long initial spin period of $P_0 = 139$ ms (Kramer et al. 2003) or strong magnetic field decay (Guseinov, Ankay & Tagieva 2004a). The parallax distance was measured as $1.47^{+0.23}_{-0.27}$ kpc (Ng et al. 2007) and the DM distance is $1.2$ kpc (Chatterjee et al. 2009) and the NE2001 model of Cordes & Lazio (2002) which are consistent with each other. The most precisely measured pm is $\mu = -23.57^{+0.10}_{-0.10}$ mas yr$^{-1}$, $\mu = 52.87^{+0.09}_{-0.10}$ mas yr$^{-1}$ corresponding to a transverse velocity of $357^{+59}_{-54}$ km s$^{-1}$ at $1.3^{+0.22}_{-0.16}$ kpc (Chatterjee et al. 2009). Although it presents no clear $\gamma$-ray emission (Katsuta et al. 2012), the pulsar is observable in soft X-rays due to thermal emission. PSR J0538+2817 is famous for being one of the few thermal pulsars: Based on a blackbody model, the surface temperature and the emitting radius are given as $T = 2.12 \times 10^6$ K and $R = 1.68 \pm 0.05$ km (McGowan et al. 2003). The hydrogen atmosphere model with $B = 1 \times 10^{12}$ G gives $T = 2.12 \times 10^6$ K and $R \approx 10$ km (Zavlin & Pavlov 2004). A faint pulsar wind nebula is observed in X-rays but not in radio (Gaensler et al. 2000). It is not known whether the observed elongated structure is the torus or the jets of the pulsar wind nebula. But assuming that it is due to the torus, it provides valuable information on the spin–kick alignment.

HD 37424 is a sound OB runaway star at 10.3 arcmin away from the GC to the west at $\alpha = 05^h39^{m}44^{s}$, $\delta = +27^\circ46'51'$.2. Photometric and kinematic information on the star is given in Table 2. While pm values were retrieved from the UCAC4 catalogue (Zacharias et al. 2013), the photometric magnitudes are obtained from the ASCC-2.5V3 catalogue (Kharchenko 2001). Its spectral type was previously identified as B0.5/I IV/V (Clausen & Jensen 1979). As there were no public data nor a visualized

Table 1. Distance estimates for S147. ($R^*$) denotes the radius lower limit of the SNR.

| Distance ( kpc) | Method | Reference |
|----------------|--------|-----------|
| 1.6 ± 0.3      | $\Sigma-D$ | Sofue et al. (1980) |
| 0.8−1.37       | $R^*$, $\Sigma-D$ | Kundu et al. (1980) |
| 0.6            | $R^*$ | Kirshner & Arnold (1979) |
| 0.9            | $\Sigma-D$ | Clark & Caswell (1976) |
| 0.8 ± 0.1      | $V_\alpha$ | Fesen et al. (1985) |
| 1.06           | $\Sigma-D$ | Guseinov et al. (2003a) |
| 0.88<          | High-Vel Gas | Sallmen & Welsh (2004) |
| 1.2            | Pulsar DM | Kramer et al. (2003) |
| 1.47$^{+0.42}_{-0.27}$ | Pulsar Plx | Ng et al. (2007) |
| 1.3$^{+0.16}_{-0.16}$ | Pulsar Plx | Chatterjee et al. (2009) |

Table 2. BVHK (in mag) and pm (in mas yr$^{-1}$) values of HD 37424.

| Parameter | Value |
|----------|-------|
| $B$      | 9.062 $\pm$ 0.017 |
| $V$      | 8.989 $\pm$ 0.019 |
| $J$      | 8.666 $\pm$ 0.017 |
| $H$      | 8.696 $\pm$ 0.026 |
| $K$      | 8.699 $\pm$ 0.019 |
| $\mu_\alpha$ | 10.8 $\pm$ 0.8 |
| $\mu_\delta$ | $-10.2$ $\pm$ 0.6 |
spectrum, we established the spectral type again by taking a spectrum. The star has a very high pm compared to other early-type and possibly distant stars. There is no reported variability or bina-

rity in the literature. Hence, HD 37424 is a good OB runaway star candidate.

3 OBSERVATIONS

HD 37424 was observed at the TÜBİTAK National Observatory (TUG) with the TUG Faint Object Spectrograph and Camera (TFOSC) mounted on the 150 cm Russian Turkish Telescope (RTT–150). The observations were carried out on 2013 August 9 and 10. Two spectra were obtained with a 600-s exposure time for each. Grism 14 was used with a 67 μm slit. The wavelength range in this configuration is 3270–6120 Å and the resolving power (R) is ~1337. Five He lamp spectra taken in the same night with the object were used for wavelength calibration, and five halogen lamp spectra were obtained in the beginning and at the end of the night for flat-fielding. Also, two more targets had been observed in the same way on 2012 September 13 and 14 for the search for the runaway star. With the same purpose, 12 objects were observed at the Calar Alto Observatory on 2013 January 29 with Calar Alto Faint Object Spectrograph (CAFOS) on the 2.2 m telescope. The covered wavelength range of the grism B–200 is 3200–7000 Å and R ~ 550. Three HgCdAr and three halogen spectra were taken in the beginning and in the end of the night for wavelength calibration and flat-fielding. The high-resolution observations of HD 37424 were performed at the Fred L. Whipple Observatory on 2013 September 16 and 21. The Tillinghast Reflector Echelle Spectrograph (TRES) mounted on the 1.5 m telescope was used. Two spectra were taken at R ~ 44 000 in a broad wavelength range: 3800–9100 Å for 300 s exposure time. HD 36665 which is supposed to be a background object to the SNR was observed on 2014 February 11 with the Fibre Linked Echelle Astronomical Spectrograph (FLECHAS; Mugrauer, Avila & Guirao 2014) at the University Observatory Jena. The covered wavelength range is 3900–8100 Å and R ~ 9200. Three spectra with 600 s exposure time were obtained. Three tungsten and three Th–Ar lamp spectra were taken immediately before this set for flat-fielding and wavelength calibration.

The observations of SNR S147 were performed at the University Observatory Jena with the Schmidt-Teleskop-Kamera (STK), operated in the Schmidt-focus of the 90 cm telescope of the observatory (see Mugrauer & Berthold 2010). The observations were carried out with the narrow-band Hα filter of the STK, which spans a full width at half-maximum of 5 nm. In total, 22 fields on the sky were observed during five nights, each with a field of view of 52.8 arcmin × 52.8 arcmin. At each position two 600 s integrations were taken with the STK, i.e. about 7.3 h of integration time in total. The individual raw images per field were dark- and flat-field-corrected and finally averaged. Point sources detected in the overlap regions of the fully processed images were then used to create the mosaic image of SNR S147, shown in Fig. 1, which covers a total field of view of 4.8 × 4.1.

FLECHAS, TFOSC and CAFOS data were reduced with IRAF. All raw frames from TFOSC and CAFOS were overscan stripped and no further subtraction was done as long as the overscaned dark frames yields null count. Yet, FLECHAS images were subtracted by the dark frames taken in the previous night. The exposure time of a dark frame is the same as that of the corresponding science or calibration frame. Hence, the illumination effect was removed.

Then, the flat images were combined while rejecting the frames having minimum and maximum counts. Next, the object spectra were extracted by assigning an appropriate background region to each. The arc spectra were extracted as traced by the corresponding aperture of the object spectra. After wavelength calibration was performed, all spectra were normalized.

The final spectra were compared with Morgan-Keenan standard star spectra retrieved from Walborn & Fitzpatrick (1990). To maintain equally resolved spectra, the standard spectra were boxcar smoothed by 13. Fig. 2 shows the TFOSC spectrum of HD 37424 comparing with main-sequence B-type stars from various subclasses. HD 37424 shows He λ 4086 absorption indicating that the spectral type is earlier than B1. This feature is not seen in stars with a spectral type later than B0.7. On the other hand, He i lines (i.e. He i 4713) are not as weak as in O-type stars compared to He ii lines: λλ 4200, 4686. The Si iv λ 4116 line is totally blended and unmeasurable. Si iii λ 4352 is in low strength compared to Si iv λ 4089 like in the B0V type spectrum. This ratio decreases towards higher temperatures, but He i λ 4441 is not stronger than Si iii λ 4352 as seen in B0V and O9.5V spectra. Given the equal strengths of O ii λ 4640, He ii λ 4686, He i λ 4713 and more intense C iii+O ii λ 4650 blends, HD 37424 matches best with B0.2V. Considering the slightly stronger He i λ 4713, B0.5 would be the best approach to the temperature class of the star. Si iv λ 4089 strength increases against He i λ 4426–4446 as the luminosity class goes higher. However, neutral helium lines are strong enough to judge that HD 37424 is a main-sequence star; B0.5V. The spectral type is between B0.2V–B0.7V, but it is assumed as B0.5 ± 0.5V in the distance and extinction calculations to avoid underestimation of the errors.

The sources observed by CAFOS are foreground stars with a maximum distance of 671 ± 56 pc. Their spectral properties were identified by the same procedure as done for HD 37424. However, due to the lower resolution CAFOS spectra have higher uncertainty (Table 3). We used FLECHAS to identify the spectral types of the background star HD 36665. This is a B1 ± 0.5V type star (Fig. 3). TRES data were used for RV measurements of HD 37424. Due to the low signal to noise, 10 absorption features could be used (Table 4). Doublets or triplet lines are avoided as these features increased the dispersion significantly. The lines were fitted by
Table 3. Observed stars in the region. Names, angular separations to the SNR GC (in arcmin), spectral types, instruments used and distances with upper and lower errors (in pc) are given. The error in temperature subclasses is ± 1 for those with integer value and ± 0.5 for those with half integer value. The resolution of CAFOS is not enough to distinguish the luminosity classes IV and V. Yet, the stars are assumed to be in luminosity class V.

| Name                  | Angular separation | Spec. type | Inst. | Distance (error) |
|-----------------------|--------------------|------------|-------|------------------|
| TYC 1869-01281-1      | 19.4               | A2V        | C     | 574              |
| TYC 1869-01317-1      | 5.5                | B9.5V      | T     | 1013             |
| TYC 1869-01334-1      | 25.5               | F2V        | C     | 289              |
| TYC 1869-01376-1      | 27.9               | A7V        | C     | 428              |
| TYC 1869-01505-1      | 23.5               | F1V        | C     | 380              |
| TYC 1869-01610-1      | 17.6               | F7V        | C     | 245              |
| TYC 1869-01632-1      | 27.2               | F8V        | C     | 316              |
| TYC 1869-01642-1      | 5.61               | B9.5V      | T     | 952              |
| TYC 1869-01679-1      | 25.6               | G2V        | C     | 170              |
| TYC 1869-01749-1      | 20.1               | F8V        | C     | 166              |
| TYC 1873-00145-1      | 25.0               | A3V        | C     | 603              |
| TYC 1873-00307-1      | 29.2               | F8V        | C     | 326              |
| TYC 1873-00347-1      | 19.8               | A0V        | C     | 671              |
| UCAC4-589-020390      | 22.1               | F4V        | C     | 381              |

Note: *Instruments: C: CAFOS, T: TFOSC.

Table 4. RV measurements of HD 37424. The laboratory wavelength of the features, the Gaussian width (σ) of the fit, the wavelength shift obtained by the best-fitting Gaussian, upper and lower limits of the shift from different Gaussian fits and the final error are presented. The features are given in Å while all other columns are in km s⁻¹.

| Feature       | σ   | BF | UL  | LL  | E   |
|---------------|-----|----|-----|-----|-----|
| 3889.051      | 164 | −10.1 | 19.3 | −29.2 | 29.4 |
| 3970.074      | 137 | −0.5  | 21.4 | −22.3 | 21.9 |
| 4101.737      | 144 | −9.4  | 12.2 | −32.3 | 22.9 |
| 4143.759      | 98  | +0.4  | 17.1 | −10.9 | 14.9 |
| 4340.468      | 142 | −10.6 | 6.2  | −28.8 | 18.2 |
| 4387.928      | 81  | −13.1 | −7.1 | −24.1 | 11   |
| 4681.332      | 139 | −13.8 | 0.9  | −18.9 | 14.7 |
| 4921.299      | 89  | −16.5 | −1.6 | −32.4 | 15.9 |
| 6562.817      | 115 | −14.7 | 0.3  | −21.5 | 15   |
| 6678.149      | 82  | −7.5  | 0.3  | −14.5 | 7.8  |

Table 5. RV measurements of HD 37424. The laboratory wavelength of the features, the Gaussian width (σ) of the fit, the wavelength shift obtained by the best-fitting Gaussian, upper and lower limits of the shift from different Gaussian fits and the final error are presented. The features are given in Å while all other columns are in km s⁻¹.

| Feature       | σ   | BF | UL  | LL  | E   |
|---------------|-----|----|-----|-----|-----|
| 3889.051      | 164 | −12.6 | 6.2  | −28.2 | 18.8 |
| 3970.074      | 137 | −1.4  | 18.0 | −19.8 | 19.4 |
| 4101.737      | 144 | −5.1  | 14.9 | −21.2 | 20   |
| 4143.759      | 98  | −1.9  | 7.2  | −8.7  | 9.1  |
| 4340.468      | 142 | −11.5 | 11.9 | −36.6 | 25.1 |
| 4387.928      | 81  | −8.8  | 4.1  | −19.3 | 10.5 |
| 4681.332      | 139 | −11.7 | −3.0 | −19.5 | 8.7  |
| 4921.299      | 89  | −17.2 | −4.9 | −31.6 | 14.4 |
| 6562.817      | 115 | −14.4 | 1.4  | −29.7 | 15.8 |
| 6678.149      | 82  | −6.7  | 3.3  | −15.1 | 10   |

Notes: BF: Best fit, UL: Upper Limit, LL: Lower Limit, E: Error

Figure 3. The FLECHAS spectrum of HD 36665 (black) in comparison with a B1V template.

Gaussian functions and the best shifts were determined. Two more Gaussian fits with different centres were applied for each line; one fits the outer edge of the noise of the blue side while fitting the inner edge of the red. The other fits the outer edge of the red and the inner edge of the blue. By doing this, underestimating the errors is avoided. As the features are wide and the data are noisy, the centres of these secondary fits are far away from the best fits, 16 km s⁻¹ on average. The difference between the best fit and the upper limit (towards red) fit is distinct from the best fit and the lower limit (towards blue) difference. To avoid underestimating the error, the greater difference is assigned as the final error. The average heliocentric velocities of the first and the second spectra are −9.2 and −9.1 km s⁻¹ with line to line scattering standard deviations being 6.5 and 5.5 km s⁻¹, respectively.

As long as the star is inside the SNR, high-velocity gas accelerated by the SNR is expected to reveal itself as blueshifted components to Ca ii-K and H and/or Na i-D1 and D2 absorption features. The spectra show no clear high-velocity features (Fig. 4). The average heliocentric velocity of the interstellar gas is 12.1 ± 0.5 km s⁻¹.

(Figure 3). This is typical for the neighbouring stars (Silk & Wallerstein 1973). The star has no positional correspondence with bright filaments, but with fainter Hα emitting regions. It is located at the vicinity of the eastern cavity seen in the radio and γ-ray images...
The strong interstellar lines of HD37424. Left: Ca ii-K line from TRES spectrum. Despite a weak blended feature at \(-13\) km s\(^{-1}\), there is no clear high-velocity component. Middle: Ca ii-H line (He I as a background) from the same spectrum. Again there is no clear high-velocity gas component. Right: interstellar Na D1 and D2 lines. The feature with high FWHM is the He I \(\lambda 5875\) triplet. Those around sodium doublet are tellurics.

Table 5. Measured velocities for interstellar Ca ii-K and H and Na D1 and D2 lines. These lines have a low Gaussian width unlike the intrinsic features of the star. The average velocity is 12.1 km s\(^{-1}\) with a standard deviation 0.5 km s\(^{-1}\) in each observation. The data in the first column are in (Å) while the others are in km s\(^{-1}\).

| Feature | \(\sigma\) | Velocity (Day 1) | Velocity (Day 2) |
|---------|----------|-----------------|-----------------|
| 3933.664 | 7.5      | 12.3            | 11.8            |
| 3968.47  | 5.9      | 12.8            | 12.7            |
| 5889.953 | 9.0      | 11.6            | 11.6            |
| 5895.923 | 8.3      | 11.9            | 12.0            |

Note. Day 1: 2013 Sep. 16; Day 2: 2013 Sep 21.

(Kundu et al. 1980; Katsuta et al. 2012). As the star can hardly be a foreground source, we suggest that, in this direction, the shocked ejecta has not reached the dense interstellar gas yet. The reader must note that, the background stars displaying high-velocity Ca ii lines in Sallmen & Welsh (2004) are located behind bright filament knots. The high-velocity gas is found where the filaments are concentrated (Lozinskaya 1976).

Using the absolute visual magnitude from Aller et al. (1982), for a spectral type B0.5V \(\pm\) 0.5, the distance modulus yields 1868 \(\pm\) 57.2 pc for HD 37424. Using the luminosity of the same spectral type from Hohle, Neuhäuser & Schütz (2010), we find the distance as 1318 \(\pm\) 119 pc which is well consistent with the distance of the pulsar. The total visual absorption was taken into account in both calculations.

As the absolute magnitudes for early-type stars can range from star to star in the same temperature, interstellar Ca ii lines are also used in distance determination. By using the following relation from Megier et al. (2009),

\[
D = 77 + \left( 2.78 + \frac{2.60}{\text{EW}(\text{H})} - 0.932 \right) \text{EW(H)},
\]

the distance to HD 37424 is found to be 1288 \(\pm\) 304 pc which is almost in the same range as the pulsar. The equivalent widths (EWs) are 243 \(\pm\) 7 and 160 \(\pm\) 15 m Å for Ca ii-K and Ca ii-H lines, respectively. The extinction towards the star was also derived from 4430 and 4502 Å DIBs. The measured EWs have high error due to the blending. Using the EWs, the \(E(B - V)\) was calculated based on the relation mentioned in Herbig (1975). It yields 0.42 \(\pm\) 0.08 mag; points to somewhat larger colour excess but does not exclude 0.35 \(\pm\) 0.04 mag derived from photometry.

4 KINEMATICS

HD 37424 and PSR J0538+2817 have pms receding from each other and departing from the same location on the sky (Fig. 1). The pm of both objects are corrected for Galactic rotation and solar motion. The Galactocentric distance to the Sun is taken as 8.5 kpc and the solar rotational velocity as 220 km s\(^{-1}\). The local standard of rest was taken from Tetzlaff et al. (2011a) as \((U_\odot, V_\odot, W_\odot) = (10.4 \pm 0.4, 11.6 \pm 0.2, 6.1 \pm 0.2) \text{ km s}^{-1}\).

The resultant values for HD 37424 are \(\mu_* = 10.0 \pm 0.8\) mas yr\(^{-1}\), \(\mu_\delta = -5.9 \pm 0.6\) mas yr\(^{-1}\) and for the pulsar, \(\mu_* = -24.4 \pm 0.1\) mas yr\(^{-1}\), \(\mu_\delta = 57.2 \pm 0.1\) mas yr\(^{-1}\). Together with the \(-20.0 \pm 6.5\) km s\(^{-1}\) peculiar RV, HD 37424 has a space velocity of 74 \(\pm\) 8 km s\(^{-1}\) at 1.3 kpc. HD 37424 is a runaway star of which velocity is higher than typical runaway velocities 40–50 km s\(^{-1}\). The 2D space velocity of the pulsar at the same distance is 382.2 \(\pm\) 0.8 km s\(^{-1}\).

We constructed the past 3D trajectories of PSR J0538+2817 and the runaway star HD 37424 to evaluate whether these two objects could have been at the same place at the same time in the past. Since we applied the same method already in preceding papers (Tetzlaff et al. 2010, 2011b, 2012), we refer to these publications for details. We construct three million past trajectories of PSR J0538+2817 and HD 37424 throughout Monte Carlo simulations by varying the observables (parallax, pm, RV) within their error intervals. For the RV of the NS, we assume a uniform distribution in the range of \(-500\) to \(+500\) km s\(^{-1}\). From all pairs of trajectories, we evaluate the smallest separation \(d_{\text{min}}\) and the past time \(\tau\) at which it occurred. The distribution of separations \(d_{\text{min}}\) is supposed to obey the distribution of absolute differences of two 3D Gaussians (see e. g. Hoogerwerf et al. 2001, equations A3 and A4; Tetzlaff et al. 2012, equations 1 and 2), if it is assumed that the stellar 3D positions are Gaussian distributed. Since the actual (observed) case is different from this simple model (no 3D Gaussian distributed positions, due to e. g. the Gaussian distributed parallax that goes into the position distribution (up to the peak plus a few more bins, see Tetzlaff et al.)
2012). The derived parameter \( \mu \) then gives the positional difference between the two objects.¹

We find that both stars were at the same position in the past, i.e. \( \mu = 0 \) at \((l, b) = (84.82 \pm 0.01, 27.84 \pm 0.01) \) deg at 30 \( \pm 4 \) kpc (Fig. 5). This predicted position of the SN is 4.2\(^{+0.8}_{-0.6}\) arcmin offset from the nominal geometric centre. The predicted distance of the SN (as it is seen from the Earth today) is 133\(^{+103}_{-112}\) pc.

### 5 ASSOCIATIONS

There is no known OB association within 4.5 (\( \sim 100 \) pc at 1300 pc) from SNR S147. Considering the angular separations and radial distances, the progenitor star cannot be linked to any of the young open cluster around. Hence, it is considered to be a runaway star ejected e.g. from the cluster NGC 1960, which is 217 pc away from the SNR, several million years ago (Ng et al. 2007). However, binarity among cluster ejected runaway stars are rare (Gies & Bolton 1986). So, as the progenitor was the previous binary companion to HD 37424, it may be unlikely that they were ejected from a cluster. Therefore, the neighbouring stars are investigated to search for any association. All of the OB-type stars within 4.5 (100 pc at 1.3 kpc distance) of the GC of the SNR were selected from The Catalogue of Stellar Spectral Classifications (Skiff 2013). The spectral types are known through spectroscopic observations. There are some discrepancies in spectral types reported by different papers. So, always the latest reference was chosen. Together with 14 stars from our observations at TUG and Calar Alto, 99 stars are used.

The photometric data were obtained from the catalogue ASCC-2.5 V3 (Kharchenko 2001) except for UCAC4–589–020390 of which photometric data were retrieved from the UCAC4 catalogue.

¹ The uncertainties on the separation are dominated by the kinematic uncertainties of the NS that are typically of the order of a few hundred km s\(^{-1}\) (because of the assumed RV distribution). As a consequence, the distribution of separations \( d_{\text{min}} \), shows a large tail for larger separations. However, the first part of the \( d_{\text{min}} \) distribution (slope and peak) can still be explained well with the theoretical curve (here equation 2 in Tetzlaff et al. 2012) since the kinematic dispersion for only those runs are much smaller, a few tens of km s\(^{-1}\) for the NS, i.e. a few tens of pc after 1 Myr.

For each star having an integer spectral subclass, distance and extinction are calculated in an interval between one spectral subclass above and below, e.g. B0V–B2V for a B1V-type star. For those having half integer subclass, half spectral subclass above and below are used e.g. B0V–B1V for a B0.5V-type star. The total visual extinction, \( A_V \), was determined by using BVHK colours and intrinsic colour differences of corresponding spectral types. Using the following relation, \( A_V \) values were derived for each colour difference: \( B - J, B - H, B - K, V - J, V - H, V - K \).

\[
A_V = \frac{(\lambda_1 - \lambda_2) - (\lambda_1 - \lambda_2)_0}{A_{\lambda_1}/A_V - A_{\lambda_2}/A_V}.
\]

The intrinsic colours are obtained from Kenyon & Hartmann (1995) and Wegner (1994), while \( A_{\lambda}/A_V \) ratios are from Rieke & Lebofsky (1985). Colour differences of short intervals, i.e. \( H - K \) have high errors as they are multiplied by higher coefficients. The colour excess \( E(B - V) \) is mentioned separately. (Table 6) \( A_V \) values obtained from six colour differences were averaged and their standard deviation were calculated. This was applied for all three possible spectral types of the source. As long as the error due to the spectral type uncertainty is larger than the standard deviation of the colour differences, it was assigned to be the final error. When the error is asymmetric due to the intrinsic colours of different spectral types, the larger one was accepted. In some cases, the uncertainty is dominated by the error in colour differences. Then, these were preferred to be the final error for such sources. \( E(B - V) \) versus \( A_V \) fit yields a total to selective absorption ratio is 3.24 \( \pm 0.06 \). In individual cases, \( E(B - V) \) deviates strongly from \( A_V \). However, the large sample reveals that the ratio of total to selective absorption has a usual value. The distances were derived from distance moduli using the absolute magnitudes from Aller et al. (1982). Errors in distances are due to the uncertainty in spectral type and the error in \( A_V \) were also taken into account.

The spectrophotometric distance alone is not enough due to the high dispersion in the brightness of OB-type stars (Wegner 2006, hereafter W06). Assuming that the stars beyond 1 kpc are within 100 pc from the SNR GC, the absolute visual magnitudes were calculated. Although the dispersion mentioned in W06 is high, 24 of the stars fit well in the comparison with the W06 values. Hence, we suggest that these stars are members of an OB association. (Tables 6, 7, 19 of them have similar pm values. The average pm in right ascension is \(-1.39 \) and \(-4.17 \) mas yr\(^{-1}\) in declination with 0.99 and 1.45 mas yr\(^{-1}\) standard deviation, respectively (Table 8). At 1.3 kpc, five of them are runaway stars exceeding 20 km s\(^{-1}\) 2D peculiar velocity. This is consistent with the general ratio of the runaway stars to the normal stars which is 10–30 per cent (Gies 1987).

### 6 DISCUSSION

The runaway nature of HD 37424 is clear. The chance projection of such a massive runaway star moving away from the GC of an SNR in the Galactic anticentre direction must be very low. In addition, combining with the central compact object after tracing back both objects at the same time shows that HD 37424 is clearly the pre-SN binary companion of the progenitor of SNR S147 and PSR J0538+2817. BSS is the favoured explanation for its runaway nature.

HD 37424 is a B0.5V-type star with a mass of \( \sim 13 \) M\(_{\odot}\) (Hohle et al. 2010). So, the progenitor of the pulsar must have a higher mass. Based on the lack of O-type stars in the field (see Table 6), we set an upper mass limit of 20–25 M\(_{\odot}\). It may even imply a
24 stars beyond 1 kpc are presented. Angular distances are given in degrees, distances in parsecs, extinctions and brightness in visual band in magnitudes. In the column: SpT adopted, the average spectral types that are used in distance calibrations are given.

| Ang. Sep. | Name               | SpT    | SpT (adopted) | $A_V$ (Err) | $E(B-V)$ (Err) | Distance (Err) | $V$ (Err) | Ref# |
|-----------|--------------------|--------|---------------|-------------|----------------|----------------|----------|------|
| 0.09      | TYC 1869-01317-1   | B9.5V  | B9.5V         | 0.83        | 0.1            | 0.26           | 0.090    | 1013 |
| 0.09      | TYC 1869-01642-1   | B9.5V  | B9.5V         | 1.00        | 0.1            | 0.3            | 0.090    | 952  |
| 0.17      | HD 37424           | B0.5V  | B0.5V         | 1.28        | 0.06           | 0.35           | 0.036    | 1868 |
| 0.52      | HD 36993           | B0.5iIV | B0.5iIV       | 1.35        | 0.06           | 0.39           | 0.028    | 1961 |
| 0.63      | HD 37318           | B0.5Ve | B0.5V         | 2.29        | 0.15           | 0.59           | 0.026    | 903  |
| 1.00      | BD+27 797          | B0.5Ve | B0.5V         | 2.50        | 0.62           | 0.094          | 1788     | +485 |
| 1.35      | HD 37696           | B0.5IVV| B0.5IV-V      | 1.12        | 0.06           | 0.29           | 0.023    | 1549 |
| 1.35      | BD+27 850          | B1.5Ve | B1.5V         | 1.31        | 0.04           | 0.35           | 0.056    | 1525 |
| 1.52      | HD 245770          | B0/IIIVe | B0/II-V       | 2.11        | 0.13           | 0.79           | 0.053    | 2595 |
| 1.76      | HD 36441           | B0.5iV | B1V           | 1.13        | 0.13           | 0.33           | 0.058    | 1153 |
| 1.97      | BD+26 943          | B2V    | B1.5V         | 1.41        | 0.14           | 0.37           | 0.040    | 1357 |
| 2.61      | HD 38010           | B1III  | B1III         | 1.29        | 0.11           | 0.22           | 0.028    | 967  |
| 2.98      | HD+30 938          | B3III  | B3III         | 1.44        | 0.04           | 0.45           | 0.030    | 1332 |
| 3.06      | Sh 2-242.1         | B0V    | B0V           | 2.17        | 0.13           | 0.78           | 0.056    | 2318 |
| 3.07      | HD 37366           | O9.5V  | O9.5V         | 1.22        | 0.06           | 0.35           | 0.016    | 1375 |
| 3.24      | BD+30 976          | B3III  | B3III         | 0.73        | 0.08           | 0.25           | 0.044    | 1523 |
| 3.45      | BD+25 989          | B1Vn   | B1V           | 1.59        | 0.13           | 0.43           | 0.082    | 1872 |
| 3.61      | BD+27 909          | B2III  | B2III         | 1.87        | 0.1           | 0.55           | 0.076    | 2063 |
| 4.05      | BD+31 1065         | B3III  | B3III         | 0.67        | 0.04           | 0.27           | 0.043    | 2304 |
| 4.07      | BD+31 1050         | B3III  | B3III         | 1.01        | 0.03           | 0.35           | 0.047    | 1791 |
| 4.09      | HD 38909           | B3III  | B3III         | 0.56        | 0.03           | 0.17           | 0.033    | 2057 |
| 4.28      | BD+31 1021         | B7V    | B7V           | 1.05        | 0.12           | 0.14           | 0.106    | 1007 |
| 4.46      | HD 40297           | B9.5hVb | B9.5hVb       | 1.07        | 0.13           | 0.25           | 0.015    | 1337 |

Notes: *Ref# 1: Clausen & Jensen (1979); 2: Steele, Negueruela & Clark (1999); 3: Wang & Gies (1998); 4: Cucchiara et al. (1976); 5: Hunter & Massey (1990); 6: Walborn (1971); 7: Bougie, Boulon & Pedoussaut (1961); 8: Christy (1977); 9: Morgan, Code & Whitford (1955); 10: Christy (1977); tw: this work.

twin binary. The Roche lobe radii calculated for 15, 20 and 25 M\(_\odot\) vary between 91 and 311 R\(_\odot\) which shows that the system might have an interacting binary. Hence, the progenitor star should be a naked helium star at the final stage of its evolution with a mass even as low as 2 M\(_\odot\) (van den Heuvel 1993; Woosley et al. 1995). However, how conservative the mass transfer was, will be understood after further observations. Assuming a circular orbit, pre-SN binary parameters are calculated for 2, 5, 10, 15, 20 and 25 M\(_\odot\) (Table 9) progenitor masses.

As discussed in the previous section, the OB stars around might be members of an unidentified old OB association of which all of the O-type stars underwent SN explosions. This also makes a plausible explanation for the low-density medium in which the SNR expands symmetrically. But, an ejection of the pre-SN system is also possible. A membership to an OB association or to a cluster is important also regarding the distance determination. In this work, the distance derived from pulsar parallax (1.3\,±\,0.2 kpc) is accepted as the most reliable estimation. Also, the distance to the star measured from interstellar lines is in the same range, 1288 \,±\, 100 (see Section 3). The spectrophotometric distance is much larger by using absolute magnitudes from Aller et al. (1982). Yet, by using typical luminosities for B0.5V type suggested in Hohle et al. (2010), it is 1318 \,±\, 119 pc. Hence, the distance to the star and the SNR can be assumed to be 1.3 kpc. However, the $A_V$ measured directly towards S147 is much lower than the $A_V$ towards the stars beyond 1 kpc. Furthermore, two stars, HD 36665 and HD 37318, show highly shifted interstellar Ca ii and Na i lines related to the SNR implying that these objects are background sources (Sallmen & Welsh 2004). Their distances based on the reported spectral types are closer to the Sun than HD 37424 is. HD 36665 has 837 \,±\, 245 pc for B1V type and HD 37318 is 903 \,±\, 228 pc far away adopting B0.5V. On the
It must have been an interacting binary.

\[ \frac{A}{RA} = 10 \pm \beta - 9 \pm 2.5 \]

\[ 0.01, 27.84, 1983 \]

for 2–25 M

\[ 448, \text{regions driven by this old association.} \]

\[ 6.5 \text{ km s}^{-1} \mu \text{pc and from spectrophotometry} \]

1318 (84.82 ± 0.01, 27.84 ± 0.01) deg at 30 ± 4 kyr in the past. The position of the explosion is 4.2\text{°} \pm 0.8 arcmin away from the GC. The distance of the SNR is found as 1333\pm112 pc. \( \alpha \) towards the SNR is 1.28 ± 0.06 mag.

Today's kinematics of the stars are well known, further detailed calculations should be done to find the true kick vectors of the pulsar and a possible spin–kick alignment.

There is no known OB association reported close to the SNR. 19 OB-type stars within 100 pc from the SNR GC have very similar 2D velocities with the five runaway stars including HD 37424. This might be an old OB association having no bright O-type stars. The low-density medium in which the SNR is expanding is probably due to the previous SNe and H II regions driven by this old association.

The progenitor was a massive star with a zero-age main sequence mass greater than 13 M\(_\odot\). Considering the lack of O-type stars in the field, a progenitor mass much larger than 20 M\(_\odot\) is not expected. Assuming a circular orbit, the pre-SN binary separation is in the range of 8–711 R\(_\odot\) for 2–25 M\(_\odot\) final mass of the progenitor. The corresponding Roche lobe radii for 15–25 M\(_\odot\) masses vary from 91 to 311 R\(_\odot\). It must have been an interacting binary.

For 1.3 kpc distance and 1.3 mag extinction, the SN which happened 30 ± 4 kyr ago had an apparent brightness of −2.1 to −9.1 mag.

The source will be investigated regarding the elemental signatures of binary accretion and the possible SN debris on its photosphere through high-resolution and high-S/N spectra.

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### Table 8

| Name             | \( \mu_\alpha^* \) | err | \( \mu_\delta \) | err | \( V_{\text{REL}} \) | max | min |
|------------------|-------------------|-----|----------------|-----|-------------------|-----|-----|
| HD 37318         | −0.8              | 0.6 | −5.9           | 0.6 | 11.2              | 16.1| 6.9 |
| TYC 1869-01642-1 | −1.5              | 1.1 | −2.4           | 1.2 | 11.0              | 19.8| 7.1 |
| HD 38010         | −1.7              | 1.0 | −3.3           | 1.0 | 5.7               | 14.1| 0.0 |
| BD+30 976        | −3.5              | 0.9 | −5.3           | 0.5 | 14.7              | 21.1| 8.4 |
| BD+31 1021       | −2.8              | 0.7 | −5.5           | 0.8 | 11.9              | 18.4| 5.4 |
| TYC 1869-01317-1 | −0.9              | 0.9 | −5.1           | 0.9 | 6.5               | 14.2| 0.0 |
| HD 36441         | −2.0              | 0.6 | −6.6           | 0.6 | 15.4              | 20.1| 11.2|
| BD+30 938        | −1.7              | 0.8 | −3.6           | 0.6 | 4.0               | 9.9  | 0.0 |
| HD 40297         | −1.4              | 1.0 | −3.7           | 1.0 | 2.9               | 11.0| 0.0 |
| BD+26 943        | −0.9              | 0.8 | −3.7           | 0.8 | 4.2               | 11.2| 0.0 |
| BD+30 987        | −2.0              | 0.6 | −4.7           | 1.2 | 4.9               | 13.0| 0.0 |
| BD+27 797        | −0.1              | 0.7 | −3.1           | 1.4 | 10.4              | 19.6| 4.2 |
| BD+31 1050       | −1.0              | 0.6 | −4.0           | 0.6 | 2.7               | 7.8  | 0.0 |
| BD+25 989        | −1.5              | 0.9 | −2.5           | 1.6 | 10.3              | 21.1| 4.9 |
| HD 36993         | −0.2              | 0.9 | −5.8           | 0.6 | 12.4              | 18.8| 6.6 |
| HD 38909         | +0.7              | 0.5 | −4.2           | 1.5 | 12.9              | 18.4| 0.0 |
| BD+31 1065       | −1.0              | 0.6 | −1.3           | 0.5 | 17.9              | 21.7| 14.7|
| Sh 2-242 1       | −0.1              | 0.7 | −1.8           | 1.0 | 16.7              | 24.2| 9.2 |
| HD 245770        | −2.0              | 0.5 | −4.3           | 1.1 | 3.8               | 10.2| 0.0 |

### Table 9

| Progenitor mass (M\(_\odot\)) | 2    | 5    | 10   | 15   | 20   | 25   |
|-----------------------------|------|------|------|------|------|------|
| Binary separation (R\(_\odot\)) | 9.1±1| 49.9±9| 152.26±33| 281.49±48| 425.75±101| 576.101±137|
| Orbital velocity (km s\(^{-1}\)) | 481±49| 192±20| 96±10| 64±7| 48±5| 38±4|
| Orbital period (d) | 0.85±0.22| 9.2±4| 45.11±17| 103.26±39| 176.66±46| 259.65±98|
| Roche lobe radius (R\(_\odot\)) | 110±31| 277±19| 177±42| 251±60|      |      |
