Non-linear combined MHD- Monte Carlo simulations of proton acceleration in colliding wind binaries

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Abstract

We combine **Monte Carlo simulations** of particle acceleration, and **semi-analytical calculations** for obtaining a self-consistent **nonlinear modification** of collisionless shocks, induced by protons accelerated via **diffusive shock acceleration (DSA)**. The initial background is obtained from **MHD simulations** of **colliding-wind binary (CWB) systems**. Our approach allows the injection efficiency of DSA in the considered system be obtained from the simulations in a locally self-consistent way.

System

- **OB star** (left) and **WR star** (right)
- Stellar separation: $R = 1440 R_\odot$

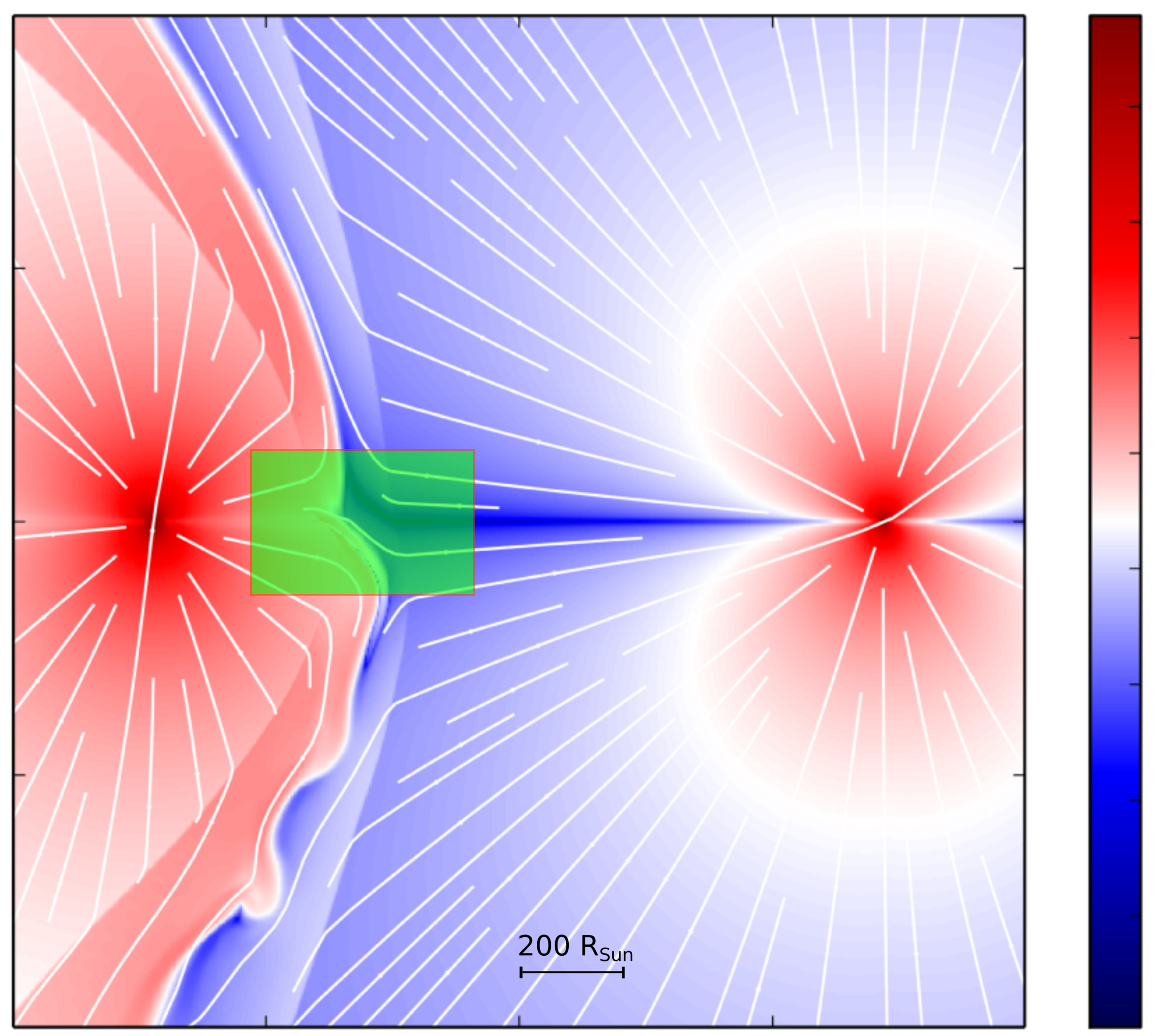

Fig. 1 : Intensity of magnetic field at the *y*-*z* plane. Highlighted region: simulation box for Monte Carlo shock acceleration simulations.

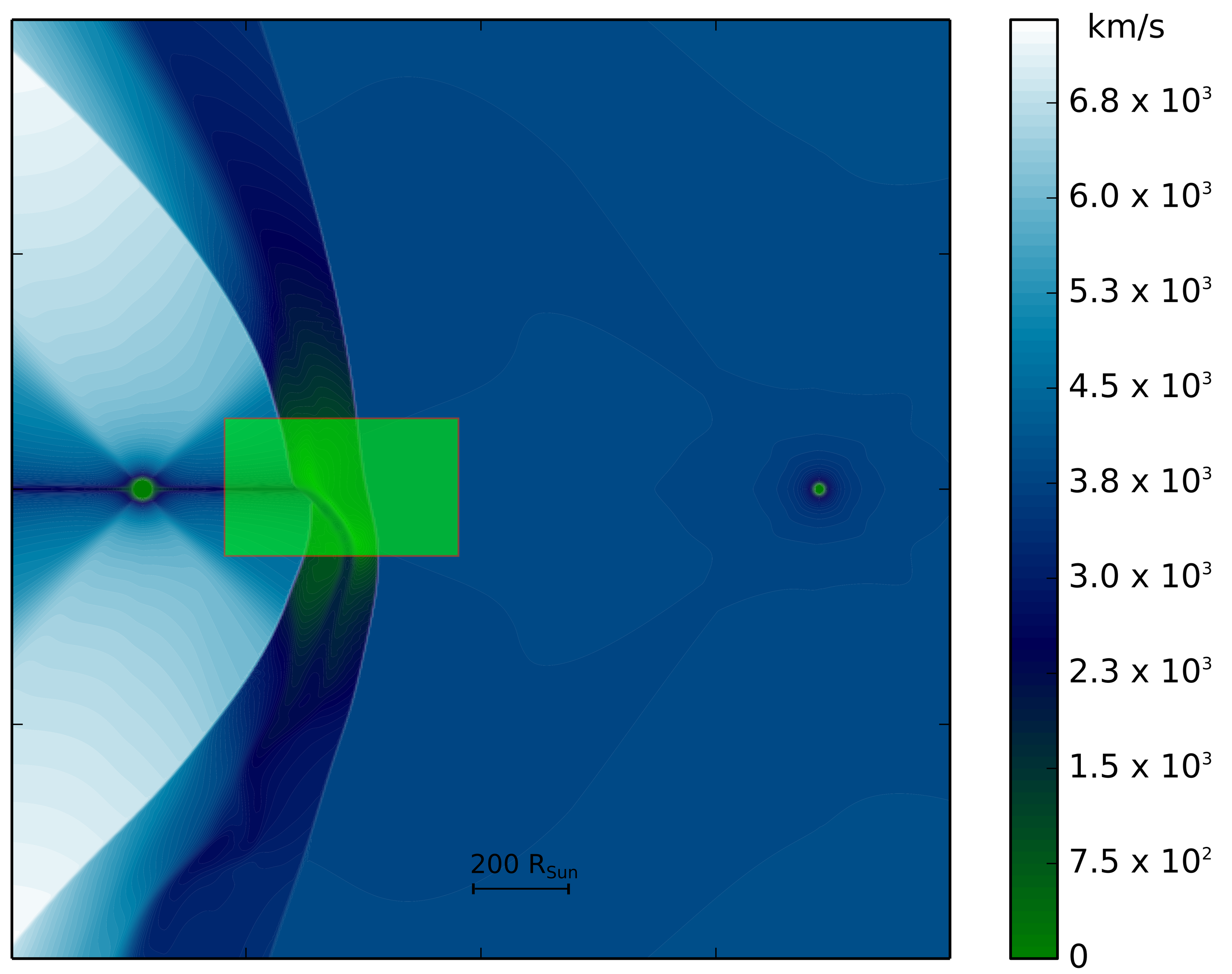

Fig. 2 : Absolute velocity of stellar wind at the *y*-*z* plane. Highlighted region: simulation box for Monte Carlo shock acceleration simulations.

Results

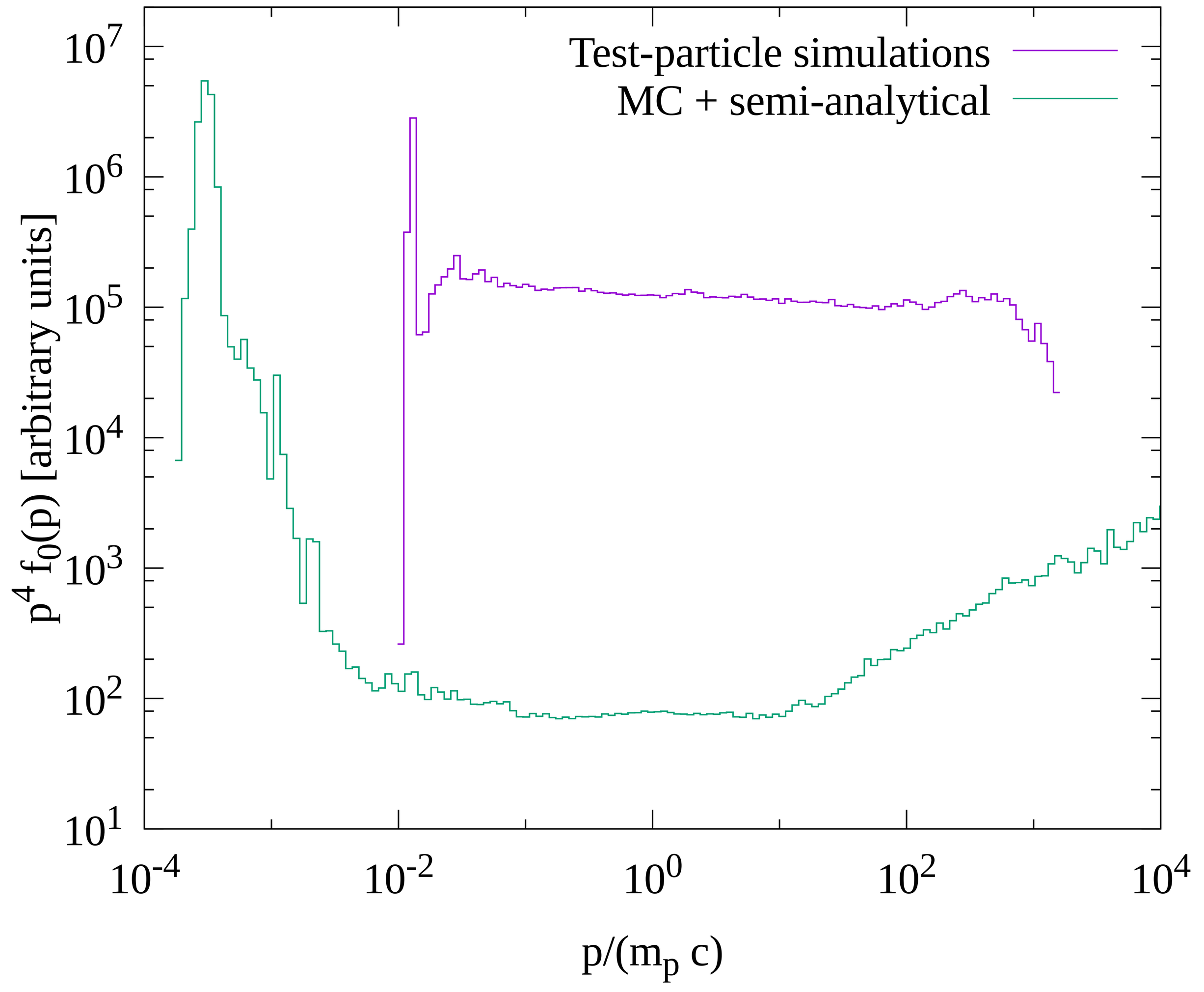

Fig. 3 : Spectra of accelerated protons with the test-particle approach and the nonlinear approach.

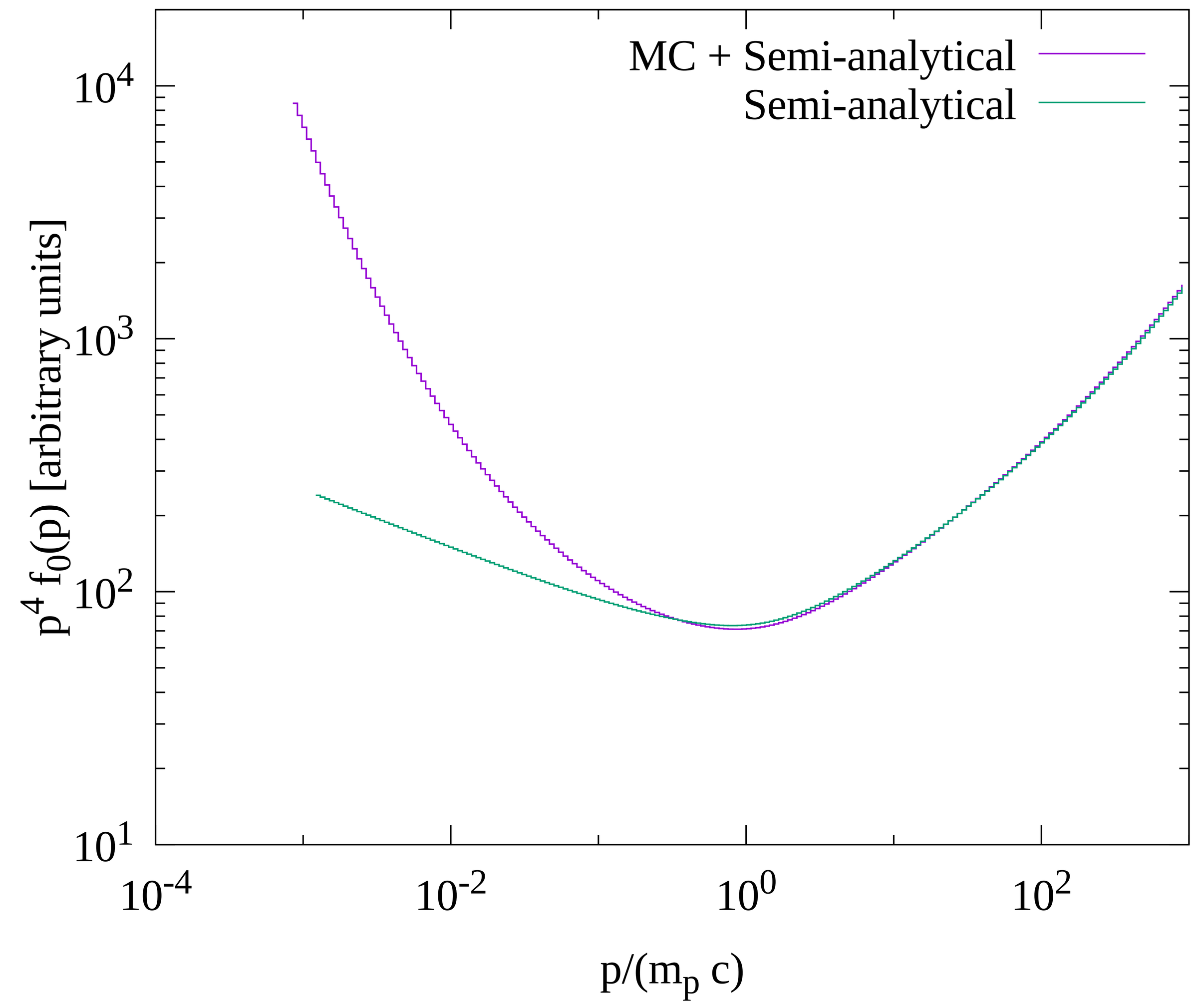

Fig. 5 : Nonthermal tail of the particle distribution obtained with the purely semi-analytical method and the semi-analytical combined with MC.

Conclusions

Comparison of methods:

- Different fraction of particles injected into the acceleration process
- Same spectrum at relativistic energies

Application to CWB system:

- Shock modification due to accelerated particles produces appreciable differences in both normalization and spectral shape of nonthermal tail

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Introduction

In **colliding-wind binary (CWB) systems**, the supersonic winds of two stars collide, forming a **wind-collision region (WCR)** delimited by two shocks. Such systems are expected to produce a nonthermal distribution of energetic particles via **diffusive shock acceleration (DSA)** at the collisionless shocks. Interacting with the environment, relativistic electrons and/or protons are in turn expected to produce γ-rays. Test-particle Monte Carlo simulations suggest that the energy put into nonthermal protons is non-negligible. Their backreaction on the shock itself therefore has to be taken into account. We perform **Monte Carlo simulations** of particle acceleration, obtaining the background from **MHD simulations** of an archetypal CWB system. We further take into account the **feedback** of the accelerated protons **on the local shock structure**, where the particles are injected. Global changes to the system are neglected here. Our approach allows the injection efficiency of DSA in the considered system be obtained from the simulations in a locally self-consistent way.

MHD simulations of colliding wind binaries

Being interested in studying particle acceleration in CWBs, we obtain the initial background from MHD simulations of such systems.

- Used code: CRONOS [1]
- The influence of the stellar magnetic field on wind acceleration is considered
- The magnetic field and the plasma (fluid) evolve solving the MHD equations
- The wind collision region forms when the two winds collide

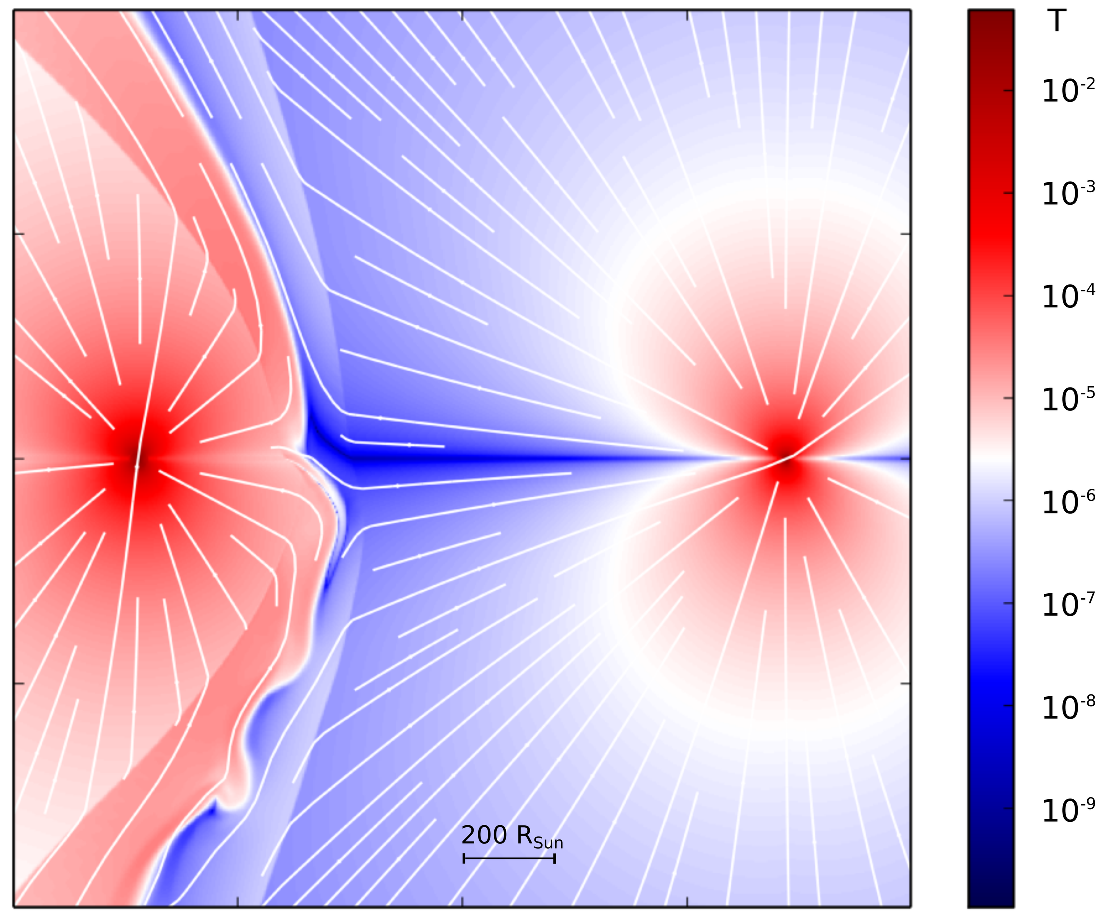

Fig. 6 : Intensity of magnetic field at the *y*-*z* plane.

Monte Carlo simulations of particle acceleration

Monte Carlo simulations allow to simulate single particles representing the protons of the winds. These are scattered by the background and can be accelerated via Fermi acceleration.

- Full trajectory calculation
- Large angle scattering
- Mean time between scatterings: $t_c = \eta r_g / v$
  - r_g gyroradius
  - v particle speed
  - $\eta = 1$ proportionality factor (highly turbulent medium) [2]
- Particles injected close to the selected shock
- Spectra recorded at the corresponding shock front

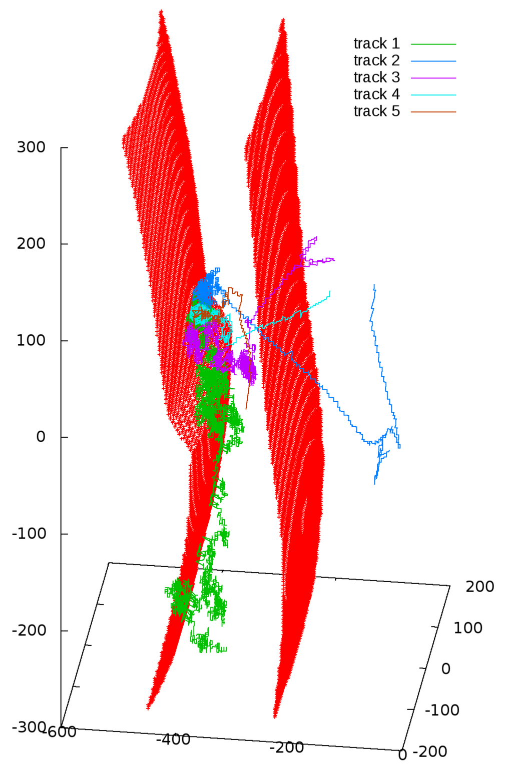

Fig. 7 : Particles moving and being scattered in the simulation box.

Semi-analytical method for nonlinear shock modification

The semi-analytical approach of Amato and Blasi [5] computes the shock modification caused by the accelerated protons.

- Conservation of momentum flux
- The pressure of accelerated protons modifies the flow velocity of the incoming plasma
- Formation of a subshock and a shock precursor
- Two compression ratios: r_{Sub} and r_{Tot}, smaller and higher than the unmodified compression ratio, respectively

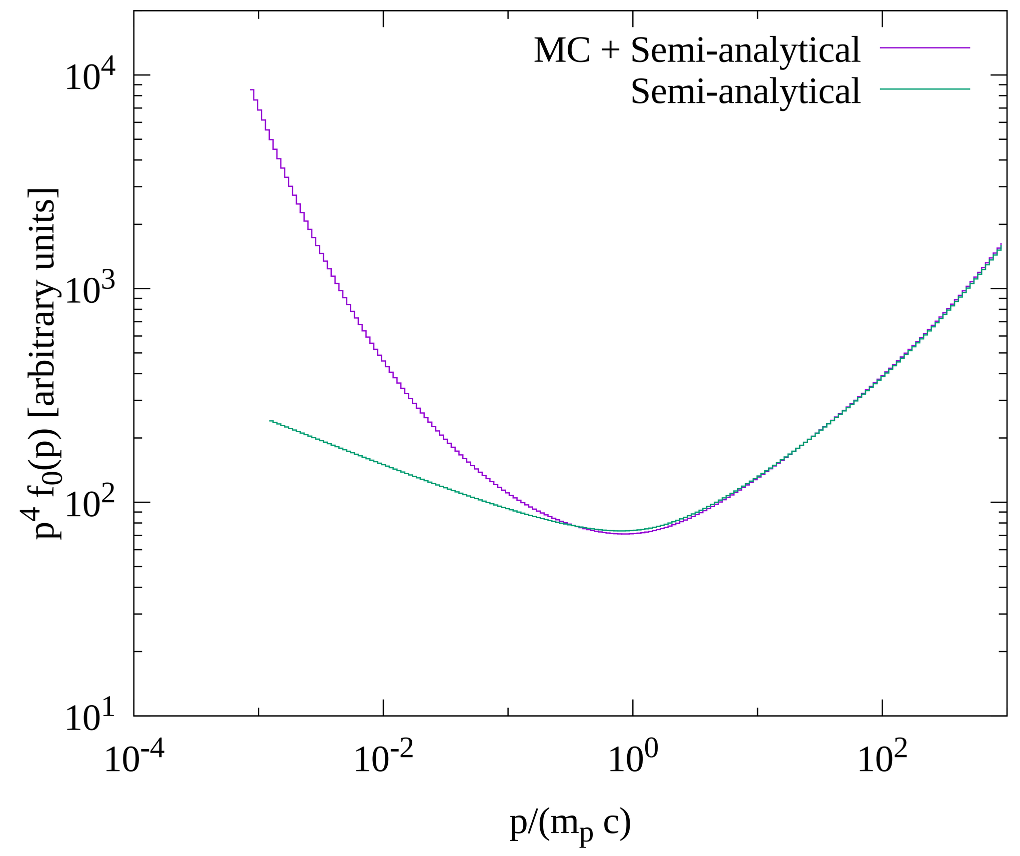

Fig. 8 : Example of nonthermal particle distribution of a modified shock.

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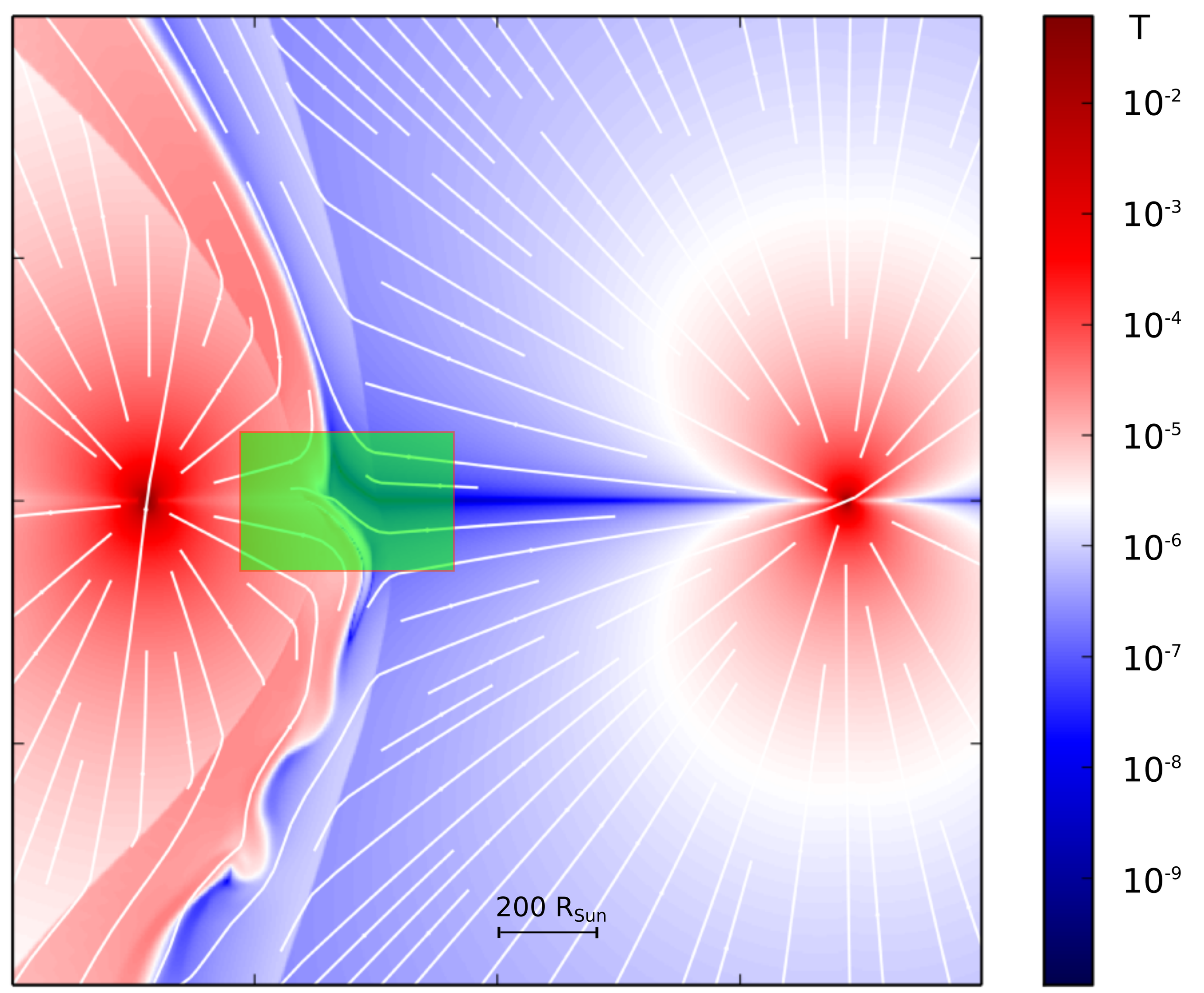
System



- **OB star** (left) and **WR star** (right)
- Stellar separation: $R = 1440 R_\odot$
- **Parameters of the system** [3]:

Star	M_* [$M_\odot$]	R_* [$R_\odot$]	T_* [K]	L_* [$L_\odot$]	$\dot{M}$ [$M_\odot$ yr^{-1}]	v_∞ [km s^{-1}]	B_* [G]
OB	30	20	23000	10^5	10^{-6}	4000	100
WR	30	10	40000	2.3×10^5	10^{-5}	4000	100

- M_* stellar mass
- R_* stellar radius
- T_* effective temperature
- L_* luminosity
- $\dot{M}$ mass loss rate
- v_∞ terminal velocity of wind
- B_* surface magnetic field

Fig. 7 : Intensity of magnetic field at the y-z plane. Highlighted region: simulation box for Monte Carlo shock acceleration simulations.

Results

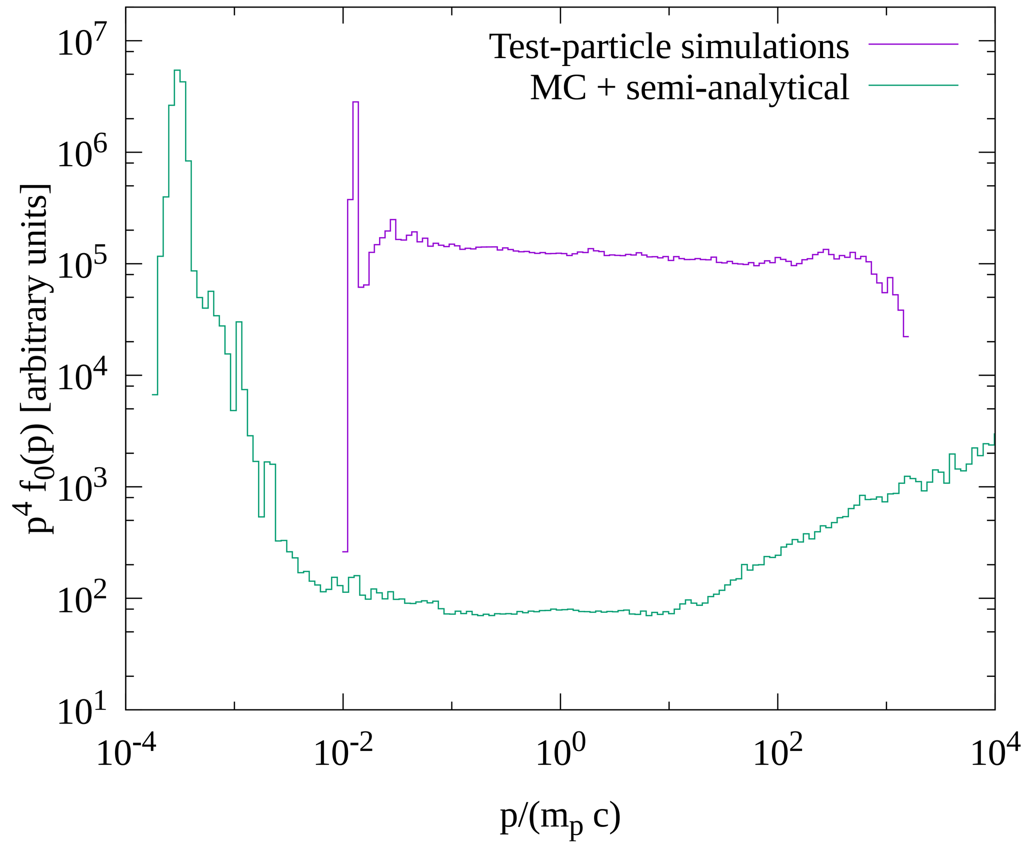


Fig. 8 : Spectra of accelerated protons with the test-particle approach and the nonlinear approach.

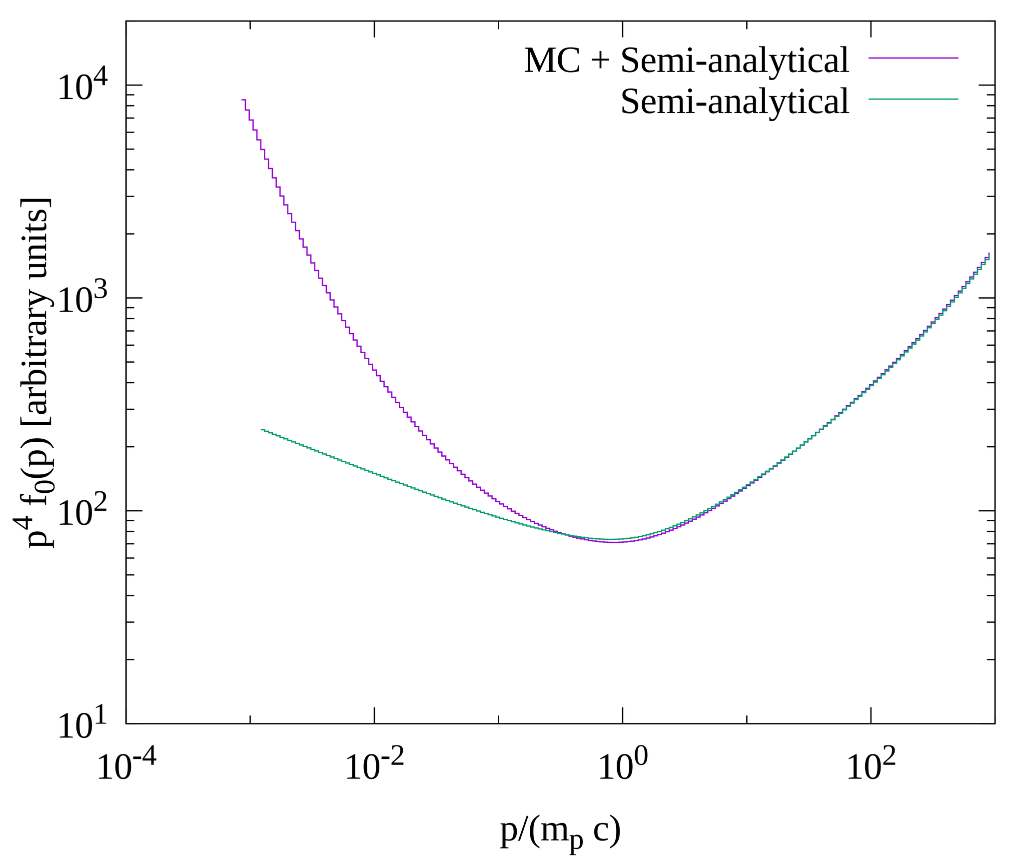


Fig. 9 : Nonthermal tail of the particle distribution obtained with the purely semi-analytical method and the semi-analytical combined with MC.

Method	Subshock compression ratio r_{Sub}	Total compression ratio r_{Tot}	Fraction of thermal protons injected η_0
MC + SA	2.1	94	$\approx 10^{-2}$
SA	3.4	80	$\approx 4 \cdot 10^{-4}$

Discussion

Comparison of purely semi-analytical and Monte Carlo + semi-analytical methods:

- Purely semi-analytical method: η_0 set "by hand". Only particle with momentum greater than an certain multiple of the thermal momentum of the downstream plasma can take part in DSA.
- Monte Carlo method: η_0 not prescribed. Thickness of the shock considered infinitesimal, scattering law needed.
- Present work: maximal momentum is set at $p_{max} = 10^3\, m_p c$.
- Despite very different fractions of injected particles at low momenta, the accelerated protons modify the shock in such a way that the relativistic part of the nonthermal tails of the proton distribution coincide. This happens because most of the pressure of accelerated particles, which modifies the shock structure, is exerted in the relativistic regime.

Comparison of test-particle and nonlinear methods:

- With test-particle Monte Carlo simulations, the energy in the accelerated protons is unrealistically high
- The Monte Carlo method combined with the semi-analytical one yields a solution which conserves energy and momentum fluxes.
- Both normalization and spectral shape are clearly different in the two cases, with possible observable consequences.

Conclusions and Outlook

We presented a method for simulating particle acceleration at the shock fronts of a colliding wind binary system. This combines three different simulations, taking advantage of their strengths, in order to obtain proton spectral energy distributions as realistic as possible. We show that the combining Monte Carlo simulations and the semi-analytical model with the same maximal energy yields similar results for the high-energy part of the spectra. This despite a difference in the fraction of thermal particles injected in the acceleration process between the Monte Carlo method (where no prescription is needed) and the semi-analytical prescription.
The comparison of test-particle and nonlinear simulations applied to an archetypal CWB system highlights appreciable differences in both normalization and spectral shape of the nonthermal tail of the proton distribution. Our simulations suggest that the flow velocity of the winds can be modified by the accelerated protons. A caveat is therefore necessary, since the spectra obtained here cannot consider the global changes of the wind structure.
Future work will test models of real systems, aiming at obtaining predictions for γ-ray fluxes.

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References and Acknowledgements

References:

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