Young neutron stars and supernova explosions of runaway stars above the Galactic plane

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Runaway OB stars

- runaway stars - young early-type stars observed outside star-forming regions; they have kinematics different from typical early-type MS stars in the disc
- OB stars are mostly found in binaries (around 70%)
- more than 30% of the O stars and about 5–10% of the B stars in the Solar proximity are runaways
- binary ejection mechanism (BEM)
- dynamical ejection mechanism (DEM)

Gaia observations

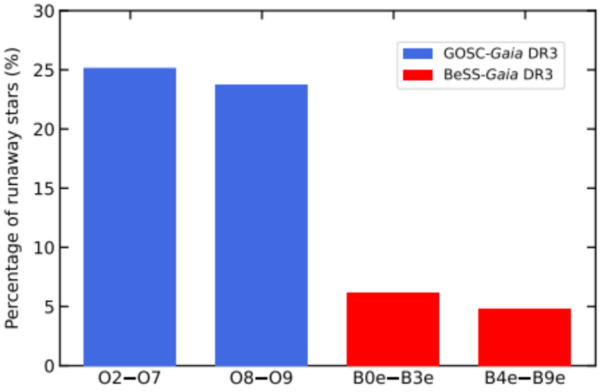


Figure 1: Percentage of runaway stars as a function of spectral type. (Adopted from Carretero-Castrillo et al. 2023)

Why are we interested in runaway stars?

- young NSs above the Galactic plane (e.g. Calvera)
- SNRs above the Galactic plane
- SNIa vs. SNII

Aim

To take statistics of runaway stars and calculate the rate and distribution of SN above the Galactic plane!

Previous studies

- explaning SNRs detected by the SRG/eROSITA by Type Ia SN (Churazov et al. 2021) - analysis for $|z|>1$ kpc
- following motion of runaways in the Galactic plane (Bisht et al. 2024) - 98.5% end up with $|b|<15°$

Initial parameters

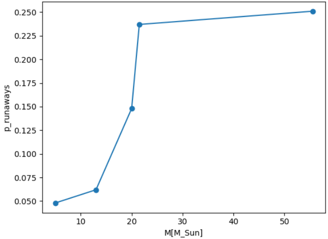
- birth rate
- initial spatial distribution
- initial velocity distribution
- time of ejection and life time

Birth rate

- Miller-Scalo IMF: $\frac{dN}{d(logM)} = D_0 M^{D_1}$
- $1 < M/M_{Sun} < 10$: $D_0 = 32$, $D_1 = -1.5$
- $M/M_{Sun} > 10$: $D_0 = 180$, $D_1 = -2.3$
- $\frac{N_{<10}}{N_{>10}} = 55$
- inverse sampling from the distribution, $N_{total} = 1000000$

Birth rate

- taking only stars with $8M_{Sun} < M_{initial} < 55M_{Sun}$
- considering the percentage of runaways over mass, checking for every star if it is a runaway or not
- $N = 2534$



We got the initial masses of N runaway stars!

Initial spatial distribution

- considering only r and z dependence, neglecting spiral arms
- inverse sampling from the pulsars' spatial distribution

$$\rho(r,z) = \rho_{Sun} \left(\frac{r}{R_{Sun}} \right)^{\alpha} \exp\left(-\beta \frac{r - R_{Sun}}{R_{Sun}} \right) \exp\left(-\frac{|z|}{h} \right)$$

- $\alpha = 1.93, \beta = 5.06$ and $h = 0.181$ kpc, $R_{Sun} = 8.2$ kpc (Ahlers et al. 2016)
- why pulsars' distribution?

We have the initial masses and spatial positions of N runaway stars!

Velocity distribution

- at the beginning, the velocity distribution is Maxwellian $\mu = 0$ km/s, $\sigma = 20$ km/s
- due to BEM or DEM, the stars get kicked at some moment
- Maxwellian which peaks at 156 km/s (Silva & Napiwotzki, 2011)
- isotropic distribution

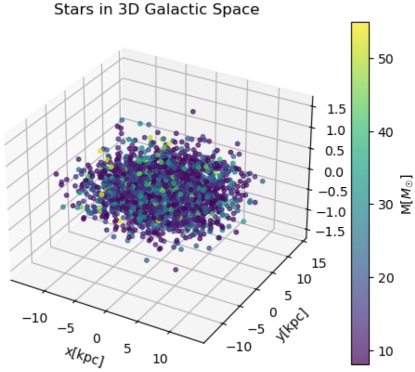
We have the initial masses, spatial positions, random velocities and kick velocities vectors of N stars!

Time-lag and ages

- 2/3 kicks due to DEM: kick-time = 1 Myr (Fujii & Zwart, 2011)
- 1/3 kicks due to BEM: kick-time $= 10^{10}/M_1^{2.5}$ yr and finding M_1 using $f(q) = const.$ (Sana et al. 2012)
- lifetime $= 10^{10}/M^{2.5}$ yr

Initial parameters

Now, we have the initial masses, spatial positions, and kick velocities vectors, as well as the time when the kicks are obtained, and the lifetime of N=2534 runaway stars!



Galactic plane

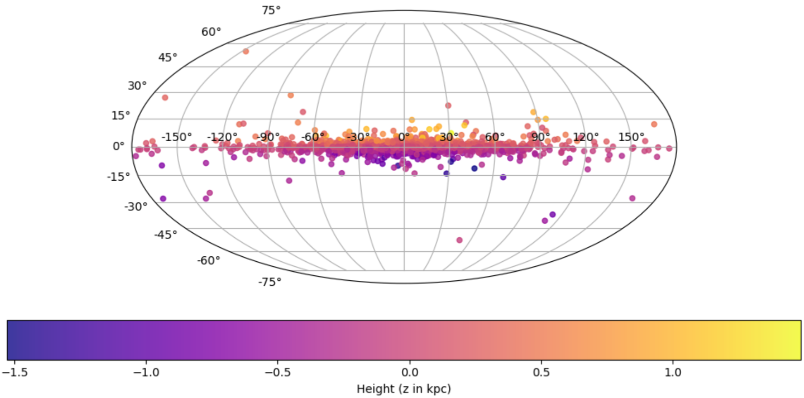


Figure 2: Initial position of the runaway stars in the Galactic plane.

Galactic potential

- positions at the moment of SN explosion
- MWPotential2014 in the GalPy library
- disk: Miyamoto and Nagai (1973) potential
- bulge: a power-law density profile that is exponentially cut-off
- dark halo: Navarro-Frenk-White potential

Galactic plane

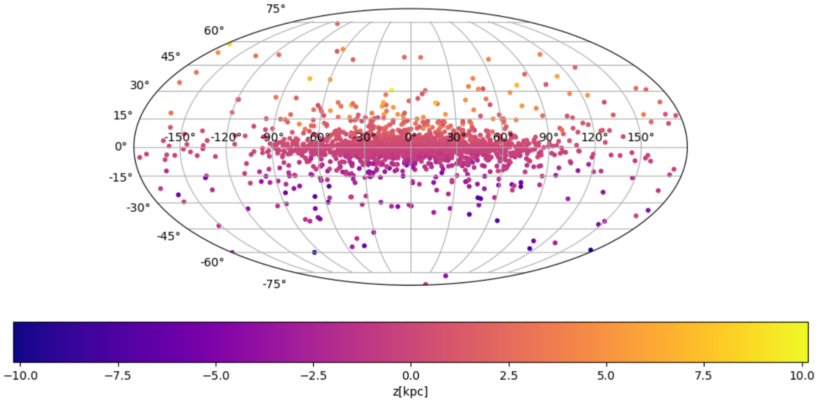


Figure 3: Final positions of the runaway stars just before the explosion, in the Galactic plane.

Galactic plane

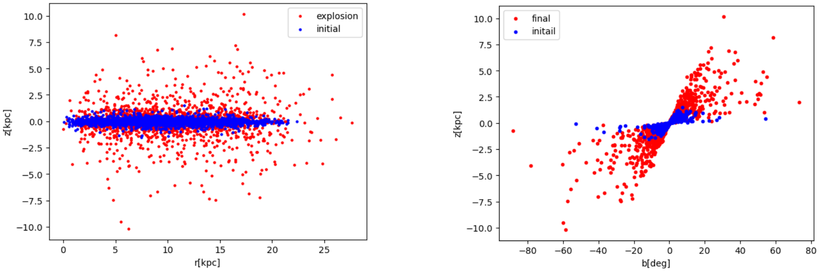


Figure 4: Distribution of the runaway stars just before the explosion in r-z and b-z space. The results obtained here are more scattered than those shown by Bisht et al. (2024).

CDF

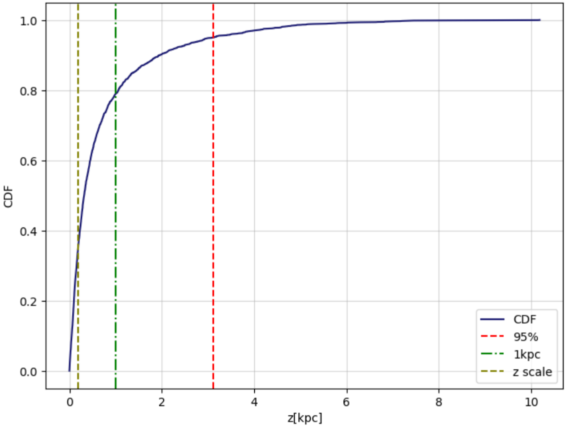


Figure 5: Cumulative distribution function of height above the Galactic plane.

Normalization

- the weighted percentage of runaways $p_{runaways} = \frac{\Sigma p_i N_i}{\Sigma N_i}$
- around p=0.097 of stars with masses 8-55M_{Sun}
- typical lifetime of SNR is t = 100 kyr
- normalization using SFR and CCSN rate

Normalization

- SFR = 1.65 M_{Sun}/yr (Licquia & Newman, 2015)

During the time of 100kyr, we will have around 73 runaway stars in our mass range.

- CCSN rate $= 1.9 \pm 1.1 CCSN/century$ (Bisht et al. 2024)

During the 100-kyr time, we will have around 185 runaway stars in our mass range.

What is Calvera?

- high galactic latitude pulsar (1RXS J141256.0+792204)
- detected only in soft thermal X-rays
- $(l, b) = (118.32°, +37.02°)$
- characteristic age 285 kyr
- high b - consistent with a B type runaway progenitor
- pulsar proper motion, likely resulting from a SN kick, bears no information on the origin of the progenitor star
- (Rigoselli et al. 2024)

Calvera

- r = 3.3 kpc and z above 2 kpc (Rigoselli et al. 2024)
- looking for a probability density at fixed rho, with $z > 2$ kpc
- $p = \frac{N_{outer}}{N_{total}}$
- multiplying with normalization factors, we get 0.42 (SFR) and 1.07 (CCSN rate)

SNIa

- in order to compare probabilities of SNIa and SNII, we reproduced results of Churazov et al. 2021 using bigger number of stars
- halo: spheroidal distribution along the galactocentric distance $r^2 = R^2 + (z/q)^2$ (q = 0.6) and a broken power law profile $\rho \propto r^{-\beta}$, $\beta = 2.3$ for R $\leq$ 27 kpc and $\beta = 4.6$ for R $\geq$ 27 kpc
- thick disc: $f \propto exp(-R/h_R)exp(-z/h_z)$, $h_z = 0.9$ kpc and $h_R = 2.1$ kpc

SNIa

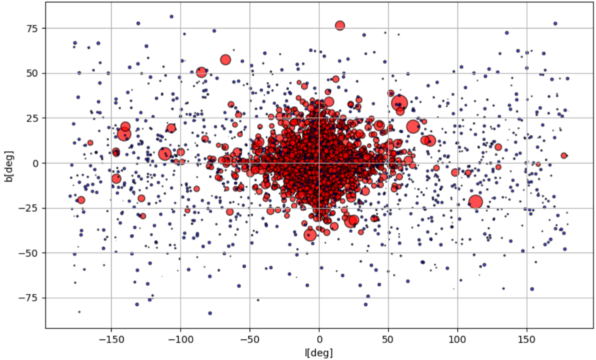


Figure 6: Positions of SNIa in the Galactic plane, where red circles correspond to the thick disc and blue circles to the halo stars, and the size of the circe is proportional to the distance.

SNIa vs. SNII

- SN Ia rate of $1.3{\times}10^{-4}$ SN Ia yr -1 in the halo and of $5.4{\times}10^{-4}$ SN Ia yr^{-1} in the thick disc (Churazov et al. 2021)
- combining two of them, SNIa rate $6.7{\times}10^{-4}$ SN Ia yr^{-1}, for |z| $>$ 1 kpc
- SNII rate is around 28x greater

SNIa vs. SNII

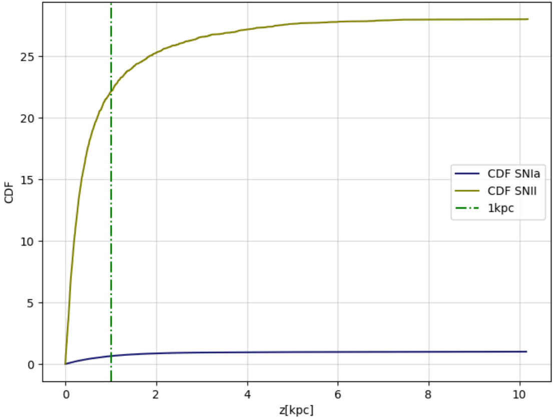


Figure 7: Cumulative distribution function of height above the Galactic plane for SNIa and SNII.

SNRCat

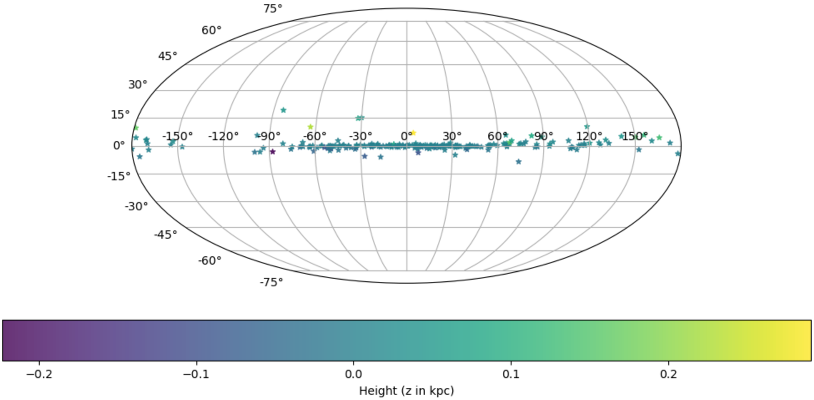


Figure 8: Positions of Galactic SNR, using the data presented in SNRCat (Ferrand & Safi-Harb, 2012).

Conclusion

- after explosion, around 95% objects are at $|z| < 3$ kpc, comparing to 95% objects at $|z| < 1.5$ kpc from Bisht et al. (2024)
- differences between SN rate and SFR normalization are inside the error bars
- Calvera could be explained by SNII
- greater probabilities of explaining such SNRs with SNII than SNIa
- the results cannot be compared with catalogues, as SNRs in catalogues are with $|z| < 1$ kpc

Possible upgrades

- stars with masses greater than 55 M_{Sun} - should not bring important differences
- changes in choosing the initial parameters - birth rate and velocity distribution
- more precise expression for lifetime
- using $f(q) = 0.1$ for BEM

THANK YOU!