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

Emanuele Grimaldo¹, Anita Reimer¹, and Ralf Kissmann²

¹Institute for Theoretical Physics, University of Innsbruck, Austria
²Institute for Astro- and Particle Physics, University of Innsbruck, Austria

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: \( R = 1440R_\odot \)

RESULTS

- 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.

APPLICATIONS OF THE RESULTS

- 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

CONCLUSIONS

emanuele.grimaldo@uibk.ac.at
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 $\gamma$-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

![Figure 6](image.png) Intensity of magnetic field at the y-z plane.

![Figure 7](image.png) Particles moving and being scattered in the simulation box.

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: $t_0 = \eta r_g/v$
  - $r_g$ 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

![Figure 8](image.png) Example of nonthermal particle distribution of a modified shock.

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
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 $\gamma$-ray fluxes.
**References and Acknowledgements**

**References:**


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