Mem. S.A.It. Vol. 83, 272

Memorie della

Runaway and hypervelocity stars

The supernova connection

R. Napiwotzki and M. D. V. Silva

Centre for Astrophysics Research, STRI, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK, e-mail: r.napiwotzki@gmail.com

Abstract. We present an investigation of the known sample of runaway stars. The orbits of these stars are traced back to their origin in the Galactic disc. The velocity distribution of these stars is compared to theoretical predictions. We conclude that the majority of stars is well explained by the standard binary ejection mechanism (BEM) and the dynamical ejection mechanism (DEM). However, we find a sample of ten stars which has ejection velocities in excess of those predicted by standard scenarios. We discuss how these can be explained by a variant of the BEM. This mechanism can create runaway stars exceeding the Galactic escape velocity (known as hypervelocity stars). The number of runaway stars in our Galaxy is estimated and compared to the known sample of high mass X-ray binaries, whose formation is linked to the BEM channel.

Key words. Stars: early type – Stars: kinematics and dynamics – Galaxy: halo

1. Introduction

In the commonly accepted picture, star formation in our Galaxy is confined to the star forming regions in the Galactic disc. Runaway stars are young, early-type stars observed outside young OB associations and open clusters. Starting with the seminal work of Greenstein & Sargent (1974) the existence of early-type main sequence (MS) stars in the Galactic halo is now well established. Star formation in situ in the halo is an intriguing possibility, but ejection of young stars from the disc is a possible alternative. The two channels under discussion are the binary ejection mechanism (BEM) and the dynamical ejection mechanism (DEM).

In the BEM scenario (Blaauw, 1961) the (initially), higher mass star of the binary explodes as a supernova (SN). The lion's share of the mass of the SN progenitor is ejected at high speed and leaves the system within a short interval of time – short compared to the orbital period. Now, the remaining MS star feels a much diminished gravitation pull from the SN remnant (usually a neutron star, NS). Depending on the mass ratio and the orbital parameters of the progenitor system this can already be enough to break up the binary. However, it has become clear that NS born in a SN explosion receive an extra kick, which can amount to several $100\,\mathrm{km\,s^{-1}}$ – reducing the chance of a binary surviving the SN explosion even further. In the BEM scenario the surviving MS star should leave its place of birth with

Send offprint requests to: R. Napiwotzki a ejection velocity amounting to approximately its original orbital velocity, which in the standard scenario can reach values $\lesssim 300\,\mathrm{km\,s^{-1}}$ (Leonard & Dewey, 1993; Portegies Zwart, 2000).

An alternative is the DEM scenario proposed by Poveda et al. (1967). Close encounters ("collisions") between stars in young, dense clusters can result in one or both of them being ejected from the cluster with collisions between two binaries being the most efficient mechanism to produce large ejection velocities. The DEM predicts ejection velocities up to 300–400 $\mathrm{km\,s^{-1}}$ (Leonard, 1991; Gvaramadze et al., 2009).

High mass X-ray binaries (HMXB) consists of a massive OB star with an NS (or black hole) companion. They can be interpreted as those systems which survived the SN explosion in the BEM scenario. Chevalier & Ilovaisky (1998) determined tangential velocities of a sample of HMXB finding a relatively high sample average for systems with an OB supergiant component $\overline{v_{\mathrm{tan}}} = 42\,\mathrm{km\,s^{-1}}$ while the value for systems with Be components was $\overline{v_{\mathrm{tan}}} = 15\,\mathrm{km\,s^{-1}}$ (corrected values from van den Heuvel et al., 2000).

This is consistent with expectations from the BEM. It is easier for systems with higher mass secondaries (the OB supergiant progenitors) to survive a modest kick. Note that this kick results largely from the specific momentum of the SN ejecta leaving the system with the NS kick being only a minor contribution. It is interesting to note that a number of HMXBs fulfils the definition of runaway stars – a peculiar velocity in excess of $30\,\mathrm{km\,s^{-1}}$relative to their standard of rest (SoR). However, very large kick velocities would be incompatible with the survival of the system.

The most basic test of whether MS runaway stars in the halo are explained by the BEM and DEM scenarios is to reconstruct their trajectory and check whether their flight times are compatible with a disc origin (i.e. not longer than their evolutionary lifetime). A further test is the comparison of observed velocity distribution with predicted once. We will describe an investigation of the known sample of runaway stars in Sect. 2. Links with hypervelocity stars and HMXBs will be discussed in Sects. 3 and 4.

2. The runaway stars

Investigations of runaway stars face the obstacle that they are easily confused with hot evolved stars (mainly subdwarf B stars and post-AGB stars). Good quality spectra are necessary to distinguish the different types of objects. We surveyed the literature on known runaway candidates at high Galactic latitude and created an initial sample of 174 stars for which data of sufficient quality were available (Silva & Napiwotzki, 2011). We used criteria as the position in the Hertzsprung–Russell diagram, observed abundances and rotation velocities to evaluate their status. This process left a sample of 96 bona fide runaway stars for further analysis.

The location of the remaining stars in the Galactic UVW coordinate system was determined using their position in the sky and their distance computed using T_{eff} and $\log g$ from spectroscopic and photometric analyses and interpolating their mass in theoretical main sequence tracks. Knowing the distance the 3D space velocity can be evaluated from the measured radial velocity and proper motions. These are all ingredients needed to reconstruct the orbit of the runaways stars back to their point of origin in the Galactic disc using an updated version of the Galactic potential of Allen & Santillan (1991). We carried out a rigorous error analysis using a Monte Carlo procedure (see Silva & Napiwotzki, 2011, for details).

The result of the comparison of the flight times with stellar lifetimes interpolated from the main sequence tracks shows that both are consistent within errors for the vast majority of the sample. This is in agreement with the previous findings and confirms that the BEM and DEM disc ejection scenarios are capable of explaining most of the early type MS stars found in the Galactic halo. Three notable exceptions are SB 357, EC 20252−3137 and Hip 77131 for which the derived flight times exceed the evolutionary lifetimes with high statistical significance. Possible explanations are 1) a blue straggler scenario in which a close binary is

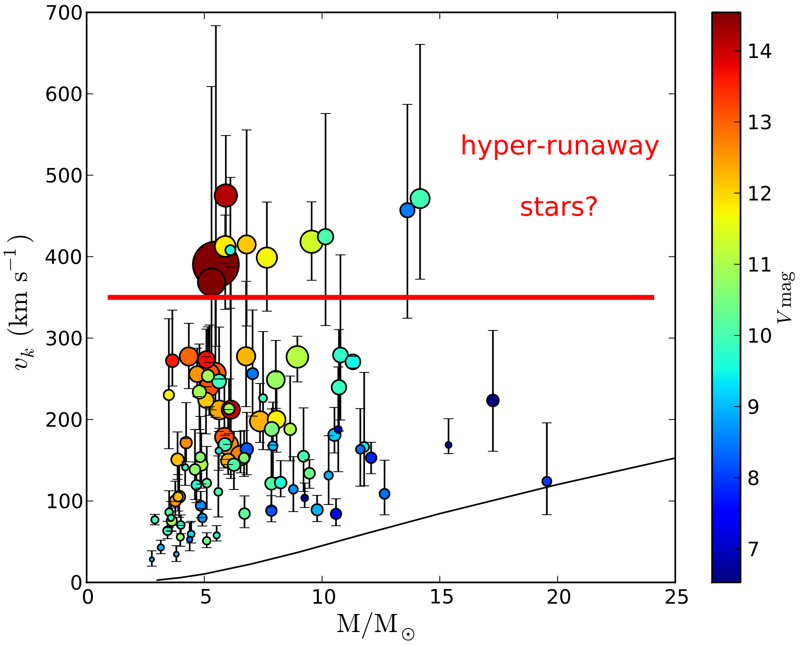

Fig. 1. Ejection velocities of the runaway stars as function of mass. The colour scale indicates the observed brightness. The size of the circles is proportional to the height above the Galactic plane. The bottom line indicates the minimum velocity needed to reach a height of 1 kpc during the MS lifetime of the star.

ejected and merges afterwards or 2) the in situ formation in the Galactic halo mentioned earlier.

Figure 1 shows the derived ejection velocities relative to the SoR at the point of origin as function of stellar mass. This figure shows a smooth distribution of velocities from a lower limit up to 300 km s^{-1}. Separated by a gap a group of ten stars with ejection velocities of ≈400 km s^{-1} is found. The lower limit results from the selection of the Silva & Napiwotzki (2011) sample from early type stars above the Galactic disc. Could this be due to a statistical fluke? To address this we constructed the cumulative distribution shown in Fig. 2 and compared it to the best fitting Maxwellian distribution. While the "low velocity" part up to 300 km s^{-1} is well reproduced, the high velocity stars are clearly not part of a continuous distribution, but form a separate group. We will discuss a possible link to the hypervelocity stars in the next section.

3. Hyper-runaway stars

Starting in 2005 a group of stars was discovered, which have Galactic rest-frame velocities in excess of the (local) Galactic escape velocity of about 550 km s^{-1} (Brown et al., 2005; Edelmann et al., 2005; Brown et al., 2007). Immediately after discovery it was "clear" that these have been formed by the interaction of (binary) stars with the supermassive black hole in the centre of our Galaxy as proposed by Hills (1988).

However, Heber et al. (2008) presented the example of HD 271791 – a hyper-runaway star. HD 271791 is a B-type supergiant found far below the Galactic plane. Its Galactic rest-frame velocity is uncertain, but a lower limit of 530 km s^{-1} has been determined, which exceeds the escape velocity at its location, fulfilling the definition of a hypervelocity star. HD 271791 could be traced back to its birthplace in the Galactic plane using the methods discussed above. Uncertainties are large, but a

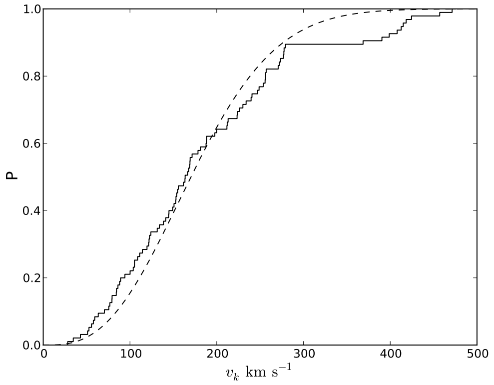

Fig. 2. Cumulative ejection velocity distribution.The dashed lines is the fit of a Maxwellian distribution function – demonstrating the sudden break in the distribution above 300km s^{-1}.

Galactic centre origin can be ruled out at a high significance level. This hypervelocity star originated in the outer regions of the Galactic disc. A more appropriate name for this class of star would thus be hyper-runaway stars. The ejection velocity of HD 271791 was ≈400 km s^{-1}, placing it within the group of high-velocity runaway stars in Fig. 1.

Przybilla et al. (2008) carried out an abundance analysis of HD 271791. The observed abundance patterns are best explained by contamination of the star by ejecta from a SN or hypernova (HN). Przybilla et al. (2008) propose a scenario in which HD 271791 was born in a binary with a high mass companion ($\geq 55 M_\odot$). When the binary evolves and expands a common envelope is formed causing a further contraction of the orbit. After the ejection of the common envelope the high mass component has become a Wolf-Rayet (WR) star. Since WR stars are more compact than MS stars the binary orbit can be closer (orbital velocity ≈400 km s^{-1}) than possible in an MS+MS binary. When eventually the massive star explodes as a SN or HN the remaining MS star is ejected with approximately its orbital velocity. Depending on the alignment with the orbit of the binary around the Galactic centre both velocities can add up to Galactic rest frame velocities of up to 650 km s^{-1}, exceeding the escape velocity.

4. Galactic populations of runaway stars and HMXBs

Defining a sample of runaway stars with well known selection criteria is difficult. Silva & Napiwotzki (2011) constructed a reasonably complete sample of known high Galactic latitude runaway stars within a cylinder of radius 1 kpc around the Sun. Low velocity runaway stars from Mdzinarishvili & Chargeishvili (2005) were added to overcome the bias visible in Fig. 1. The result of this exercise was an estimated surface number density at the position of the Sun of 13.4 kpc^{-2}.

Since we want to compare the populations of runaway stars and HMXBs, we are interested in an estimate of the total Galactic population. A *crude* estimate can be derived by scaling the surface density of the solar neighbourhood to the surface area of the Galactic disc. Adopting a truncation radius of 15 kpc (Ruphy et al., 1996) we arrive at a total population of 9500 runaway stars. Dray et al. (2005) estimated that the sample of runaway stars is consistent with a contribution of up to 70% produced via the supernova mechanism (BEM). Thus a back of the envelope estimate of the Galactic runaway stars produced via the BEM channel is 4000…5000. A further reduction to about 1500 results from the fact that many HMXBs contain O and early B components.

This compares to a Galactic sample of known HMXBs of 114 (Liu et al., 2006). HMXBs can – in principle – be detected in hard X-rays throughout the whole Galaxy. However, some HMXBs remain in low states, in which they are likely to escape detection by surveys, for a long time. This leaves quite some room for systems still waiting for detection. Nevertheless, even taking into account the large uncertainties of these estimates, it appears that the number of HMXBs is small compared to the number of runaway stars produced by the BEM channel. This is consistent with the expectation that only a small minority of binary systems survived the explosion of the more massive component.

For a significant improvement of these estimates detailed modelling will be needed taking into account the variation of the star formation rate in the Galaxy, travel of runaway stars and HMXBs to other parts of the Galaxy and a number of selection effects.

5. Conclusions

A systematic investigation of the sample of known runaway stars shows that the vast majority of them can be explained by disc ejection. The velocity distribution shows a bimodality with a continuous distribution of stars up to ejection velocities of $300\,\mathrm{km\,s^{-1}}$. These are explained by the standard BEM and DEM scenarios. A group of 10 stars with ejection velocities of $\approx 400\,\mathrm{km\,s^{-1}}$ is probably explained by a variant of the BEM in which the massive companion explodes as WR star after a common envelope phase. This mechanism is able to produce hyper-runaway stars exceeding the Galactic escape velocity. Estimates of the Galactic populations of runaway stars and HMXBs are consistent with the picture that HMXBs are the small minority of the binaries which survives the supernova explosion of the more massive companion.

6. Discussion

DANIELE FARGION: To give a kick to a runaway star (among other effects) are the neutrino explosion (10% of NS mass) a reason for the escape?
RN: Yes, mostly indirectly through their contribution to the envelope ejection and the NS kick.
VALENTI BOSCH-RAMON: How many massive (runaway) star bow shocks are in the Galactic plane?
RN: Most high velocity runaway stars will leave the gas layer of the disc very fast, unless ejected almost parallel to the plane. An order of magnitude estimate can be derived from the $5\,\mathrm{kpc^{-2}}$ (mostly) low velocity runaway stars of Mdzinarishvili & Chargeishvili (2005).

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