Particle acceleration in supernova remnant expanding inside wind-blown bubble

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Abstract

Context. Supernova Remnants (SNRs) are considered as the primary sources of galactic cosmic rays (CRs), where CRs are assumed to be accelerated by diffusive shock acceleration (DSA) mechanism. The SNR shocks expand in the complex ambient environment, particularly in the core-collapse scenarios as those SNRs evolve inside wind-blown bubbles created by the mass-loss of massive stars. Therefore, the evolution of core-collapse SNRs, as well as CRs acceleration is expected to be considerably different from SNR evolution in a uniform environment.

Aims. The aim is to observe the influence of different ambient medium of core-collapse SNR shock on the particle spectra. Furthermore, the interactions of SNR shock with fluctuations in density within the wind-blown bubble generate several transmitted and reflected shocks. So, the impact of SNR shock interactions with different discontinuities, on particle spectra, and finally the effect on emission from the remnant are also the areas of focus.

Methods. The hydrodynamic structures of wind-blown bubbles at pre-supernova stages formed by $20M_\odot$, $35M_\odot$, and $60M_\odot$ stars have been used to create the ambient environment for SNRs. Evolution of those stars through different stages from Zero Age Main Sequence (ZAMS) to the pre-supernova stage, result into formation of structurally different wind bubbles. Then, the transport equation for cosmic rays, and hydrodynamic equations have been solved simultaneously in 1-D spherical symmetry.

Result. The modifications in particle spectra depend on the hydrodynamics and magnetic field structure of SNR ambient medium. We have obtained softer spectra with spectra index close to 2.5 originated during SNR interaction with hot wind bubble and further, magnetic field structure effectively influences the emission morphology of SNR as it governs the transportation of particles.

Background and Scopes

Core-collapse Supernova Remnants (SNRs) evolve inside **wind-blown bubbles** created by the massive progenitor stars. Consequently, the ambient environment of SNRs may have impact on generated particle spectra and emission. In this regard, the investigated questions:

- How do the hydrodynamics of wind-blown bubble play role in modification of particle acceleration?
- What are the effects of magnetic field configuration?

Modelling

Applied Codes- Radiation Acceleration Transport Parallel Code (**RAT-PaC**)[1] to study particle acceleration, **PLUTO** [2] for hydrodynamics
Data for Stellar wind properties- Pre-calculated stellar evolutionary tracks [3, 4]
Progenitor Star- non-rotating **60M$_\odot$** star with stellar metallicity

- **Hydrodynamics**
  1. Constructed circumstellar medium (CSM) at pre-supernova stage in 1-D spherical symmetry by solving **Hydrodynamic equations** for interactions between stellar winds from progenitor star and interstellar medium (ISM)
  2. Introduced supernova explosion by insertion of supernova ejecta in pre-supernova CSM
  3. Studied SNR evolution inside CSM in 1-D spherical symmetry
- **Magnetic field**
  1. **Constant compressed magnetic field** ($B_{\rm const}$)- Simple magnetic field configuration with field strength in SNR forward shock upstream $B_u = 5\mu G$ and in downstream $B_d = 16.5\mu G$ [5]
  2. **Transported magnetic field** ($B_{\rm tran}$)-
     - Magnetic field in **free wind region**: Parker spiral for the toroidal field [6]
     - Parametrised CSM field, constraining magnetic pressure is dynamically unimportant
     - Calculated the field evolution, by solving **induction equation for ideal MHD** considering transport of the field to downstream through SNR forward shock
- **Particle acceleration**- Solved Cosmic-ray **transport equation** to calculate diffusive shock acceleration **(DSA)** in test-particle approximation at SNR forward shock considering **Bohm diffusion** in 1-D spherical symmetry

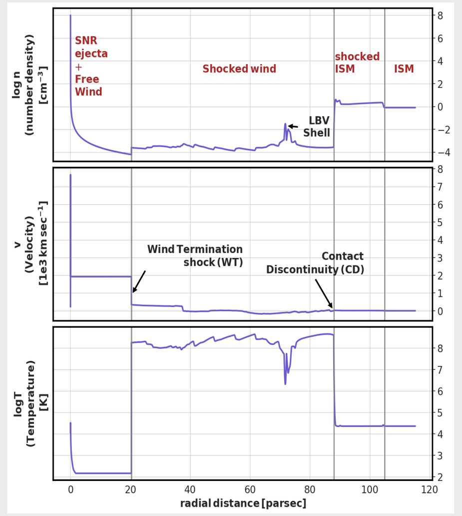

Fig. 1: Hydrodynamic parameters after supernova explosion. $60M_\odot$ star evolves through O and B type, Luminous Blue Variable (LBV), and Wolf-Rayet (WR) spectroscopic phases

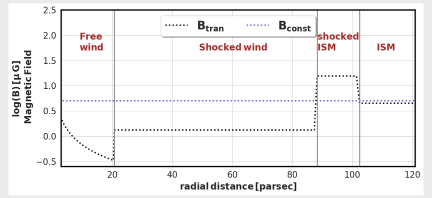

Fig. 2: CSM Magnetic Field

Shock Parameters

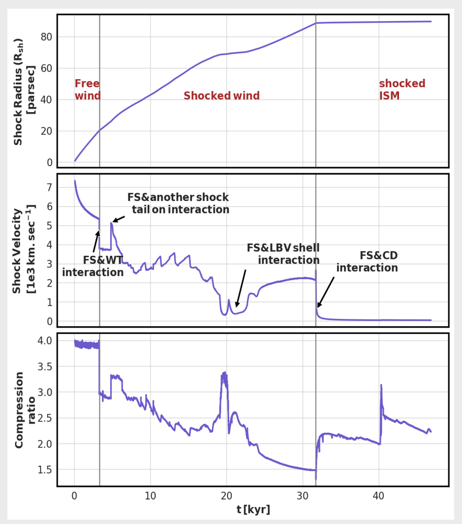

Fig. 3: SNR forward shock (FS) parameters

- **Forward shock velocity**: It depends on the interactions with different shocks and contact discontinuities as well as the density of the different regions of wind bubble.
- **Compression ratio**:
  1. It diverges from value 4 as soon as FS enters the hot shocked wind region.
  2. It is regulated by the sonic mach number of forward shock in different regions of wind bubble.

Particle Spectra

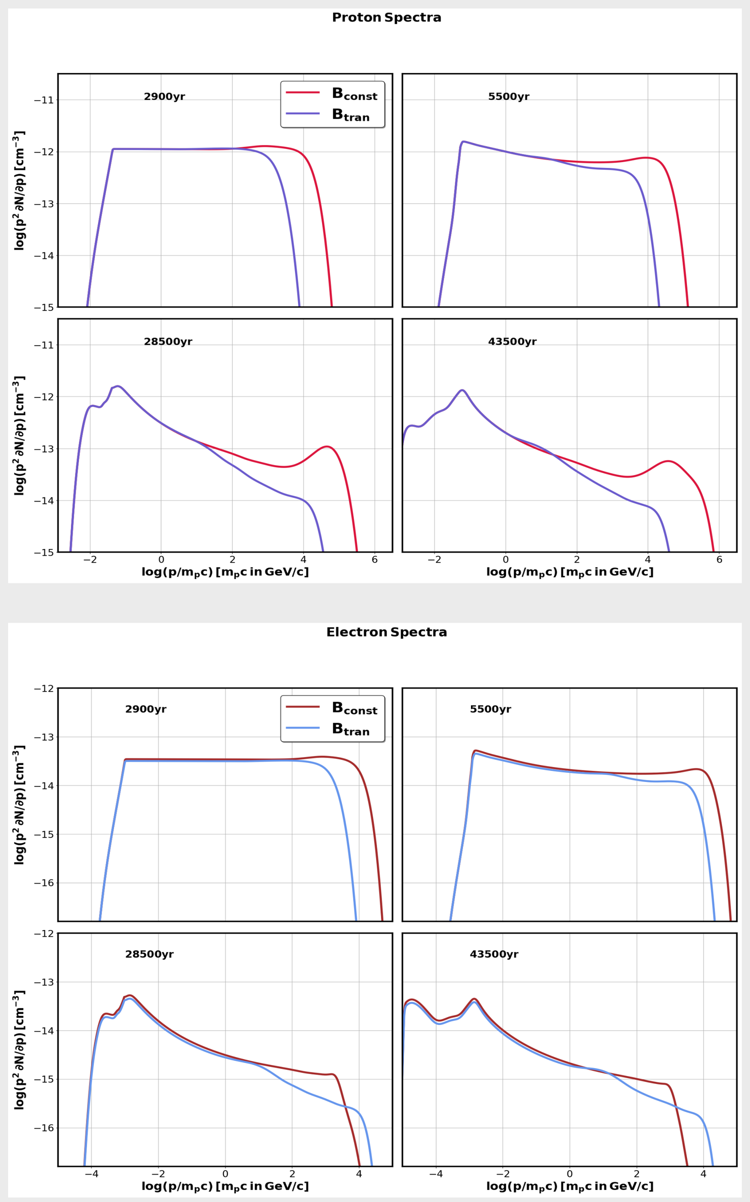

Fig. 5: Proton (Pr) and Electron (El) spectra for the entire downstream of forward shock at different ages during SNR forward shock evolution in wind bubble

N $\rightarrow$Differential Cosmic-ray density
p $\rightarrow$Momentum
m_p $\rightarrow$Proton mass

Location of forward shock in $\rightarrow$

free wind at 2900 year

- Pr, El Spectra follow almost p^{-2} spectra with maximum attainable energy constrained by magnetic field strength

shocked wind at 5500 year

- Spectral softening started along with the growth in injection of lower energy particles as FS is located in hot denser shocked wind region
- A noticeable spectral break near 10GeV for $B_{\rm tran}$ as higher energy particles penetrate deep downstream region with different magnetic field strength

shocked wind at 28500 year

- Achieved further softness in spectra with time evolution
- Maximum achievable energy for electrons, in $B_{\rm tran}$ scenario increases as lower magnetic field reduces synchrotron losses

shocked ISM at 43500 year

- Interaction between forward shock and high density contact discontinuity between shocked wind and shocked ISM causes significant injection in lower energy

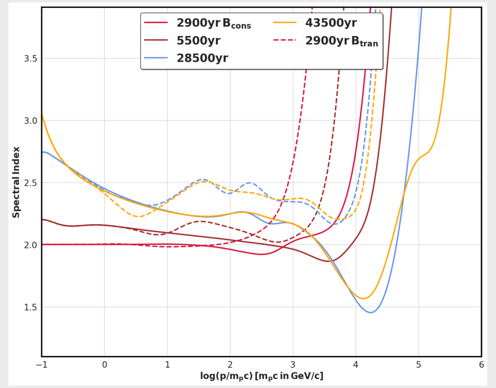

Fig. 6: Variation of the spectral index with momentum for protons at different ages of SNR

Non-thermal emissions

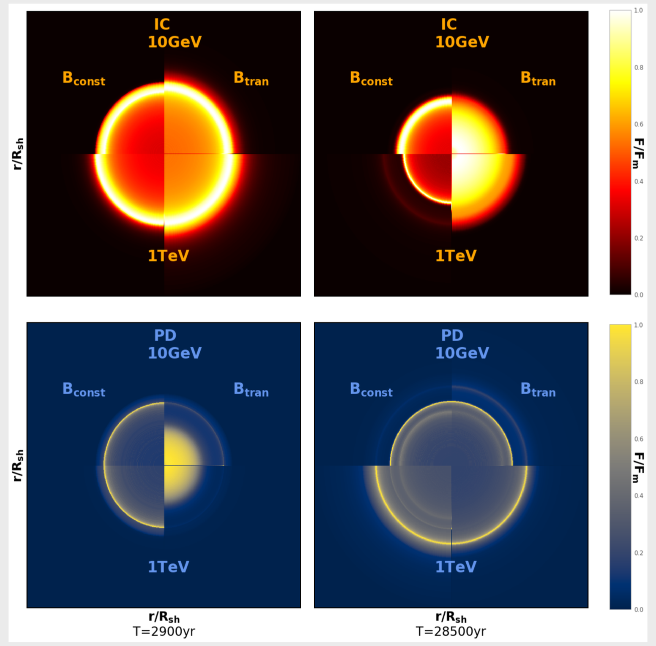

Fig. 7: Intensity maps for Inverse Compton (IC) and Pion-Decay (PD) emissions. Each panel extends in range $[-2R_{\rm sh}, 2R_{\rm sh}]$ to each direction and the calculated intensity F/F_m, normalised to its peak F_m

- At 2900 year, IC peak intensity emanates from electrons at the forward shock. For transported field, electrons penetrate to deep downstream of FS in the presence of weaker magnetic field and brighten the remnant. PD emission comes from dense ejecta region and near contact discontinuity between SNR forward and reverse shock and illumination of different regions depends on the magnetic field configuration.
- At 28500 year, the FS is approaching towards the contact discontinuity between shocked wind and shock ISM. At this time, maximum IC intensity emanates from the region near reverse shock for $B_{\rm const}$ at 1TeV. For $B_{\rm tran}$, origin of maximum IC emission is the entire region inside reverse shock. PD emission, at 10GeV comes from the region near contact discontinuity between SNR forward and reverse shock. Emission at 1TeV originated at the contact discontinuity between shocked wind and shocked ISM.

Conclusions

$60M_\odot$ progenitor star provides **spectra softer (spectral index reaches 2.5) than E^{-2} spectra as a result of hot bubble**. For comparison, considering $20M_\odot$ progenitor star ended life as Red-Supergiant stage should not provide spectra as soft as the presented scenario as the created bubble would not be hot enough. Further, for $35M_\odot$ star, the hydrodynamics would be very different depending on its evolutionary stages. Therefore, from the presented results, it can be concluded that:

- Spectral shape depends on the temperature of the bubble, forward shock interactions with different structures inside the bubble, and magnetic field. Therefore, the **evolutionary stages** in the other words, **Zero Age Main Sequence (ZAMS) mass, rotation and metallicity of progenitor stars have significant roles in spectral modification**.
- **Constant compressed magnetic field** depicts the effect of **pure hydrodynamics** whereas the more realistic **transported magnetic field** exhibits the **influence of CSM magnetic field** by constraining the diffusion and maximum achievable energy along with the hydrodynamics.
- The emission morphology suggests that **variation in magnetic field** can have an **extensive impact on emission** from SNR.

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