Evolution of pulsar wind nebula - supernova remnant systems

Transient Universe 2023 (student talk)

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07/06/2023

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Pulsar wind nebula

Pulsar: rotating, magnetized neutron star
→ highly relativistic outflows

outflow surrounded by supernova remnant
- → emitting nebula
- → interacts with surrounding SNR
- → rich evolution

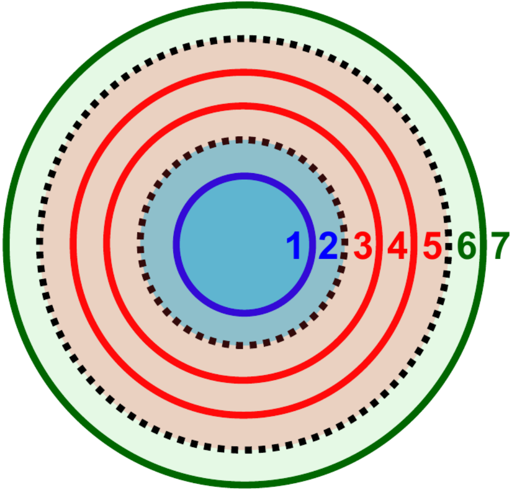
The Crab Nebula, the most well-know pulsar

Pulsar wind nebula - structure

Starting from the center:

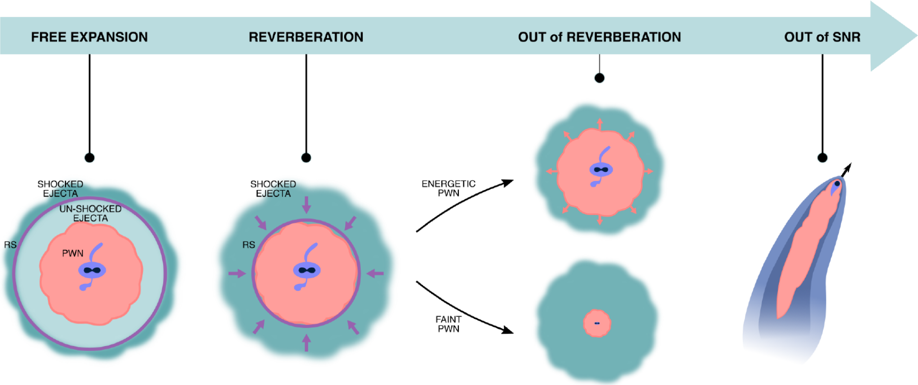
1. under-luminous, unshocked wind
2. shocked (high pressure) wind: the PWN
3. thin shocked ejecta shell
4. SNR ejecta
5. shocked ejecta
6. shocked external medium
7. external medium (ISM)

separated by shocks or contact discontinuities



Sketch of an early PWN - SNR system

Pulsar wind nebula - lifetime



Lifetime of a PWN (Olmi&Bucciantini 2023)

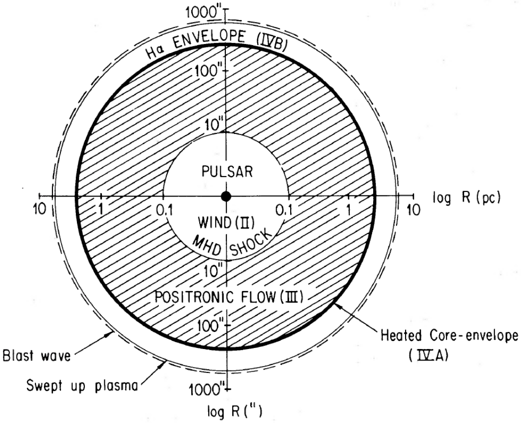
Explaining both structure/dynamics & spectral evolution of particles:
from 1D steady HD models (1974) to modern 3D RMHD simulations

Analytical modeling: 1D

Two model types:

- steady-state, spherically symmetric

→ structure separation in zones
→ central particle injection
→ good spectral modeling up except in radio
→ agrees with observations: $\sigma_w \approx 10^{-3}$
but NS wind $\sigma \sim 10^4$: the σ problem



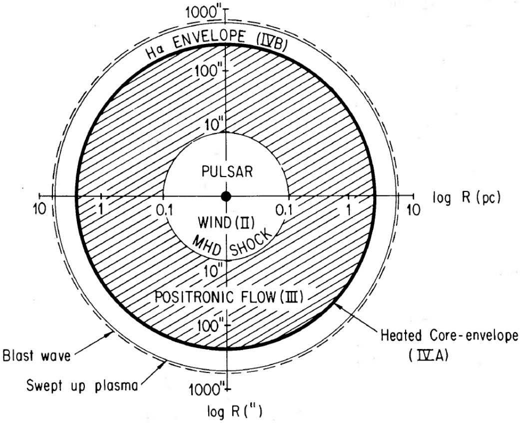
PWN schematics (Kennel&Coroniti 1984)

Analytical modeling: 1D

Two model types:

- steady-state, spherically symmetric
- one-zone ("0+1")

→ considers thin shell of shocked ejecta
→ dynamical evolution from energy and momentum conservation
→ defined evolutionary phases of ≠ spectral properties

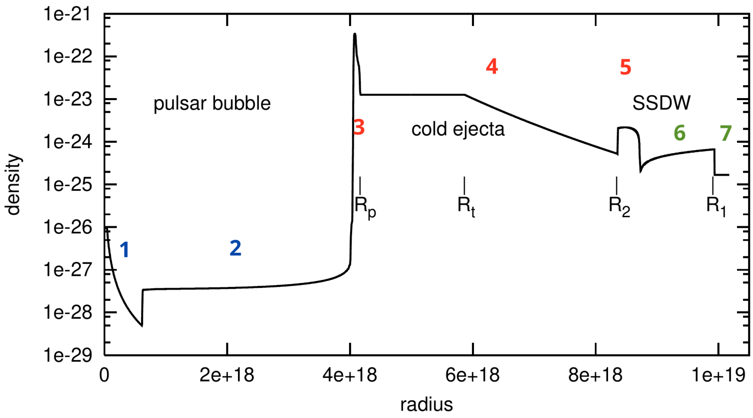


PWN schematics (Kennel&Coroniti 1984)

1D simulations

Used for large scale studies:

free-expansion → early reverberation and related emission



PWN-SNR 1D density profile (Blondin 2001)

Modern picture

Modern picture (including 2D models, 2 and 3D simulations):

- system structured in various zones
- low σ flow in wind
- torus + jet naturally obtained in 2D
- early evolution + variable features well understood
- overall spectrum reproduced (to some degree...)

Modern picture

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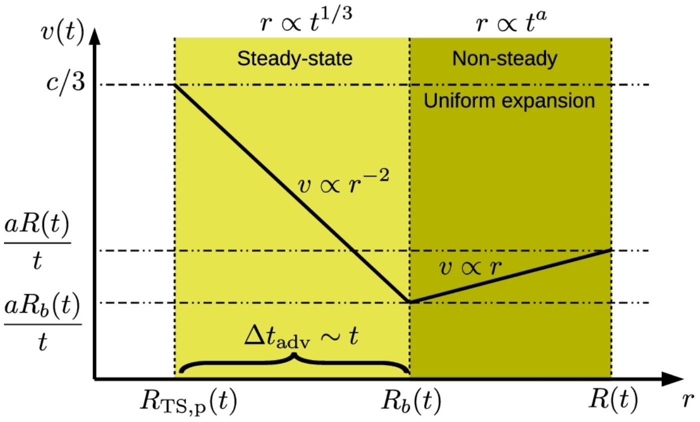
Many things are still missing...

- long-term evolution not explored in higher D
- inner nebula structure not well known
- σ problem still present

Project

Goal:

1. study nebula structure

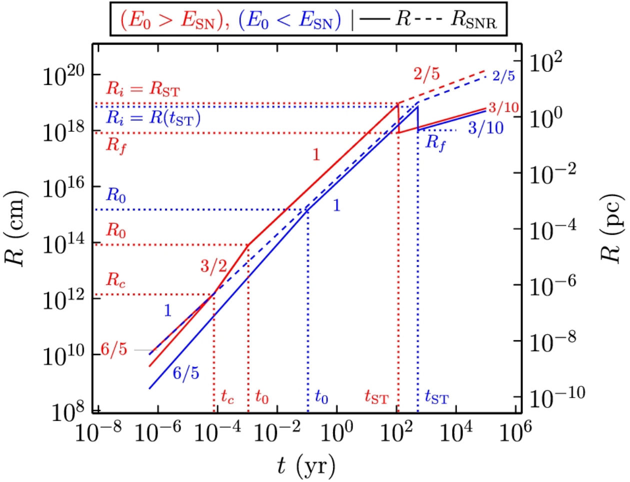


velocity structure of the nebula (Granot 2017)

Project

Goal:

1. study nebula structure
2. long term evolution



nebula radius with time (Granot 2017)

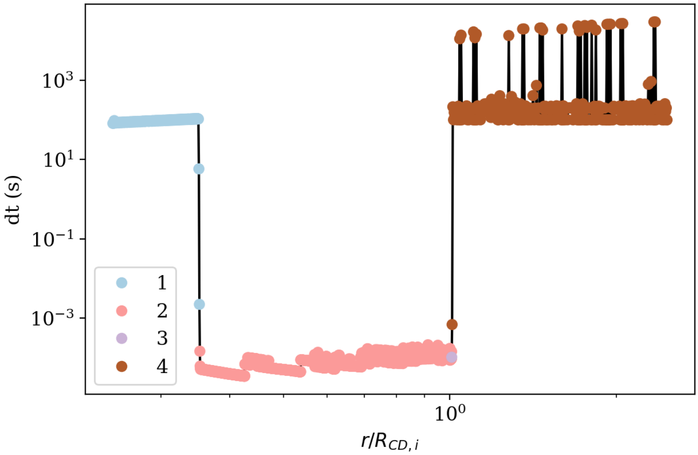
Project

Goal:

1. study nebula structure
2. long term evolution

Issue:

full simulations *very* costly
nebula the most expensive part



time step from CFL condition, nebula in pink

Methods

Can we use self-similar models to skip the expansion phase?

$\rightarrow$ shocks structure can be obtained exploiting self-similar properties

no literature on the shocked nebula part...

Project roadmap:

1. develop analytical model

Self-similar properties across regimes

$\rightarrow$ launch the simulation at any SNR age

(before reverberation)

Methods

Can we use self-similar models to skip the expansion phase?

$\rightarrow$ shocks structure can be obtained exploiting self-similar properties

no literature on the shocked nebula part...

Project roadmap:

1. develop analytical model
2. test with simulations

code used: GAMMA (Ayache et al 2022)

RHD on moving mesh

evolves e^- population (shocks, cooling)

Methods

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Project roadmap:

1. develop analytical model
2. test with simulations
3. produce lightcurves and spectra

Post-processing including various cooling regimes

Methods

Can we use self-similar models to skip the expansion phase?

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no literature on the shocked nebula part...

Project roadmap:

1. develop analytical model
2. test with simulations
3. produce lightcurves and spectra
4. upscale in 2 and 3D (wind profile, instabilities growth..)

Any possible code optimization **will** be made

Methods

Can we use self-similar models to skip the expansion phase?
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Project roadmap:

1. develop analytical model
2. test with simulations
3. produce lightcurves and spectra
4. upscale in 2 and 3D (wind profile, instabilities growth..)
5. go even further

A project with **a lot** of evolutions:

- wind effect at very early SN age
- synchrotron cooling effects on nebula
- other objects (MagnetarWN, various SNR types...)
- the same, but with RMHD


Thank you for your attention!