The environment of pulsar halo progenitors

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Geminga as seen by Chandra and Spitzer
Credits: X-ray: NASA/CXC/PSU/B. Posselt et al; Infrared: NASA/JPL-Caltech

TeV Halos

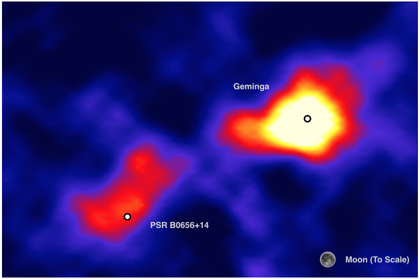


Figure: HAWC sky map of TeV emission from Geminga and its neighbour PSR B0656+14. Credits: HAWC Collaboration

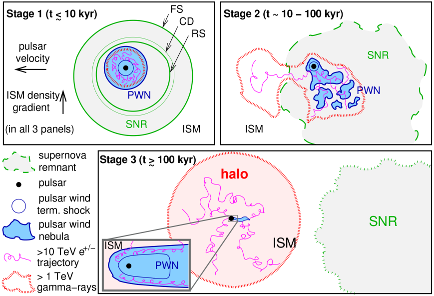
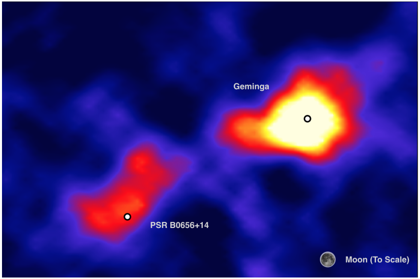


Figure: Sketch of the main evolutionary stages of a pulsar wind nebula. Credits: Giacinti et al. (2020)

TeV Halos



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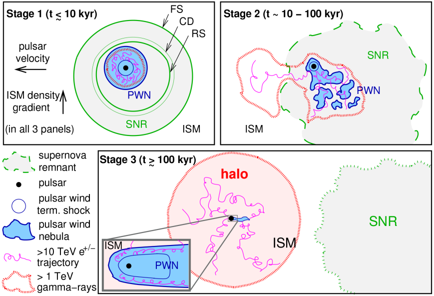

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Standard assumption

Pulsar **outside** the SNR → Low diffusion coefficient problem [Abeysekara et al. (2017)]

Solving the diffusion coefficient problem

Theoretical explanations

- Cosmic-ray induced turbulence [Evoli, Linden, et al. (2018), Mukhopadhyay et al. (2022)]
- **Environment induced turbulence** [Fang et al. (2019), Schroer et al. (2022)]

Solving the diffusion coefficient problem

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Which medium are the leptons probing when we see a TeV halo?

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Which medium are the leptons probing when we see a TeV halo?

Where is the pulsar at a given age?

Goal of this work

Method

Computation of the escape time from the SNR of a population of pulsars using a Monte Carlo approach for 3 models:

- ISM (interstellar medium)
- CSM (circumstellar medium)
- SB (superbubble)

Property of the pulsars: Kick velocity

Kick velocity distribution

Taken from Faucher-Giguère et al. (2006), modulus of all components:

$$f(v_k^{x,y,z}) = w\,\mathcal{N}(v_k, \sigma = 160\ \text{km/s}) + (1-w)\,\mathcal{N}(v_k, \sigma = 780\ \text{km/s}) \quad (1)$$

with $w = 0.90$.

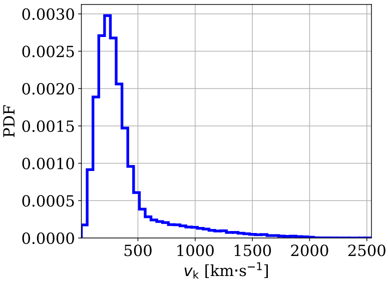

Figure: PDF of the kick velocity of pulsars.

ISM model

Assumptions

- **Constant interstellar medium** around the CC SN
- Distributions of E_{SN} and n_{ISM}

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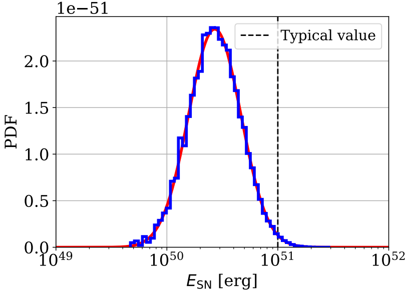
SNR evolution

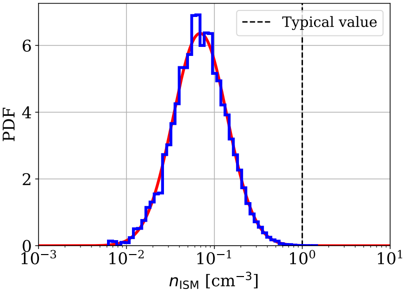
Analytical solutions following Cioffi et al. (1988), compared with the calculator by Leahy and Williams (2017):

- Sedov-Taylor phase
- Pressure-Driven Snowplough phase
- (Momentum Conserving Stage)
- Merger with the ISM

ISM model: SN energy and ISM density



(a) Effective E_{SN} PDF, $\mu = 2.7 \times 10^{50}$ erg, $\sigma = 3.5$



(b) Effective n_{ISM} PDF, $\mu = 0.069$ cm^{-3}, $\sigma = 5.1$

Figure: Lognormal distributions, following Leahy, Ranasinghe, et al. (2020). Computed by assuming a constant ISM density surrounding each of 43 SNe.

ISM model: Escape time

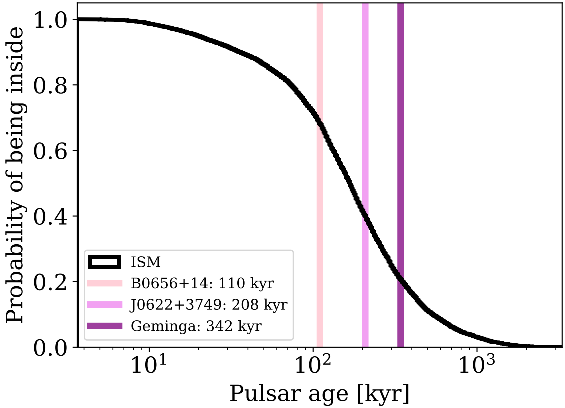


Figure: Probability of pulsars being inside the **SNR** as a function of time for the **ISM** model. Characteristic ages of pulsars are orders of magnitude, taken from the catalog of Manchester et al. (2005).

CSM model

Assumptions

- CC SN happens in the **circumstellar medium** shaped by the progenitor

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Process

- Pick a random **progenitor mass** from a Galactic Initial Mass Function (IMF),
- **Star properties** [Seo et al. (2018)],
- **Bubble properties** [Weaver et al. (1977), Härer et al. (2023)].

Neglecting post-MS phases for the wind and bubble structure.

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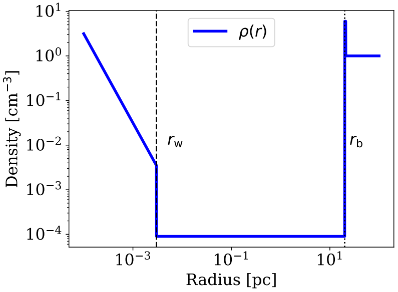

Figure: Density profile in the CSM, based on Weaver et al. (1977).

CSM model: Comparing the shell mass and the SNR mass

Parameters for a star of $\mathbf{M_{ZAMS} = 8\ M_\odot}$

- Bubble radius $\mathbf{r_b = 20\ pc}$,
- Surrounding ISM density of $\mathbf{n_{ISM} = 1\ cm^{-3}}$,
- Mass lost in winds $\mathbf{\Delta M_{MS} = 0.1\ M_\odot}$ and $\mathbf{\Delta M_{RSG} = 3.4\ M_\odot}$,
- Ejecta mass is $M_{ZAMS} - \Delta M_{MS} - \Delta M_{RSG} - M_{pulsar} = \mathbf{M_{ej} = 3.1\ M_\odot}$,
- Mass swept in the bubble by the SNR is the mass lost in winds.

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Computations

$$M_{shell} = \frac{4\pi}{3} \rho_{ISM} r_b^3 = 755\ M_\odot \qquad (2)$$

Mass ratio:

$$\frac{M_{shell}}{M_{ej} + \Delta M} = 116 \qquad (3)$$

Shell stops the expansion of the SNR

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Conclusion

Boundary: bubble radius instead of the SNR

SB model

Assumptions

- Point-like cluster surrounded by a **superbubble** [Weaver et al. (1977)]
- Ambient density of $n_{\mathrm{ISM}} \sim 100$ cm^{-3} [Parizot et al. (2004)]
- The SNR is very fast or merges within the SB [Mac Low et al. (1988)]

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Process

Pick a **random cluster mass** following a cluster IMF [Portegies Zwart et al. (2010)].

Populate with stars following the Galactic IMF.

Compute the **cluster luminosity** and SB radius [Weaver et al. (1977), Härer et al. (2023)].

Pick a **random massive star** and find the associated MS time [Seo et al. (2018)].

Creation of a pulsar at the MS time and propagation of both pulsar and SB radius.

Comparing the probability of being inside the boundary

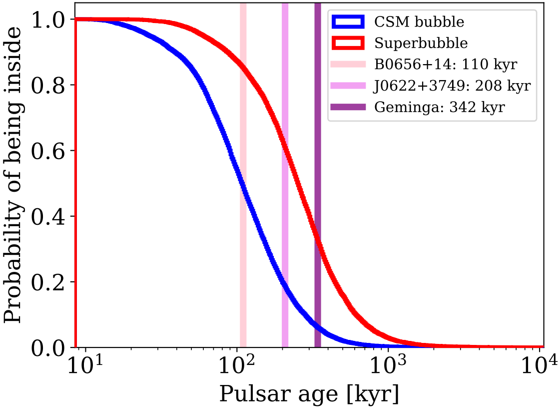

Figure: Probability of pulsars being inside the **bubble (SB)** as a function of time for the **CSM (SB) models** respectively.

Some numbers

Pulsar	Age [kyr]	Inside (CSM, 4%[1])	Inside (SB, 96%[1])
B0656+14	110	49%	85%
J0622+3749	208	19%	61%
Geminga	342	6%	33%

[1] of O stars[de Wit et al. (2005)]

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More on Geminga

Hints that Geminga is in a hot ionized medium:

- No H_α lines in the near vicinity [Caraveo et al. (2003)]
- Proximity to Gemini H_α Ring bubble [Knies et al. (2018)]

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Comparing the probability of being inside the boundary

Changing the maximum star mass

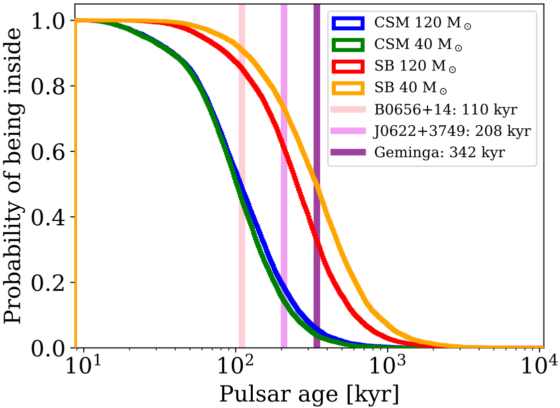

Figure: Probability of pulsars being inside the **bubble (SB)** as a function of time for the **CSM (SB)** models respectively.

Two curves are added by changing the maximum mass of massive stars that create pulsars from 120 $M_\odot$ to 40 $M_\odot$ following Sukhbold et al. (2016).

Comparing the probability of being inside the boundary

Special case: exiting the SNR inside the bubble

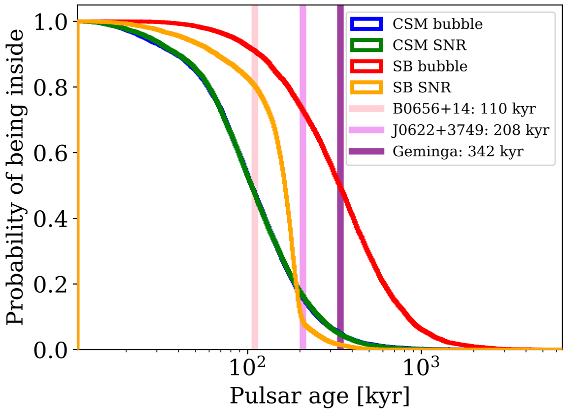

Figure: Probability of pulsars being inside the **bubble (SB)** as a function of time for the **CSM (SB)** models respectively. Max mass 40 $M_\odot$.

The green curve corresponds to the escape time of pulsars from the SNR inside the CSM, and the orange inside the SB.

Energy available for escaping pulsars

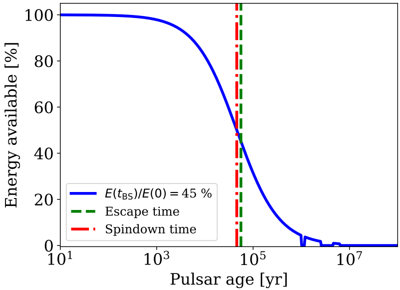

Figure: Evolution of the available energy of a pulsar as a function of time. Towards the later ages there are integration artifacts.
$P_0 = 100$ ms, $v_k = 280$ km/s as in Evoli, Amato, et al. (2021).

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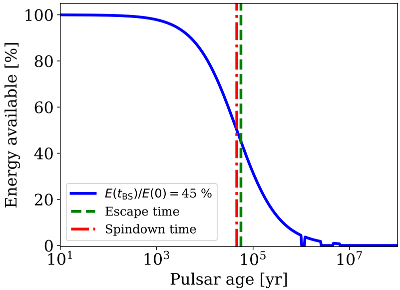

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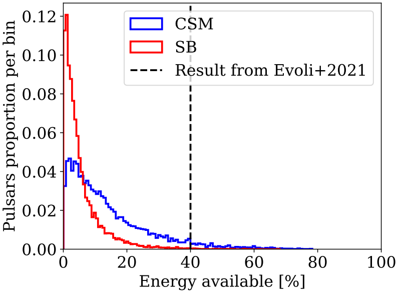

Figure: Distribution of available energies after escape. The initial period distribution comes from γ-ray observations in Watters et al. (2011).

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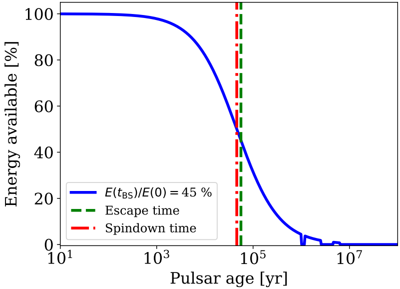

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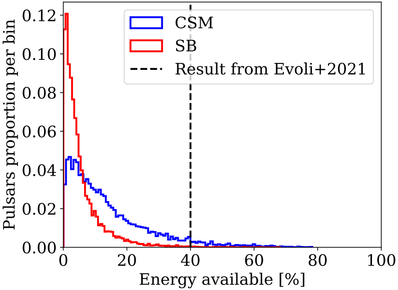

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Pulsars **DO NOT** have much energy left + leptons represent only a percentage of this energy

Summary

Main questions

Which medium are the leptons probing when we see a TeV halo?
Where is the pulsar at a given age?

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Conclusions

- Typically assumed: ~ 50 kyr and probe the ISM.
- We find instead a majority of $\gtrsim$ **100 kyr pulsars are inside the CSM/SB**.
- Are Geminga and PSR B0656+14 in a **hot and turbulent** environment?
- How are CSM/SB connected to **TeV halos**?
- How about similar pulsars in **radio**?

Perspectives

In the same project

- Add the **OB star association** as a possible model for the evolution of the system
- Create a **Galactic statistic** assuming probabilities of pulsars being born in one or another region

New projects: looking at the injection

- Investigate the contribution of **millisecond pulsars** to the CR lepton spectrum
- Work on the injection of leptons in the **interaction between the PWN and the SNR** using MHD simulations

Events attended

Conference

- **Talk in person at RICAP-2024** (Roma International Conference on Astro-Particle Physics), Roma Tre, Frascati

Workshop

- Participation in person to the **Workshop on Numerical Multi-Messenger Modelling** by Astroparticule et Cosmologie, Paris
- Participation in person to the **Conference in memory of Veniamin Berezinskii**, GSSI, L'Aquila

Summer School

- Participation in person to the **MPIK-CDY School on the Future of Gamma-Ray Astronomy** by the Max Planck Institute fur Kernphysik, Heidelberg

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CSM model

Theoretical framework for the SNR shock

Time (Numerically integrated)

$$t(R_s) = \int_0^{R_s} \frac{1}{u_s(r)} \mathrm{d}r \quad (4)$$

Speed (Analytical)

$$u_s(R_s) = \frac{\gamma + 1}{2} \left[\frac{2\alpha E_{SN}}{M^2(R_s) R_s^\alpha} \times \int_0^{R_s} r^{\alpha - 1} M(r) \mathrm{d}r \right] \quad (5)$$

with $\alpha = 6(\gamma - 1)/(\gamma + 1)$.

Mass (Analytical)

$$M(r) = M_{ej} + 4\pi \int_0^r r'^2 \rho(r') \mathrm{d}r' \quad (6)$$

CSM model

Density profile

The numbers (model from Weaver et al. (1977))

Wind region ($R_s < r_w$):

$$\rho_w(R_s) = \frac{\dot{M}}{4\pi u_w R_s^2}$$

Bubble region ($r_w < R_s < r_b$):

$$\rho_b(R_s) = \rho_b$$

Shell region ($r_b < R_s < r_{ISM}$):

$$\rho_{shell} = \frac{M_{shell}}{V_{shell}} = \frac{\frac{4\pi}{3} r_b^3 \rho_{ISM}}{\frac{4\pi}{3}\left(r_{ISM}^3 - r_b^3\right)}$$

ISM region ($r_{ISM} < R_s$):

$$\rho_{ISM} = 1 \text{ cm}^{-3}$$

CSM model

Looking at all the distributions

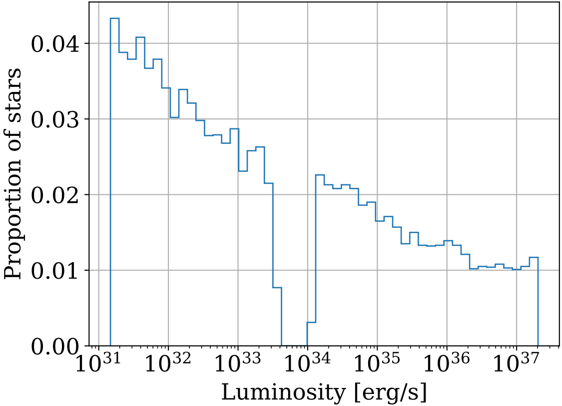

Figure: Luminosity distribution.

CSM model

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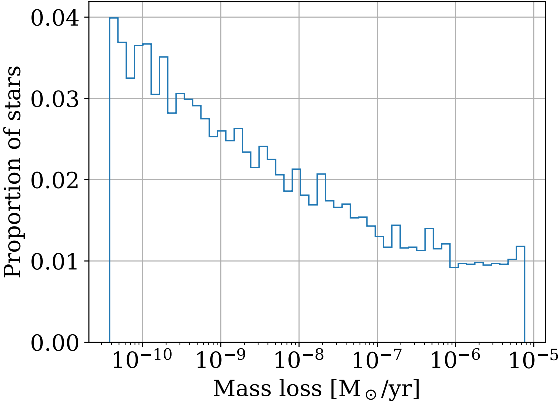

Figure: Mass loss distribution.

CSM model

Looking at all the distributions

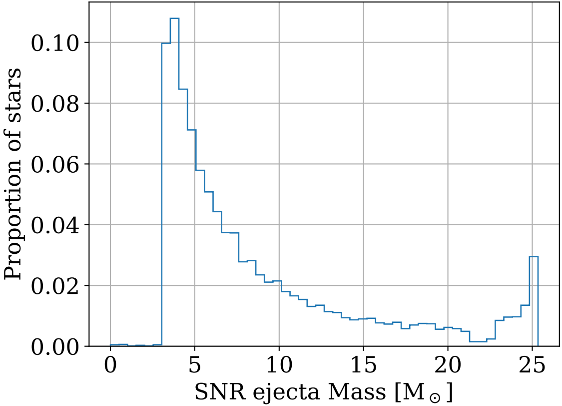

Figure: SNR ejecta mass distribution.

CSM model

Looking at all the distributions

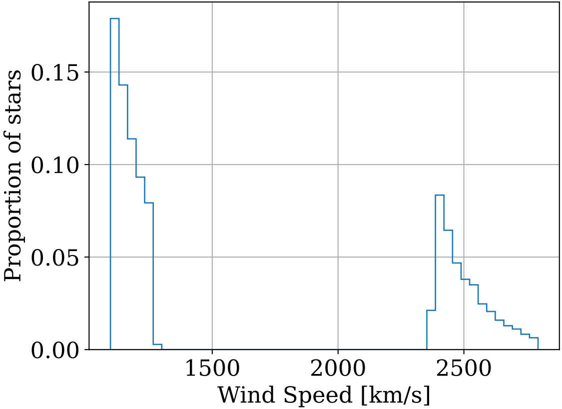

Figure: Wind speed distribution.

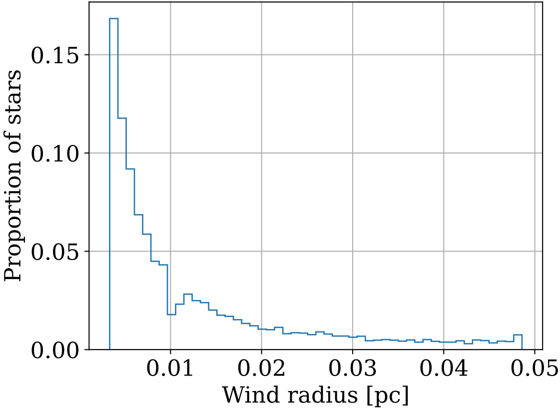

Figure: Wind radius distribution.

CSM model

Looking at all the distributions

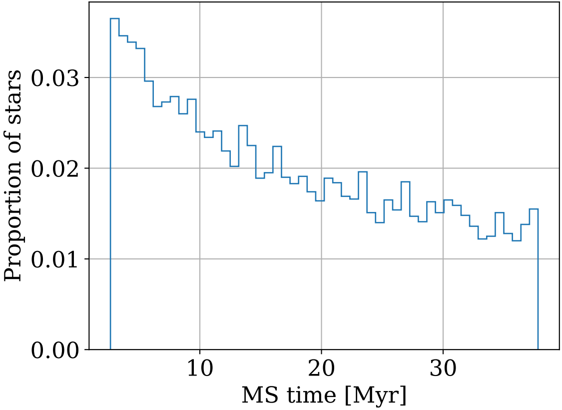

Figure: Main sequence time distribution.

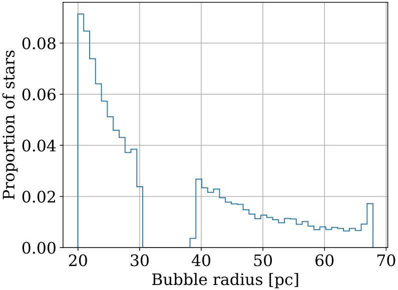

Figure: Bubble radius distribution.

Formula

From Weaver et al. (1977) and Härer et al. (2023):

$$r_{\mathrm{b}} = 21\ \mathrm{pc}\ \zeta_{\mathrm{b}}^{1/5} L_{36}^{1/5} n_{\mathrm{ISM},1}^{-1/5} t_6^{3/5} \quad (7)$$

CSM model

Looking at all the distributions

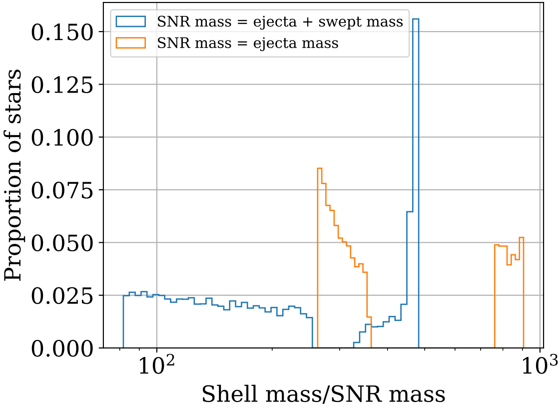

Figure: Shell mass/SNR mass distribution. We show for both the ejecta mass and the swept mass. Naturally, the swept mass is higher than the ejecta mass, resulting in a lower (by less than an order of magnitude) ratio. The shape in two parts of the orange curve is linked to the shape of the bubble radius (which is the determining factor for the parameter).

CSM model

Density profile

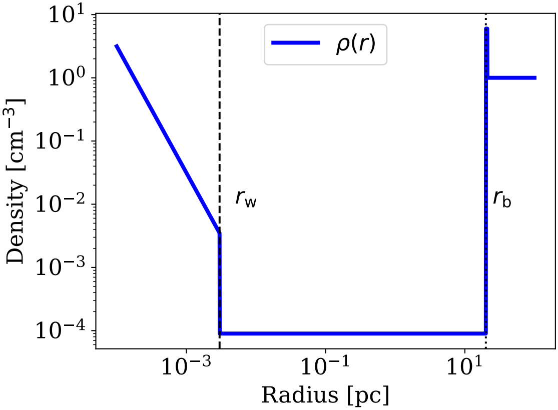

Figure: Density profile in the CSM, based on Weaver et al. (1977).

CSM model
Mass profile

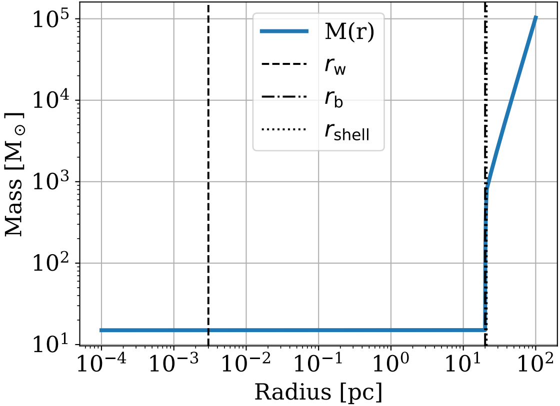

Figure: Accumulated mass profile in the CSM, analytically computed from the density profile

CSM model
Speed profile

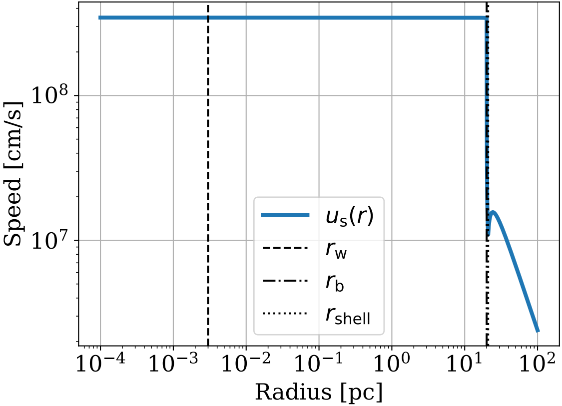

Figure: Accumulated speed profile in the CSM, analytically computed from the mass profile

CSM model

Conditions

Radiative phase

$$t_{\rm rad} = \frac{3}{2}\frac{\mathrm{k_b} T}{n\Lambda(T)}$$

with $\Lambda(T) = 1.6 \times 10^{-19}\ T^{-1/2}$ erg/cm^3/s. We always go radiative when reaching the shell.

Merger with the bubble shell

$$u_{\rm s}(R_{\rm s}) = \beta c_{\rm sound}(T(R_{\rm s}))$$

with $\beta = 3$ and the speed of sound $c_{\rm sound}$ depending on the temperature profile found in Weaver et al. (1977). Since the SNR stops inside the shell, it merges there.

SB model

Looking at all the distributions

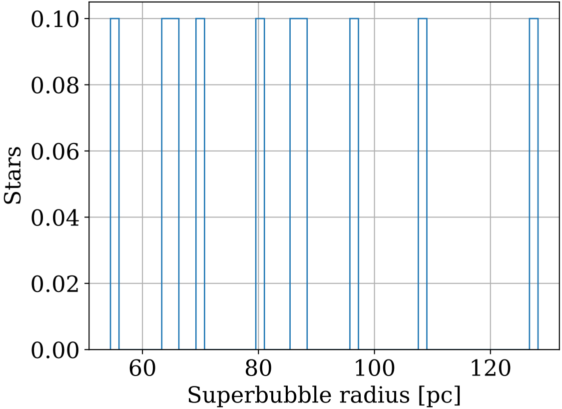

Figure: Superbubble radius distribution.