Supernova explosions of runaway OB stars and young neutron stars high 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 disk
- usually, $v > 30km/s$
- 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

Gaia observations

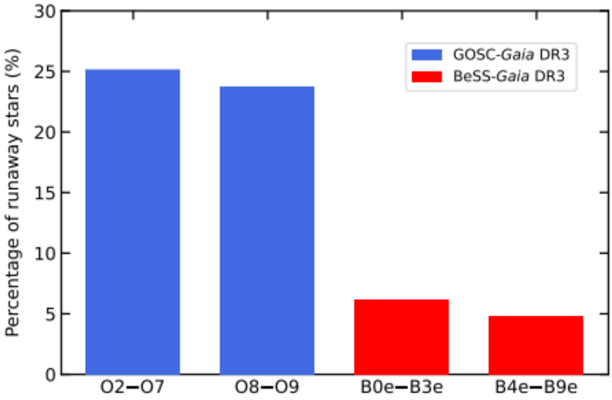

Fig. 1: Percentage of runaway stars as a function of spectral type. (Adopted from Carretero-Castrillo et al. 2023)

Ejection mechanism

- binary ejection mechanism (BEM)
- dynamical ejection mechanism (DEM)
- two-step ejection mechanism (TSEM)
- subcluster ejection scenario (SCES)
- Which mechanism dominates? Well, it’s hard to say...
- most researches says that DEM dominates by factor of 2-3 over BEM
- TSEM may work for a few percent of runaway stars
- no such researches for SCES

Why are we interested in massive runaway stars?

- the implications they have for stellar evolution and Galactic dynamics
- SNRs above the Galactic plane
- contribution of high-latitude explosions to the chemical enrichment of the Galactic halo
- SNR evolution in a lower-density environment
- young neutron stars and black holes above the Galactic plane

Previous studies

- Gaia DR3 astrometric data - percentage of runaway OB stars as a function of spectral type
- two populations: a ‘low’ velocity population, max(v) = 300 km/s and a ‘high’ velocity population, max(v) = 400–500 km/s (seems to be a bimodal distribution)
- explaining SNRs detected by the SRG/eROSITA by Type Ia SN (Churazov et al. 2021) - analysis for |z|>1 kpc $\rightarrow$ could this be explained by CCSN?
- following motion of runaways in the Galactic plane (Bisht et al. 2024) - 98.5% end up with |b| <15

Aim and initial parameters

Aim

To use a statistical approach to sample the population of runaway stars and calculate the rate and distribution of SN explosions.

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

Birth rate

- Chabrier Initial Mass Function (IMF)

$$\xi(M) \propto \begin{cases} \exp\left[-\frac{(\log_{10} M - \log_{10} M_c)^2}{2\sigma^2}\right] & \text{for } M \leq 1\, M_\odot \\ M^{-\alpha} & \text{for } M > 1\, M_\odot \end{cases}$$

- $M_c \approx 0.08 M_\odot, \sigma \approx 0.69, \alpha \approx 2.3$
- inverse sampling of 1 000 000 stars from the power-law
- considering the fraction of runaway stars as a function of stellar mass, checking for every star if it is a runaway or not
- taking only stars with $8 < M/M_\odot < 55$
- $N_{\mathrm{runaways}} \approx 7\,000$

Initial spatial distribution

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

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

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

Velocity distribution

- orbital velocity $\rightarrow$ from the Galactic potential model
- at the beginning, the star velocities are normally distributed, the dispersions along the three axes of the velocity ellipsoid given by Bobylev et al. (2022)
- due to BEM or DEM, the stars get ejected at some moment
- Maxwellian which peaks at 156 km/s (Silva & Napiwotzki, 2011)
- isotropic distribution

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 = lifetime of the more massive component M_1, calculated assuming $f(q) = const$. (Sana et al. 2012)
- lifetimes (accounts for the time right before stars of the H-burning until the end of the last burning phase) are retrieved from the evolutionary tracks for metallicity of Z=0.01 given in the PARSEC database (Costa et al. 2025)

Galactic plane

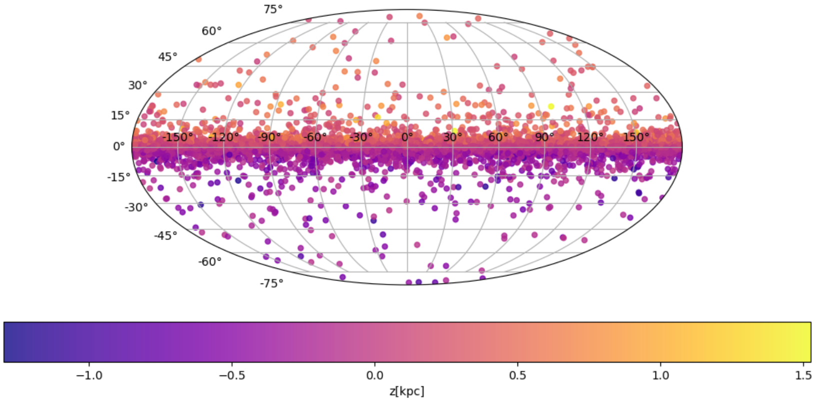

Fig. 2: Initial position of the runaway stars in the Galactic plane.

Galactic potential

We have the initial masses, spatial positions, random velocities vectors, kick velocities vectors, as well as the time at which the kicks are imparted, and the lifetime of $N_{\mathrm{runaways}} \approx 7\,000$ runaway stars!

- integration using 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

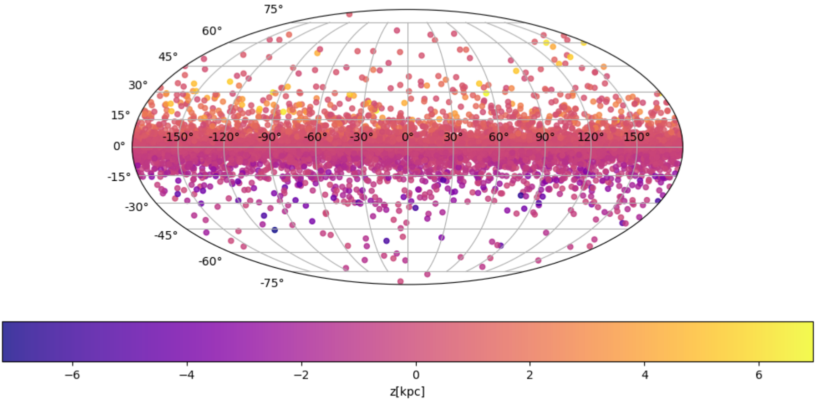

Fig. 3: Final positions of the runaway stars just before the explosion, in the Galactic plane.

Results

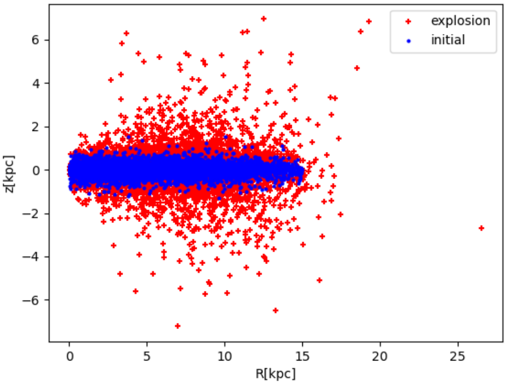

Fig. 4: Initial and final distribution of the runaway stars just before the explosion in R-z plane.

Results

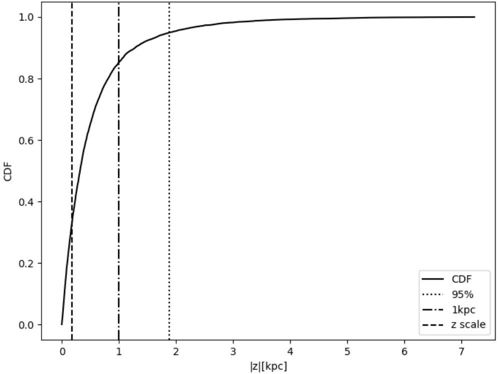

Fig. 5: Cumulative distribution function of height above the Galactic plane.

Results

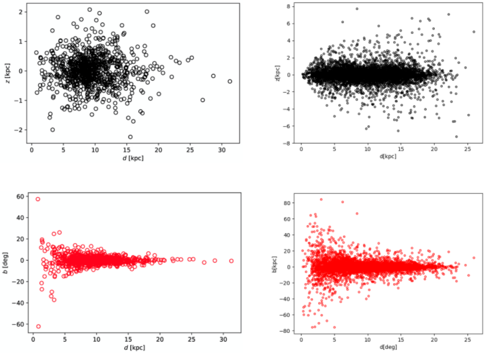

Fig. 6: The final position of runaway massive stars when they explode as CCSN in dz- (black) and db-plane (red). Left panels present results obtained by Bisht et al. (2024), while right panels show the results obtained in this work.

Possible upgrades

- more detailed model of the distribution of young massive stars
- the model is not accurate in the central few kpc or in the outer regions beyond $\sim$ 12 kpc (upgrade Galactic potential model)
- the bimodality of the observed distribution
- the percentage of runaway stars as a function of spectral types and also the dominance of ejection mechanism
- our upper mass limit of a runaway star is $55 M_{\odot}$

Normalization

- the real number of SNRs coming from runaway OB stars in the Galaxy
- normalization using SFR and CCSN rate
- typical lifetime of SNR is t = 100 kyr
- SFR = 1.65 $M_{\odot}/\mathrm{yr}$
  $N = N_{total} \times \frac{N_{OB}}{N_{total}} \times <p> = \frac{SFR \times t}{<M>} \times \frac{N_{OB}}{N_{total}} \times <p> \rightarrow$ around 310 SNRs
- CCSN rate = 1.9 $\pm$ 1.1 CCSN/century
  $N = CCSN \times t \times <p> \rightarrow$ around 210 SNRs
- or using the latest lower estimates we expect 100 SNRs (using the SFR) and around 45 SNRs (using the CCSN rate)

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 of 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
- the age from proper motion measurements < 10 kyr (Rigoselli et al. 2024)
- SNR G118.4+37.0 linked to Calvera (with an age of < 10 kyr)

Calvera

- $r \approx 3.3\ \mathrm{kpc}$, $z \approx 2\ \mathrm{kpc}$
- characteristic age 285 kyr
- kinematic age <10 kyr
- a number of Calvera-like objects at fixed ρ, with |z| > 2 kpc
- characteristic age: 0.7 - 1.3 (SFR) and 0.5 - 0.9 (CCSN)
- kinematic age: 0.02 - 0.05 (SFR) and 0.02 - 0.03 (CCSN)

SNIa vs. CCSN

- comparing probabilities of finding SNIa and CCSN high above the Galactic plane
- statistical sampling of SNIa from halo and thick disk (Churazov et al. 2021)
- halo: spheroidal distribution along the galactocentric distance $r^2 = R^2 + (z/q)^2$ and a broken power law profile $\rho \propto r^{-\beta}$, β = 2.3 for R $\leq$ 27 kpc and β = 4.6 for R $\geq$ 27 kpc
- thick disk: $f \propto exp(-R/h_R)exp(-z/h_z)$

SNIa vs. CCSN

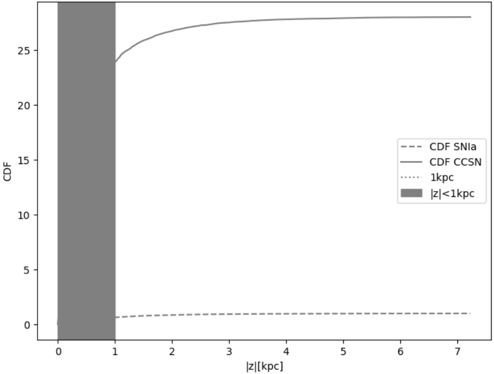

Fig. 7: Cumulative distribution function of height above the Galactic plane for SNIa and CCSN.

SNRCat

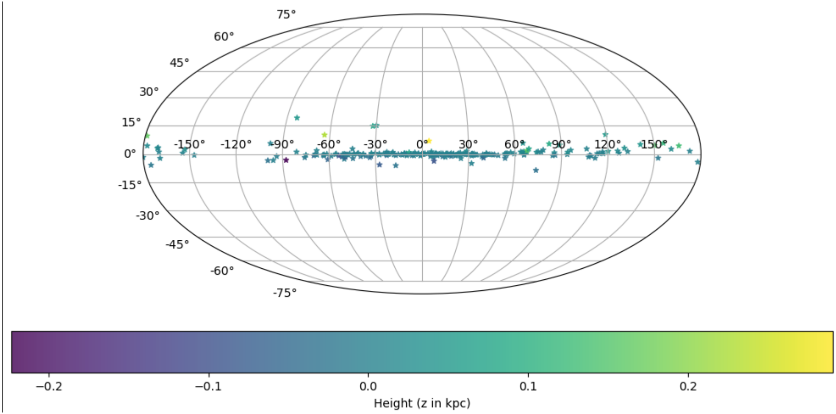

Fig. 8: Spatial distribution of SNRs from SNRCat in the Galactic plane, as seen from the Sun. Only the subset of SNRs with determined distances is shown.

Conclusions

- a significant fraction of runaway OB stars may undergo SN explosions in the Galactic halo
- we expect to have around 310 (SFR) and 210 SNRs (CCSN) originating from runaway OB stars in t = 100 kyr
- there is a possibility to explain Calvera using our model, and the probability is greater for a larger age of Calvera
- the SNRs from CCSNe predominate over those resulting from SN Ia
- future investigations in estimating the age of Calvera and the SNR G118.4+37.0, and in refining the Galactic SFR and the CCSN rate, are essential for accurately interpreting our results
- new surveys are needed for high latitude SNRs to validate our predicted numbers and distribution

THANK YOU!