Runaway Stars in Supernova Remnants

Anna Pannicke[1,2], Baha Dinçel[2], Ralph Neuhäuser[1]
[1]Astrophysical Institute and University Observatory Jena, Germany
[2]Abastumani Astrophysical Observatory, Ilia State University, Georgia
[3]Dr. Karl Remeis-Observatory, Bamberg, Germany

Motivation

The majority of massive stars is part of a multiple system. After the core collapse supernova (SN) of the more massive component the formed neutron star is ejected by the SN kick whereas the companion star either remains within the system and is gravitationally bounded to the neutron star, or is ejected with a spatial velocity comparable to its former orbital velocity (up to 500 $\mathrm{km s^{-1}}$). Such stars with a large peculiar space velocity are called **runaway stars**.

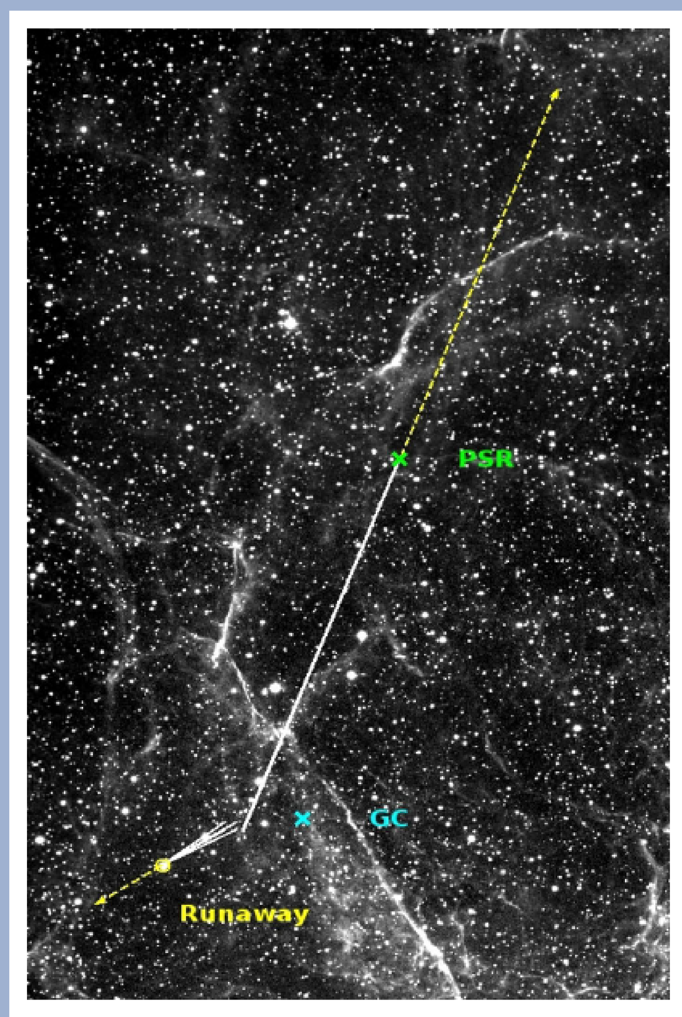

Fig.1: The NS-runaway pair in the SNR S 147 (Dinçel et al. 2015).

We deal with the second scenario. A recent discovery in our working group of an OB runaway star inside SNR S 147 has been published (Dinçel [2]).
In the given project we focus not only on OB runaways but also on low mass stars. Here we discuss our initial observational results on Cygnus Loop and the Crab SNR.

Crab SNR

The SNR lies at a distance of 2 kpc (via μ and RV), with an apparent size of 7 x 5 arcmin. It contains the PSR B0531+21 with known period of 0.033 s and proper motion ($\mu_\alpha^{*} = -14.7 \pm 0.8$ mas $\mathrm{yr^{-1}}$, $\mu_\delta = 2.0 \pm 0.8$ mas $\mathrm{yr^{-1}}$).

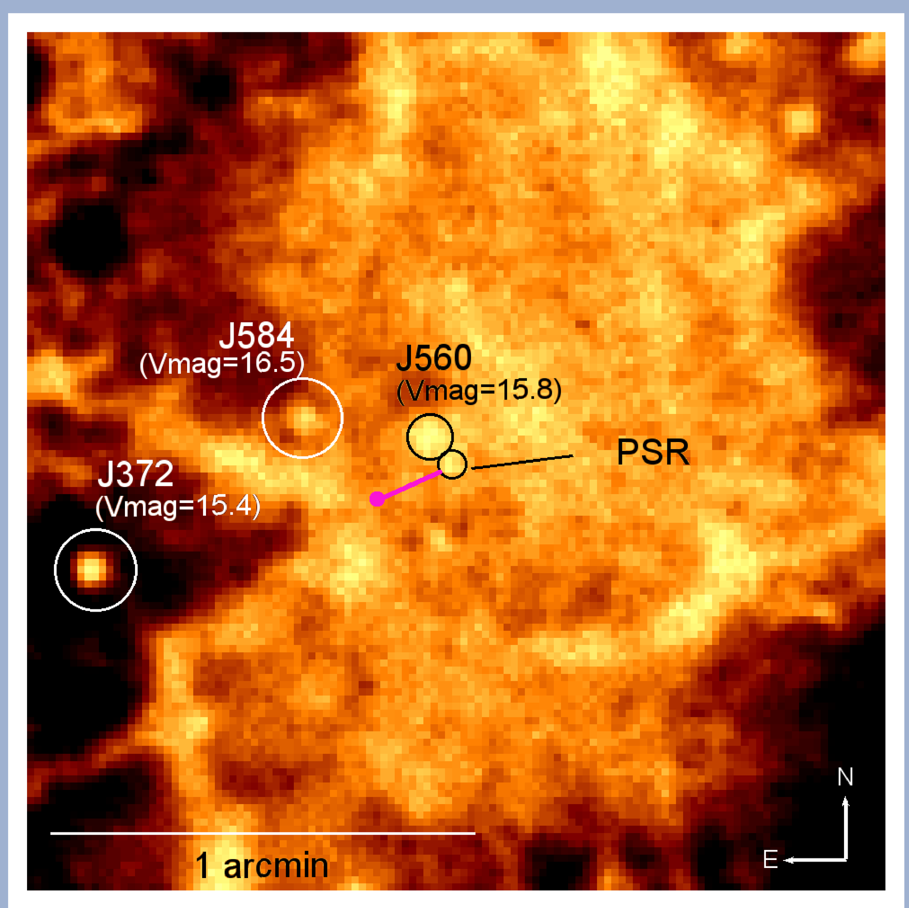

Fig.2: Observed targets of the Crab SNR. The angular distances from the center of explosion correspond to 9.7" (J560), 14.6" (J584) and 42" (J372) respectively. This correlates to expected runaway velocities of 120 $\mathrm{kms^{-1}}$, 180 $\mathrm{kms^{-1}}$ and 520 $\mathrm{kms^{-1}}$ which are consistent with the established runaway values[4](ESO DSS red image).

Cygnus Loop SNR

A large and nearby SNR (size = 230 x 160 arcmin, d = 0.44 kpc)with several compact X-ray and radio sources. Either it is a single SNR with a blow-out region or consists of two interacting SNRs. We emphasize the latter scenario and observed 25 runaway candidates in both bubbles.

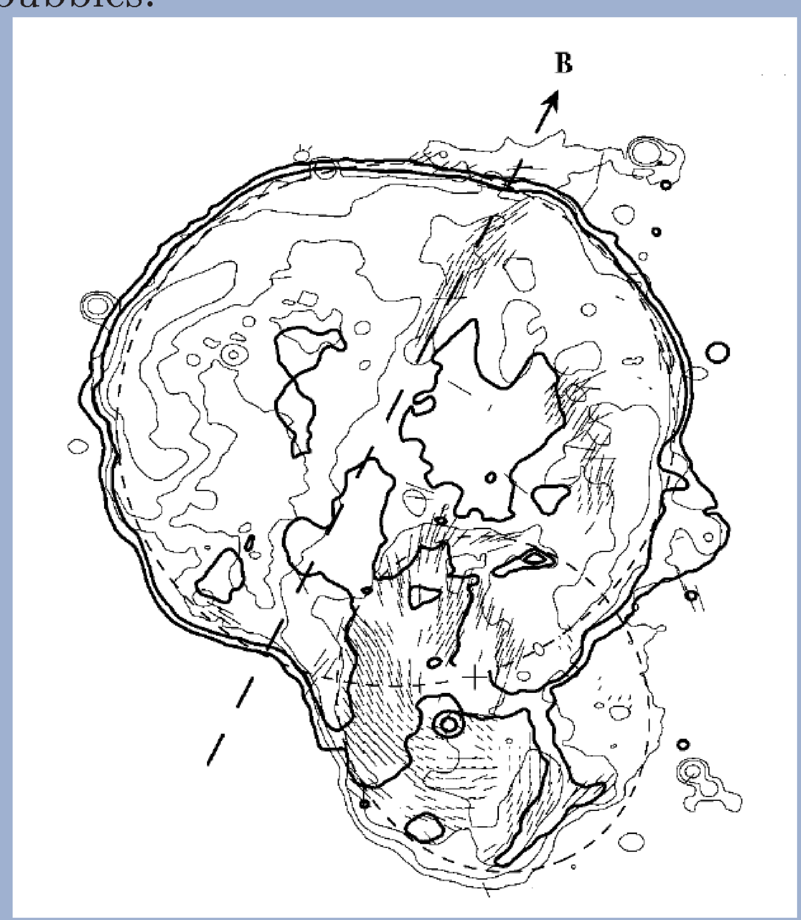

Fig.3: Radio emission (thin lines) and 0.25 keV X-ray emission from ROSAT data. The positions and extents of the two SNRs are represented by dashed ellipses. The NS in the southern part is indicated by a plus sign (adopted from Uyaniker 2002).

Selection & Observation

Selection

- Targets around proposed geometrical centers and PSRs <12 or 16 mag.
- Candidate selection via BVJHK colors or spectral type, if known.

Observations

- Calar Alto 2.2 m, CAFOS spectra, λ 3200-7000Å, R$\sim$550
- Jena 0.9 m, FLECHAS spectra, λ 3900-8100Å, R$\sim$9300

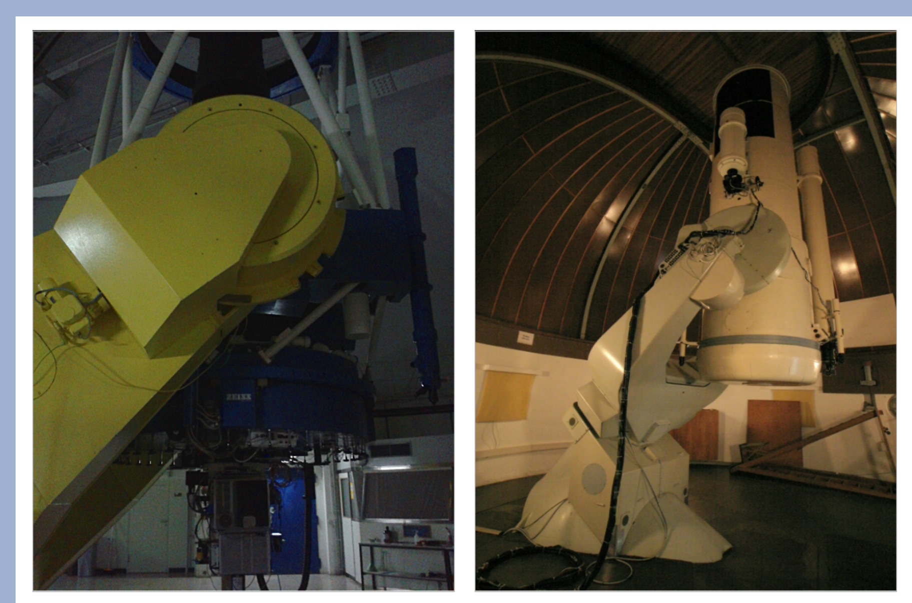

Fig.4: Telescopes of Calar Alto Astronomical Observatory and University Observatory Jena. The majority of the observations is carried out with the spectrograph in Jena.

Results Crab

The Hα regions of the three targets show red and blue shifted components coming from the SNR itself. This points out that they are located behind the SNR.

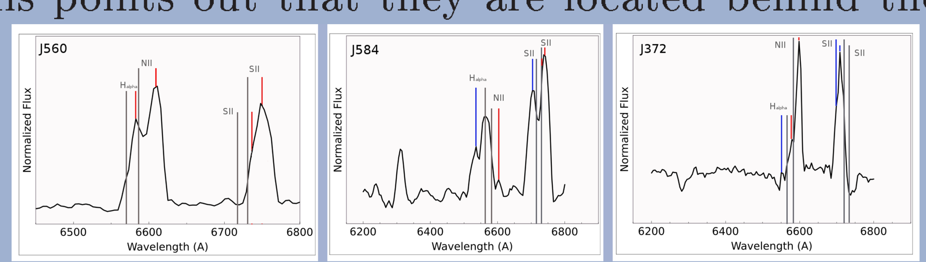

Fig.5: CAFOS spectra: *a)* Red shifted Hα (λ6581, +18Å), NII (λ6609, +26Å) and SII (λ6735, +18Å and λ6750, +19Å) lines of J560. *b)* and *c)* Blue and red shifted H and SII lines in J584 and J372 respectively. The SNR gas velocity amounts to ~ 1000$\mathrm{kms^{-1}}$ which is consistent with the known values from e.g. [7].

Target	M(V) III	M(V) V	dist III (pc)	dist V (pc)
J584	1.66 ± 0.64	3.78 ± 0.34	3500 ± 900	2200 ± 350
J560	2.26 ± 0.51	2.99 ± 0.31	3300 ± 800	2300 ± 300
J372	0.24 ± 0.25	5.46 ± 0.61	6800 ± 700	600 ± 200

Tab.1: Absolute magnitudes M and calculated MK distances for luminosity class III and V[5] with the assumed extinction A_V=1 mag. The estimated spectral types of the targets via color magnitudes and spectral lines indicate the following: J584-G0, J560-F5 and J472-K0.

Results Cygnus Loop

Candidate Run1: Spt = K3III, m_v=7.25, d = 385 pc. Lies possibly inside the SNR, however quite far away from the geometrical center proposed by Green 2014. The vector of proper motion points away from the center.

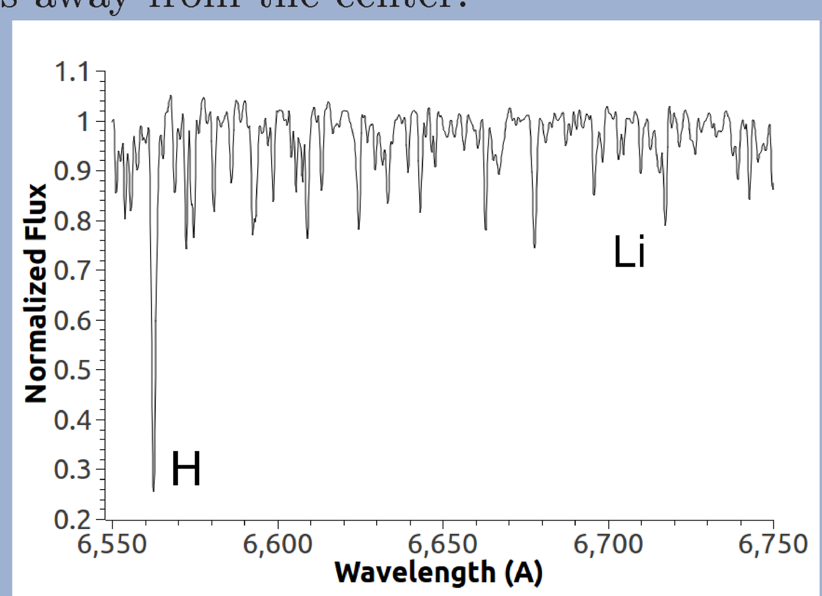

Fig.6: Red region of the candidate Run1: Narrow lines (e.g. Hα, 6563 Å) and a small Li line (6707 Å) indicate an evolved star.

References

[1] Blaauw 1961, BAIN, 15, 265
[2] Dincel et al. 2015, 2015MNRAS.448.3196D
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Discussion & Outlook

Cygnus Loop

Due to the size of the SNR, 2 different PSRs and a putative PSR in the region of the two bubbles no strong runaway candidate has been found in Cygnus Loop so far. The candidate Run1 shows optimistic proper motion and lies in the vicinity of the SNR, hence it is an evolved star. This feeds the scenario of two interacting SNRs, which have been a binary system before both of them exploded in SNe.

Crab

The spectral types of the observed targets lie between G and early K and are located behind the Crab SNR. No other objects are situated within the 1 arcmin radius around the PSR and V_{mag} <17.

This has now two conclusions: firstly all of the targets can be of LC III and thus situated more than 2.5 kpc away from the Solar system. Secondly, if the targets are dwarfs then the distance to the Crab SNR has to be closer than 2.3 kpc. The putative runaway has to be fainter than V_{mag}16.5 apparent magnitudes. At the assumed distance of 2.5 kpc this will lead to an absolute magnitude of M_V~4.5 mag[5] which corresponds to a G5V or later type stars.
We conclude that Crab SNR progenitor star either was a runaway star itself [8] or had no companion candidates earlier than G5V.