How stellar winds of progenitor massive stars shape the non-thermal emission from supernova remnants

Iurii Sushch
iurii.sushch@gmail.com
Robert Brose
Pavlo Plotko
Martin Pohl
Samata Das

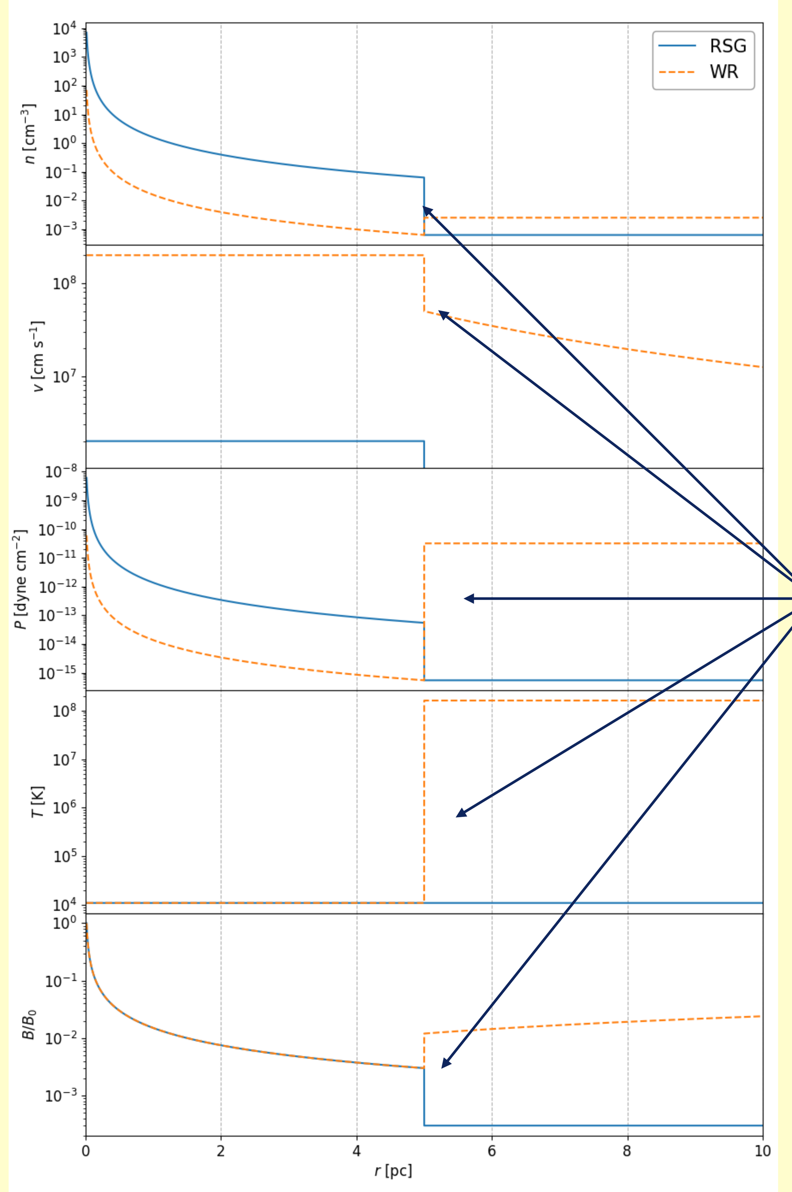
North-West University, 2520 Potchefstroom, South Africa
Astronomical Observatory of Ivan Franko National University of Lviv, Ukraine
Dublin Institute for Advanced Studies, Dublin , Ireland
Deutsches Elektronen Synchrotron DESY, Zeuthen, Germany
Institute of Physics and Astronomy, University of Potsdam,

Abstract. The very-high-energy gamma-ray emission observed from a number of supernova remnants (SNRs) indicates particle acceleration to high energies at the shock of the remnants and a potentially significant contribution to Galactic cosmic rays. It is extremely difficult to determine whether protons (through hadronic interactions and subsequent pion decay) or electrons (through inverse Compton scattering on ambient photon fields) are responsible for this emission. For a successful diagnostic, a good understanding of the spatial and energy distribution of the underlying particle population is crucial. Most SNRs are created in core-collapse explosions and expand into the wind bubble of their progenitor stars. This circumstellar medium features a complex spatial distribution of gas and magnetic field which naturally strongly affects the resulting particle population. In this work, we conduct a detailed study of the spectro-spatial evolution of the electrons accelerated at the forward shock of core-collapse SNRs and their nonthermal radiation, using the RATPaC code that is designed for the time- and spatially dependent treatment of particle acceleration at SNR shocks. We focus on the impact of the spatially inhomogeneous magnetic field through the efficiency of diffusion and synchrotron cooling. It is demonstrated that the structure of the circumstellar magnetic field can leave strong signatures in the spectrum and morphology of the resulting nonthermal emission.

Radiation Acceleration Transport Parallel Code

Powered by RATPAC

- Kinematic approach to particle acceleration
- Solves the particle transport equation time-dependently in 1-D spherical symmetry
- Coupled to 1-D hydrodynamic simulations which are performed on-the-fly with PLUTO
- Downstream magnetic field is passively transported with the plasma flow following the induction equation for ideal MHD
- Bohm-like diffusion assumed in this particular setup, but the code is capable of solving a transport equation for the magnetic turbulence spectrum (assuming Alfvén waves) in parallel to the transport equation of cosmic rays, hence calculating the diffusion coefficient self-consistently
- Synchrotron cooling is taken into account for electrons
- Products: time- and spatially-dependent spectra of accelerated particles and subsequent non-thermal emission through synchrotron, inverse Compton scattering, and hadronic interactions (including heavy elements)



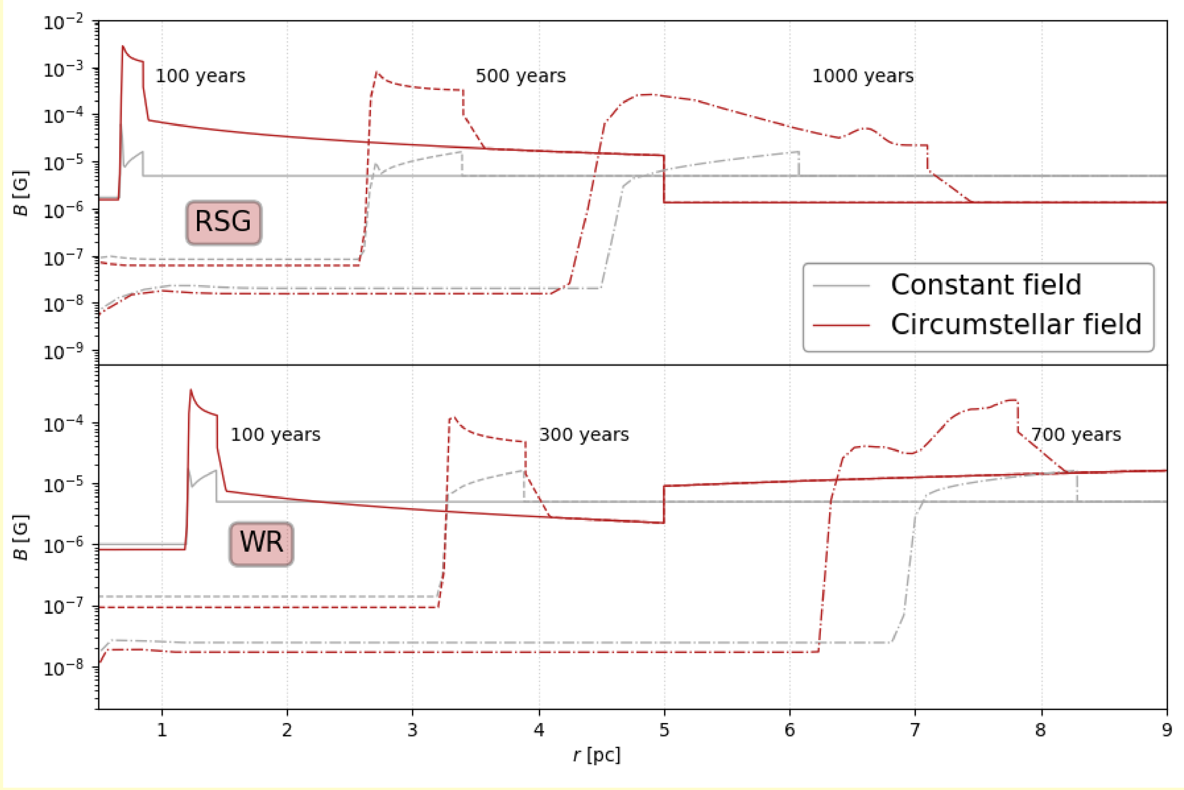
Transition point to the shocked wind from previous evolution stages

Magnetohydrodynamic profiles of the circumstellar environment right before the explosion of the supernova in the case of the Red Supergiant progenitor and in the case of the Wolf-Rayet star progenitor

Setup

Two types of circumstellar environment are considered: created by the Red Supergiant progenitor and created by the Wolf-Rayet star progenitor. We construct simplified generic magnetohydrodynamic profiles describing the environment important for the early evolution of the supernova remnant. We focus the study on the zone of the free stellar wind and the step-like transition to the next zone which constitutes the shocked wind of all previous phases. While in the case of the fast but diluted WR wind this transition is characterized by the wind termination shock, in the case of the dense RSG wind the structure is much more complex featuring a formation of the shell. We however ignore the shell, assuming that it is thin and approximate the transition by a sharp decrease of the density by a factor of 100.

Magnetic field is described by $1/r$ dependance in the free-wind zone and by the step-like change at the transition point. In the WR case the step like change is determined by shock conditions and in the RSG case we assume a decrease by a factor of 10 in line with the assumption of $B^2 \propto \rho$

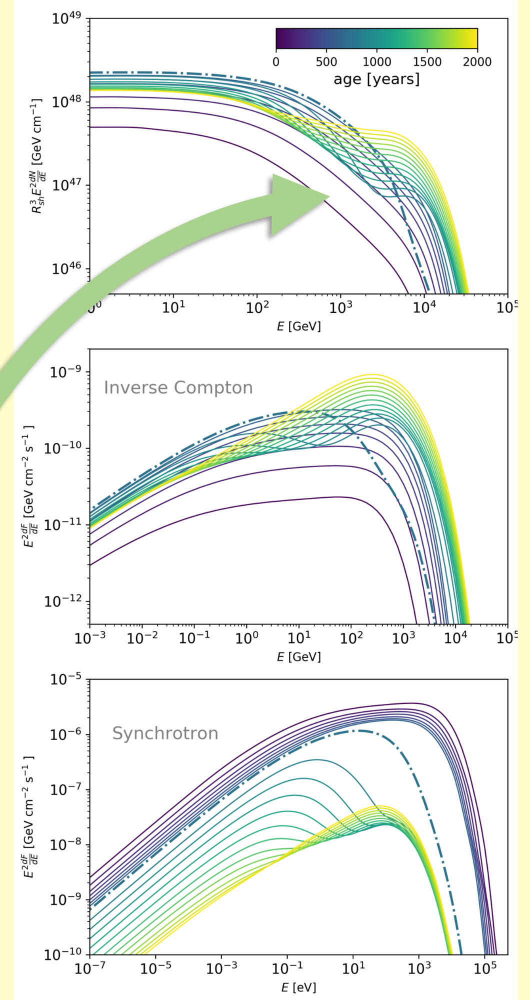


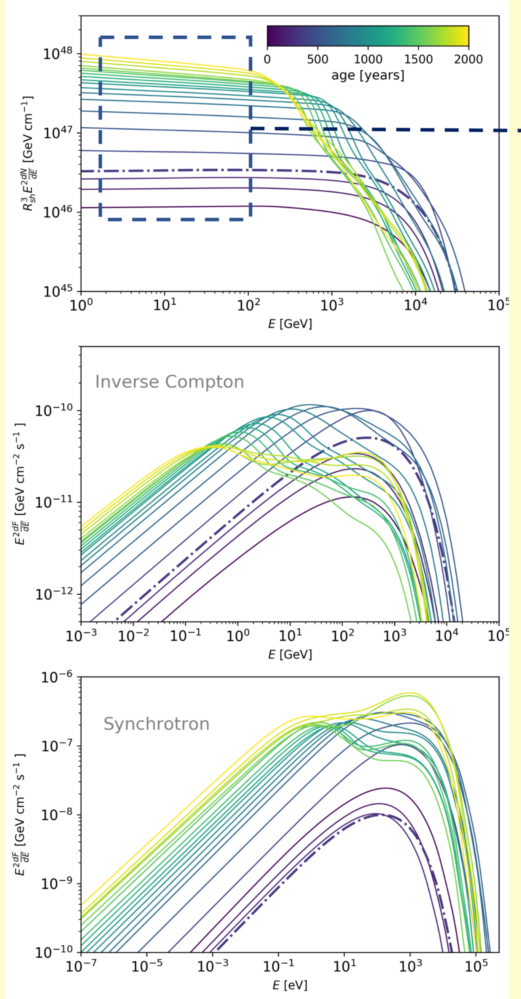
Temporal evolution of magnetic field radial distributions both downstream and upstream. The magnetic field is assumed to be amplified by a factor of 5 upstream, compressed at the shock and passively transferred downstream. The transition to the shocked wind is assumed to be at 5 pc for both cases. Grey lines correspond to the constant upstream field for comparison.

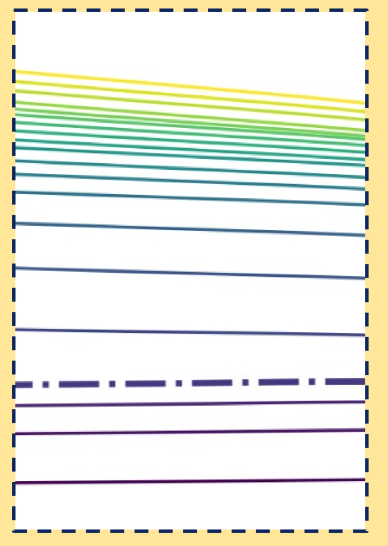
Watch videos!

Red Supergiant

Wolf-Rayet





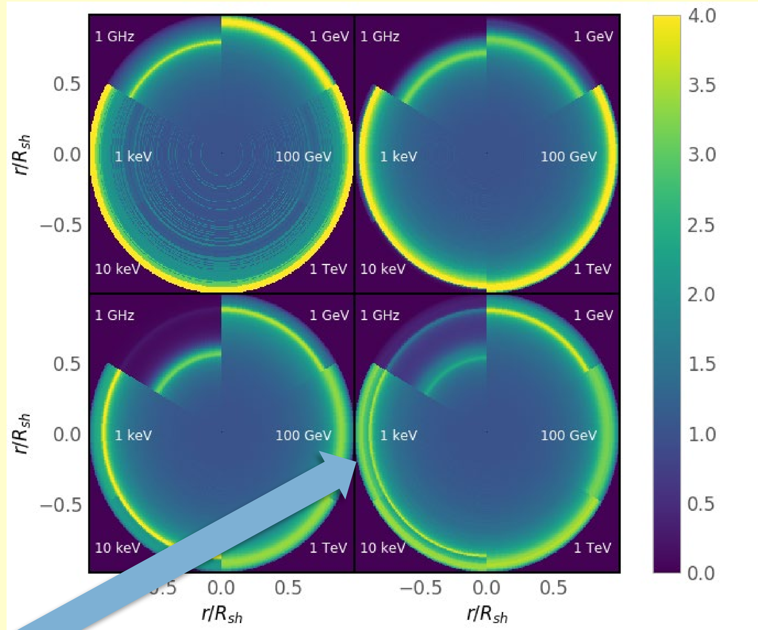


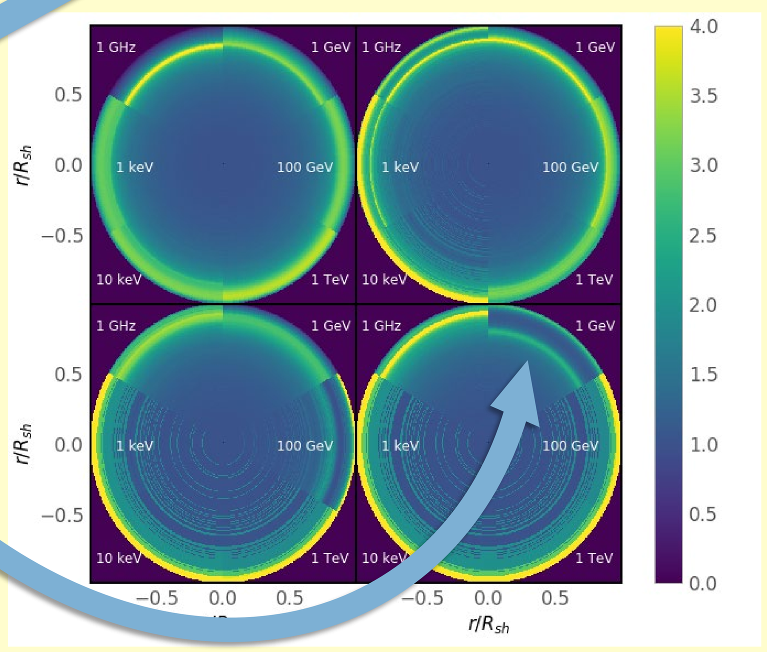
Considerable softening of the particle spectrum as the shock propagates into the hot shocked medium due to the decrease of the compression ratio at the shock.

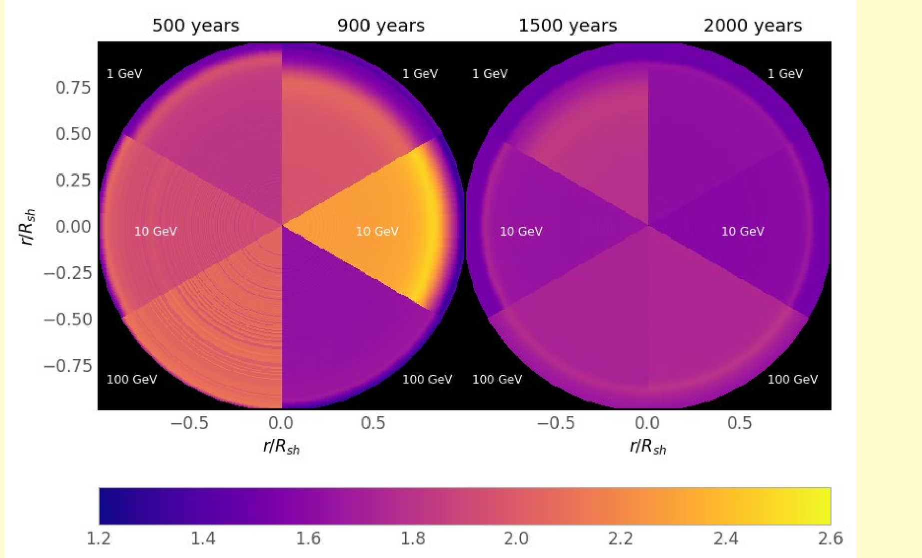
This result is more evident and better described in our work that studies particle acceleration in the SNR evolving inside the circumstellar wind-blown bubble created by a 60 $M_{\odot}$ star. The particle spectrum softens up to the spectral index of ~ 2.5.

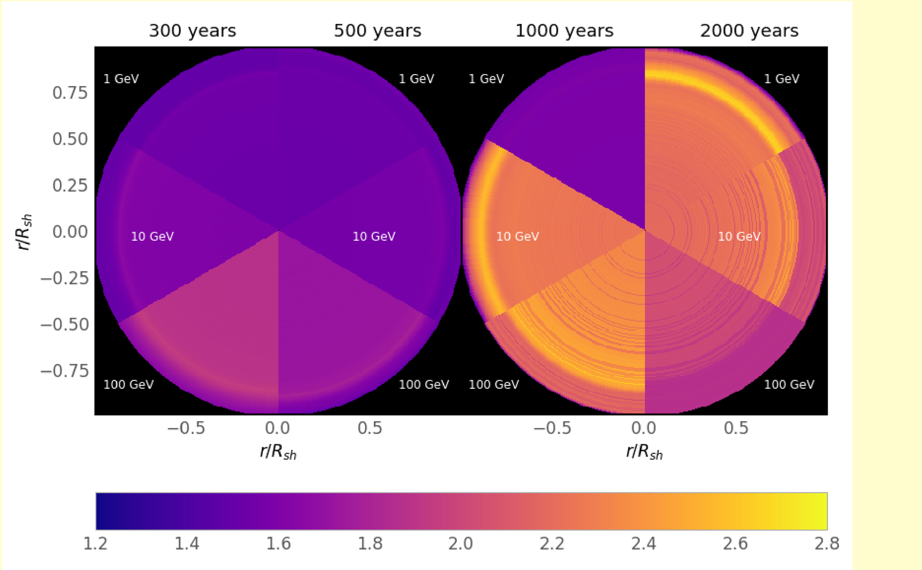
Das et al. 2022
A&A, 661, A128

Formation of two distinct population of **ELECTRONS** through the change of synchrotron cooling and diffusion conditions at the transitional point where the magnetic field changes abruptly. These two populations are both **SPATIALLY** and **SPECTRALLY** separated resulting in a **CONCAVE** total electron spectrum and subsequently **CONCAVE** synchrotron and inverse Compton spectra which shape is evolving with time. Interestingly, at some epochs the spectral shape of the gamma-ray emission generated in inverse Compton scattering strongly resembles the one expected from hadronic interactions. **SPATIAL** separation of two populations is reflected in **EMISSION MAPS** through the creation of a second bright ring





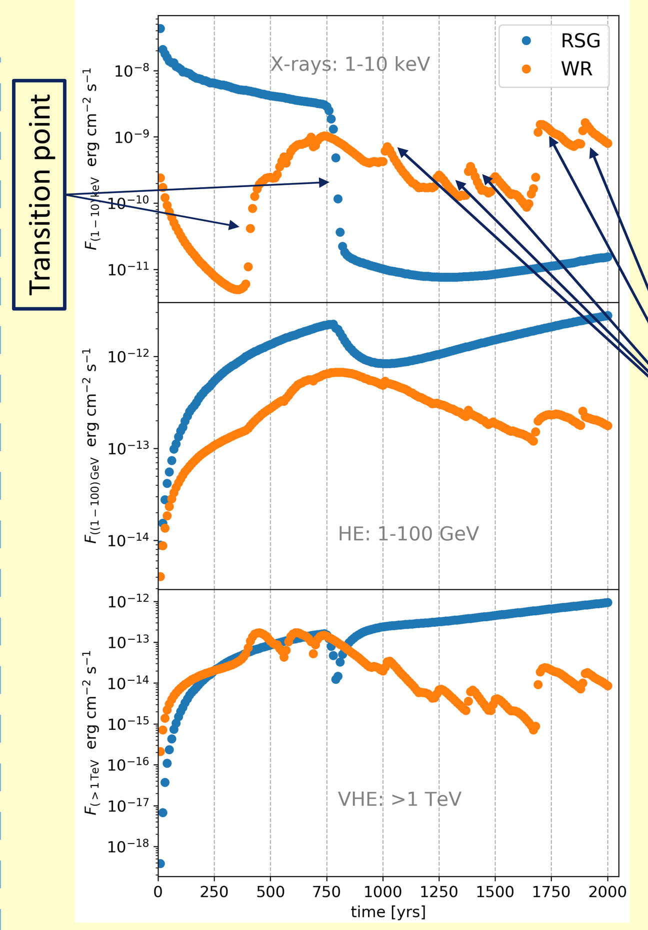




Spectral maps depicting the spectral index at different energies calculated as $\alpha(E) = \log \frac{F_\gamma(E-dE)}{F_\gamma(E+dE)} / \log \frac{E+dE}{E-dE}$

At certain times related to formation of two components spectral variation could reach up to $\Delta\alpha \sim 1$ (detectable!)

Transition point



Events of reflected shock – forward shock interactions

X-ray and gamma-ray light curves for supernova remnants evolving in the circumstellar medium created by Red Supergiant and Wolf-Rayet progenitors. At the transition point the flux in all the energy bands changes dramatically on rather short time scales. Especially this is relevant for the X-ray flux. Significant change can be detected even on ~ 10 year time scales and in fact this could be a plausible explanation for the detected decrease of X-ray emission in the Cassiopeia A supernova remnant.

Later on, interactions of the reflected shock formed at the passage of the transition point with the forward shock result in a speed-up of the forward shock and therefore boost of the X-ray and high-energy gamma-ray emission. These "flares" happen on short time scales and can be potentially detected already by current generation instruments.

Based on the paper:

Sushch+ 22,
ApJ, 926, 140

Defending UKRAINE together!

Charity foundation
COME BACK ALIVE
www.comebackalive.in.ua

γ 2022
7th Heidelberg International Symposium on High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022