Particle acceleration in core-collapse supernova remnant expanding inside the wind bubble

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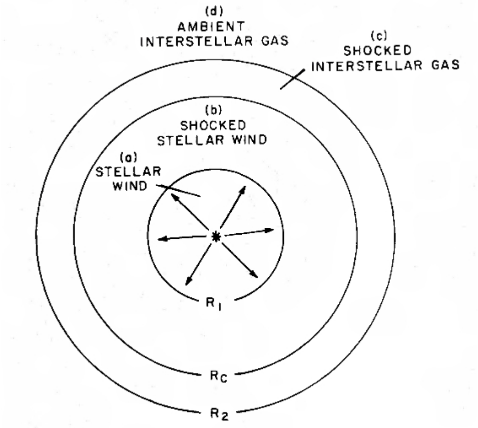
Overview

The bubble nebula, NGC 7635, HST 2016

bubble created by BD+60°2522 (44M)

[Credit:NASA, ESA, Hubble Heritage Team]

Stellar wind bubble



Schematic diagram of wind bubble

Weaver et al. [1977]

Mass loss during different evolutionary stages of massive star leads to create **wind bubble**

$$_{wind}(r) = \frac{M_\star(t)}{4\ r^2 v_{wind}(t)}$$

Massive star explodes as **core-collapse supernova** which evolves through the modified circumstellar medium (**CSM**) before the Interstellar medium (**ISM**)

The complex environment of CSM, **hydrodynamics** and **magnetic field** should have impact on generated particle spectra and emission.

Diffusive Shock Acceleration In test-particle approximation

Diffusion of charged particles back and forth through the shock) **Energy gain of particles**

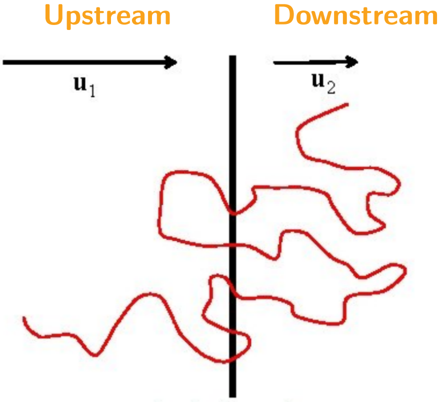
$$< \frac{E}{E} >_{up \quad down \quad up} = \frac{4}{3}\frac{u_1 \quad u_2}{c}$$

Particles acceleration to a power-law spectrum

$$n(p) \ / \ p^{\frac{r+2}{r-1}}$$

$$r = \frac{(1 + \quad)M_s^2}{(\quad 1)M_s{}^2 + 2}$$

where $u_1 = r$ (= 4, strong shock) u_2

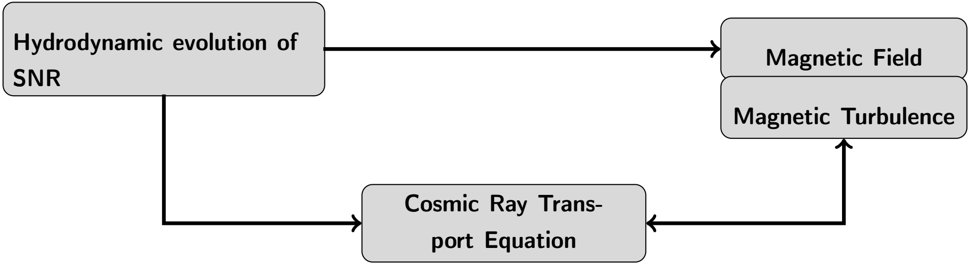


In Shock rest frame

Schematic diagram of DSA

[Schematic credit: https://slidetodoc.com/Diffusive-shock-acceleration, by Michal Ostrowski]

Diffusive Shock Acceleration



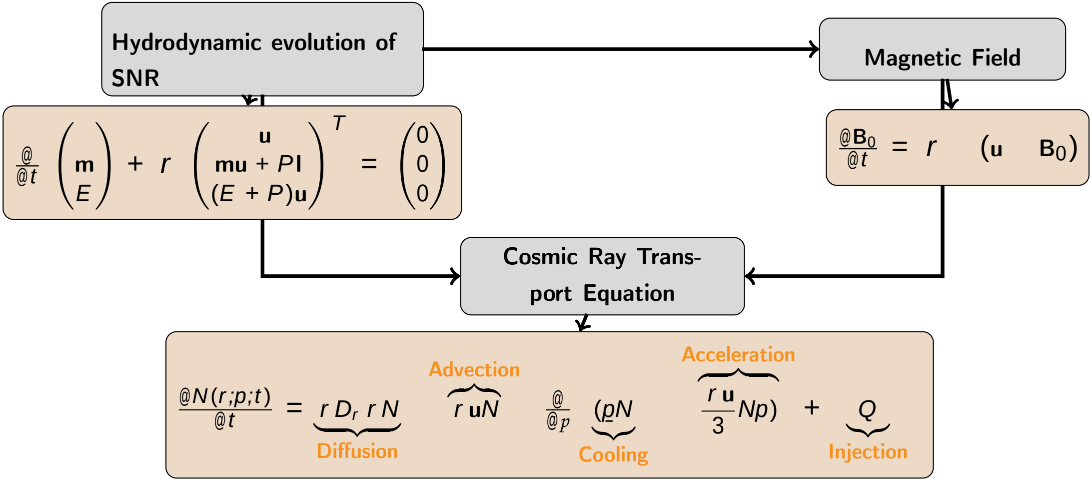
Applied Codes- Radiation Acceleration Transport Parallel Code (**RATPaC**) to study particle acceleration, **PLUTO** for hydrodynamics

Solve the equations

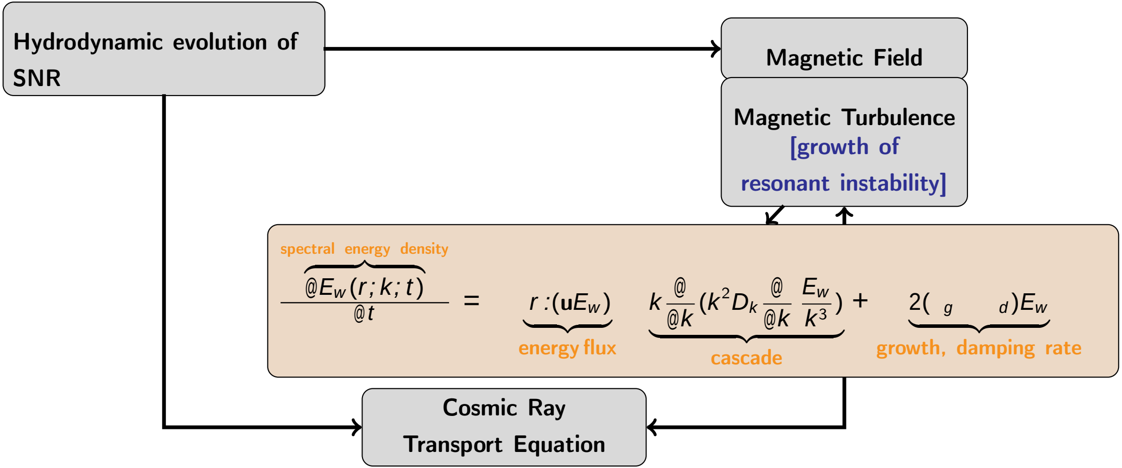
in one dimensional spherical symmetry

on a co-moving grid for CR transport equation, and turbulence

Diffusive Shock Acceleration



Diffusive Shock Acceleration



Diffusive Shock Acceleration Model descriptions

Hydrodynamics

Evolution of wind bubbles created by **progenitor stars** with $20M$, $60M$ ZAMS mass using pre-calculated stellar evolutionary tracks (**Groh et al. [2014]** and **Geneva grids of stellar evolution models**).

- **Post Main-sequence evolution**
  $20M$ -**Red Supergiant phase**
  $60M$ -**Luminous Blue Variable +Wolf Rayet phases**

Introduced supernova explosion in pre-supernova CSM.

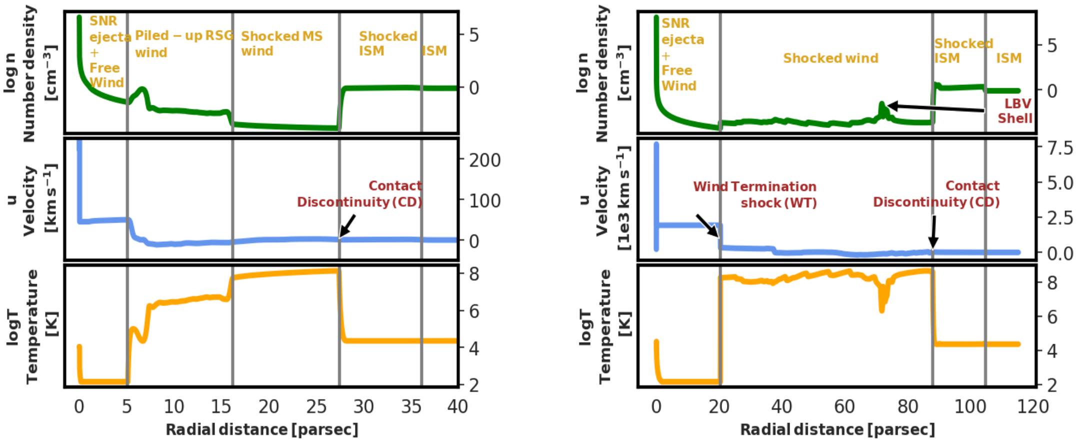
Diffusion coefficient prescriptions

Bohm-like diffusion$(D_r) = \zeta \frac{v}{3} r_g(r,p)$; $\zeta = 10$ **[time-independent]**

Alfvenic diffusion- $D_r = \frac{4v}{3\pi} r_g \frac{U_m}{E_w}$ **[time-dependent]**

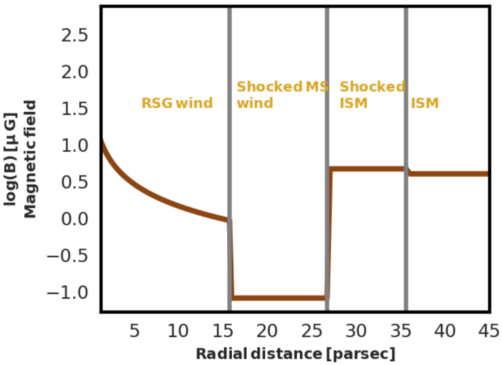
U_m) energy density of ambient magnetic field

Hydrodynamics after supernova explosion

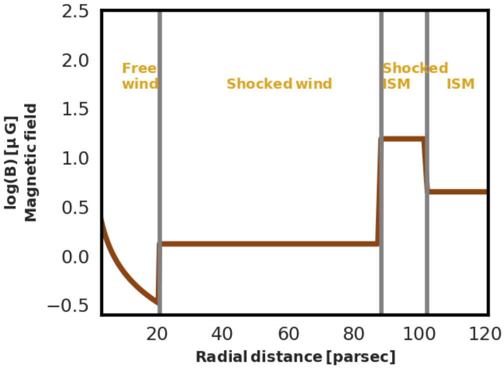


20M 60M

CSM magnetic field (B)

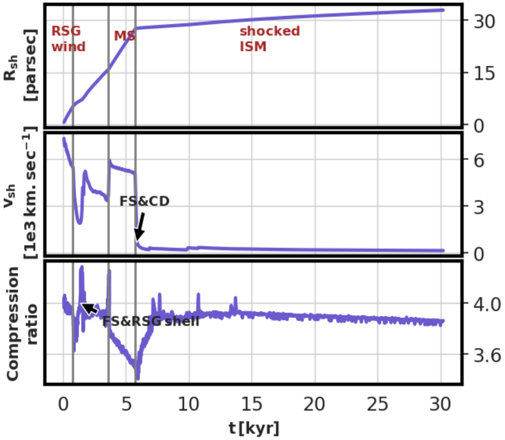


20M

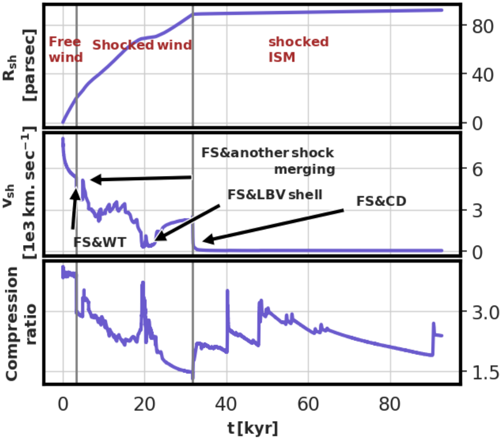


60M

FS Parameters

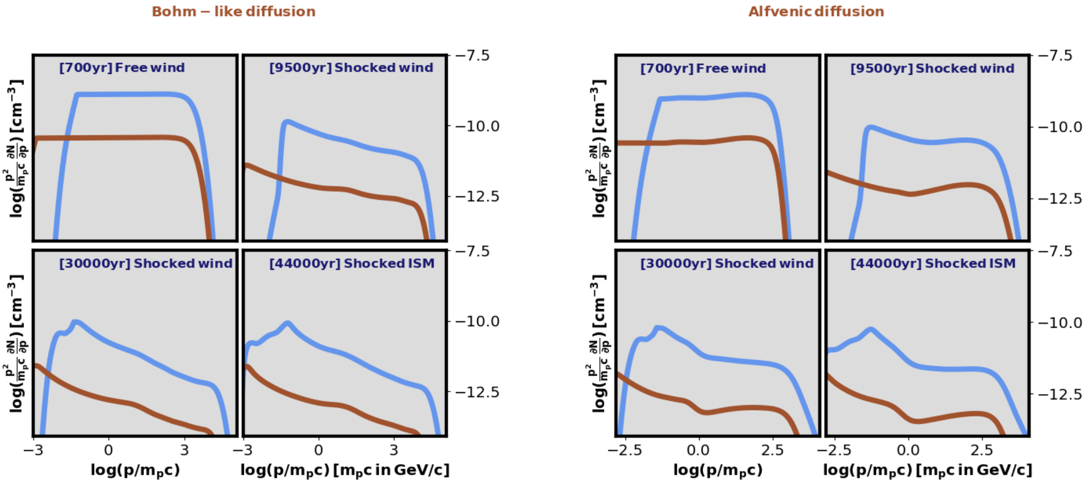


20M



60M

Spectra-Volume-averaged FS downstream [60 M]

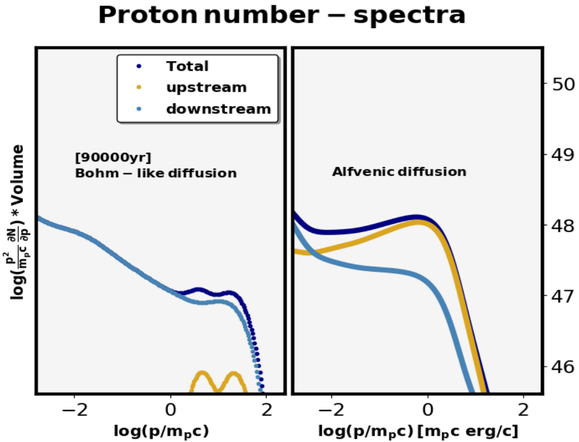


Cosmic-ray escape [60 M]

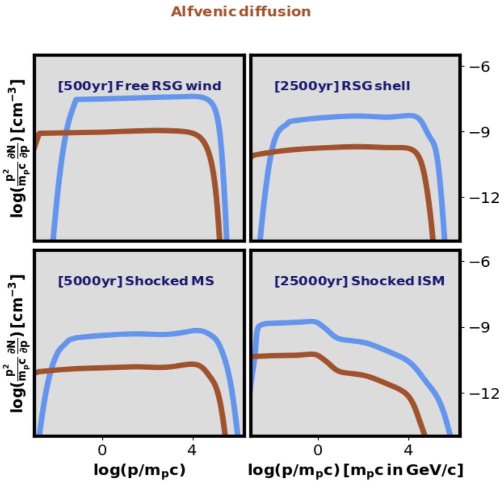
Alfvenic diffusion-The diffusion coefficient increases at later times, hence particles at higher energies diffused in the upstream region would not participate in the shock acceleration mechanism.

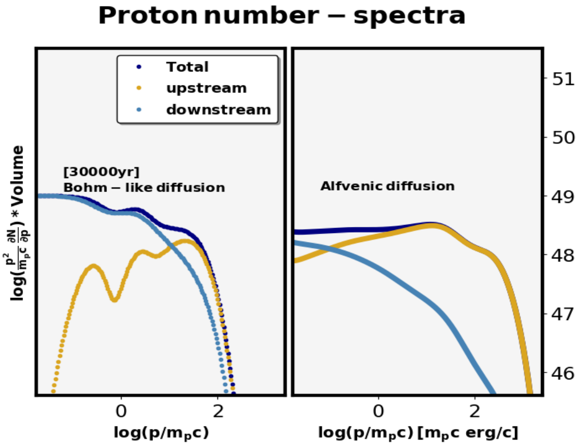
Downstream spectra-Spectra become rapidly softer at later times around above 1-10GeV, **signature of particle "escape" from downstream to upstream**

The spectral index of obtained total production spectra is harder than the downstream particle spectra



Particle acceleration at SNR with $20M_{\odot}$ progenitor





Conclusions

The stellar evolutionary stages, **ZAMS mass, rotation, and metallicity of progenitor stars have significant roles in spectral modification.**

The spectral shape depends on the temperature of bubble, and FS interactions. Although, the considered diffusion models have extensive effects on spectral index, **softer spectra are prominent during the FS evolution inside hot bubble for 60M .**

In Alfvenic diffusion, rapid particle escape from downstream above **1-10GeV at later times produces the softer downstream spectra** at higher energies.

CSM magnetic field as well as diffusion play significant role in emissions from the spectra and in remnant morphology.

For more details regarding this study, please go through

"Leptonic non-thermal emission from supernova remnants evolving in the circumstellar magnetic field"- Sushch et al. 2022, ApJ, 926,140 -Impact of CSM magnetic field on SNR emission

"Spectral softening in core-collapse supernova remnant expanding inside wind-blown bubble"- Das et al. 2022, AA, 661, A128 - Extensive study of particle acceleration with Bohm diffusion for SNR with 60M progenitor

Thank You

for your attention!