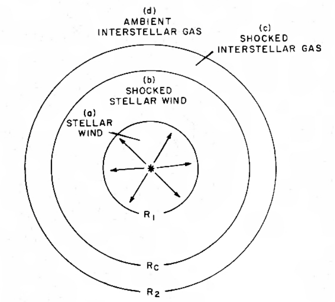
On the spectral softening in core-collapse supernova remnant expanding inside the wind bubble

Samata Das, Robert Brose, Dominique M.-A. Meyer, Martin Pohl, Iurii Sushch

DESY and University of Potsdam

TeVPA 2021
25-29 October

Stellar wind bubble



Schematic diagram of wind bubble

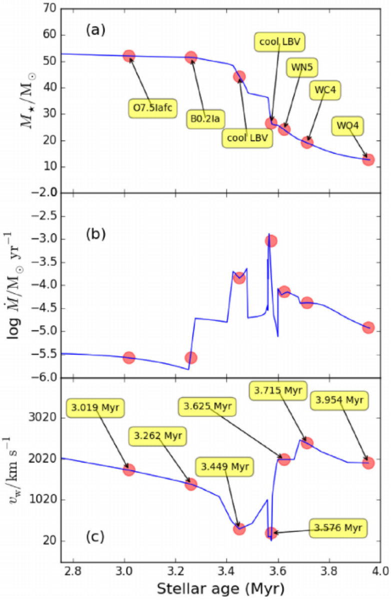
Weaver et al. [1977]

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

$$\rho_{wind}(r) = \frac{\dot{M}_\star(t)}{4\pi r^2 v_{wind}(t)}$$

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

$60 M_\odot$ Stellar evolution



- **Post Main-sequence evolution Luminous Blue Variable + Wolf Rayet phases**

Meyer et al. [2020]

following the stellar track of non-rotating $60\ M_\odot$ star at solar-metallicity **Groh et al. [2014]**

DSA
In test-particle approximation

- Particles acceleration to a power-law spectrum

$$n(E) \propto E^{-\frac{r+2}{r-1}} \qquad r = \frac{(1+\gamma)M_s^2}{(\gamma-1){M_s}^2+2}$$

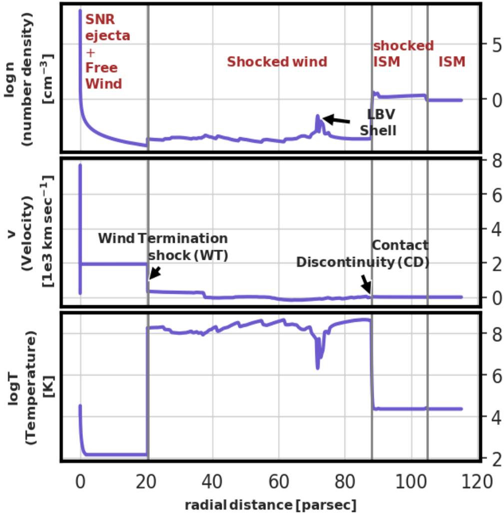
where $u_1 = r$ $(= 4,$ **strong shock**$)$ u_2
u_1 and **u_2** are **upstream** and **downstream** flow velocity respectively **in shock rest frame**.

- **Ingredients**

1. **Hydrodynamic evolution** of SNR inside CSM
2. Large-scale **magnetic field** profile and prescription for **diffusion**
3. Solution for **cosmic ray transport equation**

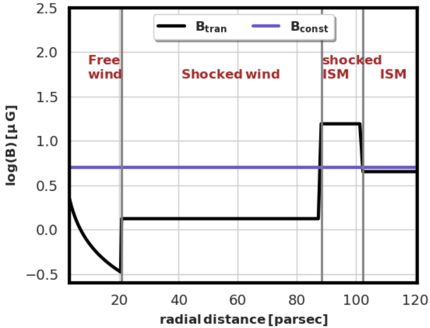
Numerical Method

Hydrodynamics after supernova explosion



Numerical Method

CSM magnetic field (B)



- $\mathbf{B_{const}}$ → Simple field configuration

$$B_u = B_d.\left(\frac{1+2R_{sub}^2}{3}\right)^{-1/2}$$

$$B_d = 16.5\mu G,$$
$$B_u = 5\mu G$$

- $\mathbf{B_{tran}}$ → Realistic configuration

Calculated field time evolution by solving **induction equation for MHD**

Transported magnetic field (B_{tran})

Stellar magnetic field

1. $B_r = B_\star \frac{R_\star^2}{r^2}$
2. $B_\phi = B_\star \frac{V_{rot}}{V_{wind}} (\frac{R_\star}{r})^2 (\frac{r}{R_\star} - 1)$
   $= B_\star \frac{V_{rot} R_\star}{V_{wind} r}$ $\quad r >> R_\star$

CSM magnetic field

$B_{CSM} = (0.33\,\mu G)\,\frac{R_{WT}}{r},$ *region* 1(excluding ejecta region)

$= 1.32\,\mu G,$ *region* 2 & 3

$= B_{shell} = 3.46 B_{ISM},$ *region* 4 $\quad B_{shell} = \frac{R^2 B_{ISM}}{R^2 - (R-D)^2}$

$= B_{ISM} = 4.5 \mu G,$ *region* 5

Radiation Acceleration Transport Parallel Code

Hydrodynamic evolution of SNR

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \mathbf{m}\\ E\end{pmatrix} + \nabla\begin{pmatrix}\rho\mathbf{u}\\ \mathbf{m}\mathbf{u}+P\mathbf{I}\\ (E+P)\mathbf{u}\end{pmatrix}^{T} = \begin{pmatrix}0\\0\\0\end{pmatrix}$$

Magnetic Field

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B})$$

Cosmic Ray Transport Equation

$$\frac{\partial N(r,p,t)}{\partial t} = \underbrace{\nabla D_r \nabla N}_{\text{Diffusion}} - \overbrace{\nabla\mathbf{u}N}^{\text{Advection}} - \frac{\partial}{\partial p}\Big(\underbrace{\dot{p}N}_{\text{Cooling}} - \overbrace{\frac{\nabla\mathbf{u}}{3}}^{\text{Acceleration}}Np\Big) + \underbrace{Q}_{\text{Injection}}$$

Numerical Method (RATPaC)

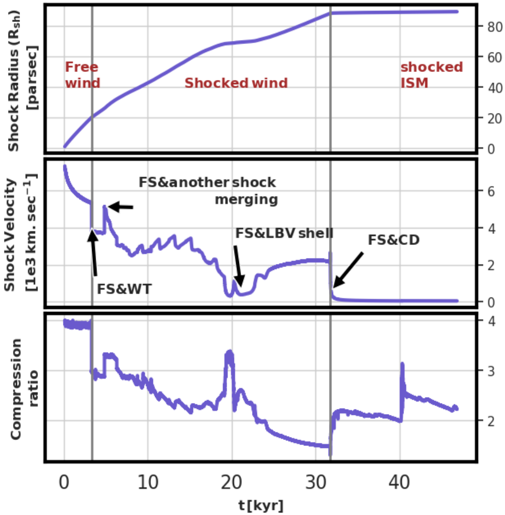
Solved the transport equation:

- 1-D spherical symmetry in a shock-centred coordinate system
- Included Synchrotron and inverse Compton losses for electrons
- Bohm-like diffusion close to shock and in downstream

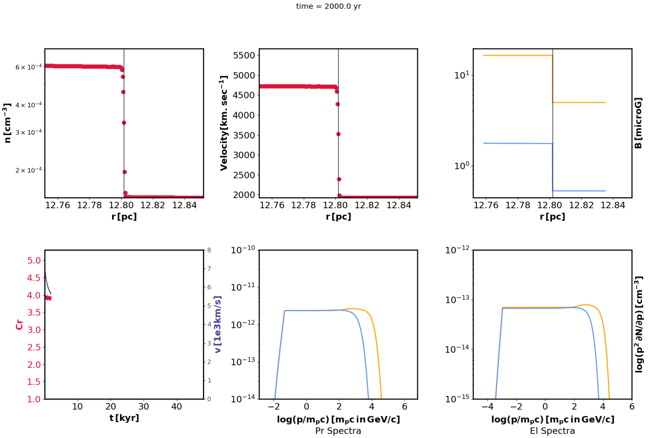
$$D = \zeta' \frac{v}{3} R_g = 10 D_B$$

- Test-particle limit ($\frac{P_{cr}}{P_{ram}} < 10\%$)

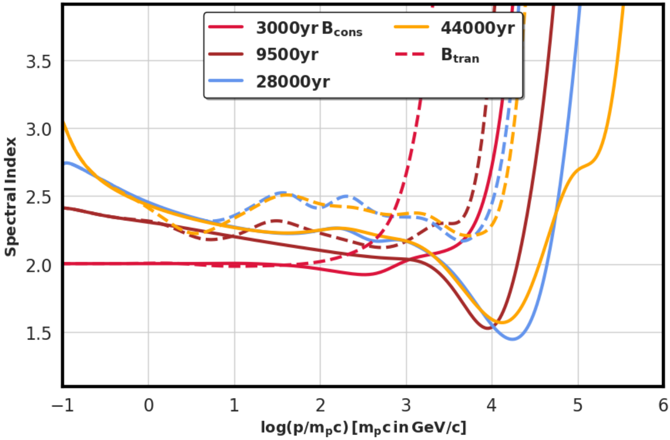
FS Parameters



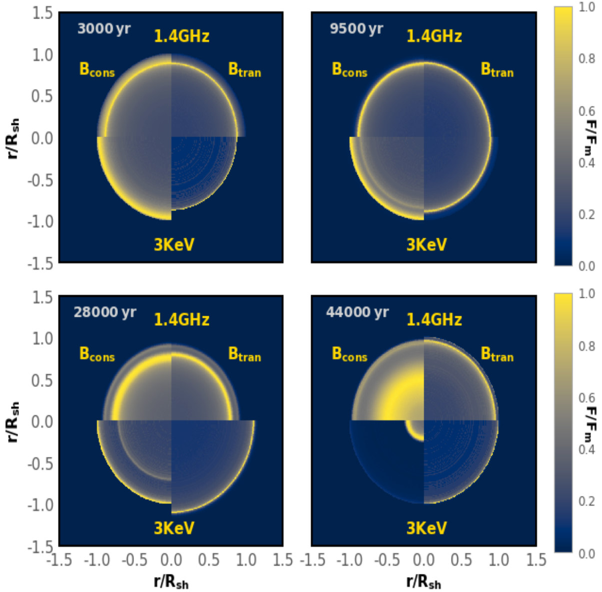
Particle Spectra



Variation of spectral index for proton

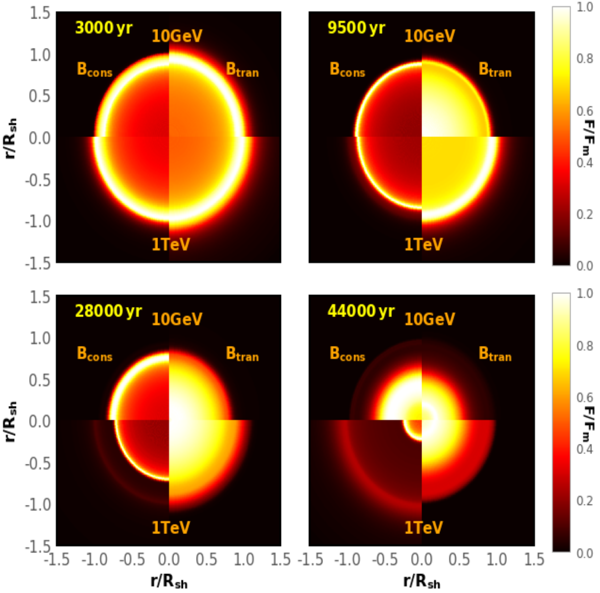


Synchrotron Emission Map



Gamma Emission Map

Inverse-Compton dominated



Conclusion

- Achieved particle spectra and emission theoretically from a SNR with one of the most massive progenitor stars.
- Spectral shape depends on the **temperature**, **FS interactions** and **magnetic field** in the bubble.
- Spectral index of cosmic ray spectra reaches $\mathbf{s} \approx \mathbf{2.5}$ with time. As a consequence, the synchrotron spectral index varies $\alpha \approx \mathbf{0.62 - 0.78}$ from **radio to infrared** in shocked wind.
- The magnetic field can have an extensive impact on emission from SNR.

Thank You

for your attention!

References

Jose H. Groh, Georges Meynet, Sylvia Ekström, and Cyril Georgy. The evolution of massive stars and their spectra. I. A non-rotating 60 M star from the zero-age main sequence to the pre-supernova stage. , 564:A30, April 2014. doi: *10.1051/0004-6361/201322573*.

D. M. A. Meyer, M. Petrov, and M. Pohl. Wind nebulae and supernova remnants of very massive stars. , 493(3): 3548–3564, April 2020. doi: *10.1093/mnras/staa554*.

R. Weaver, R. McCray, J. Castor, P. Shapiro, and R. Moore. Interstellar bubbles. II. Structure and evolution. , 218: 377–395, December 1977. doi: *10.1086/155692*.