Monte Carlo Simulations of Proton Acceleration in Colliding Wind Binaries

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Abstract

Regions where the strong stellar winds of binary systems of massive, hot stars collide, forming two shock fronts, are expected to be suitable environments for particle acceleration. We investigate injection and acceleration of protons in a typical colliding wind binary (CWB) system by means of Monte Carlo simulations with a test-particle approach. We rely on hydrodynamic simulations for determining the background conditions in the wind collision region. Both shocks on either side of the contact discontinuity are considered, looking for different accelerated particle populations, that could result in different components of the γ-ray spectrum. Such studies may contribute to understand the lack of detection of γ-rays from most of these CWB systems up to now.

Motivations

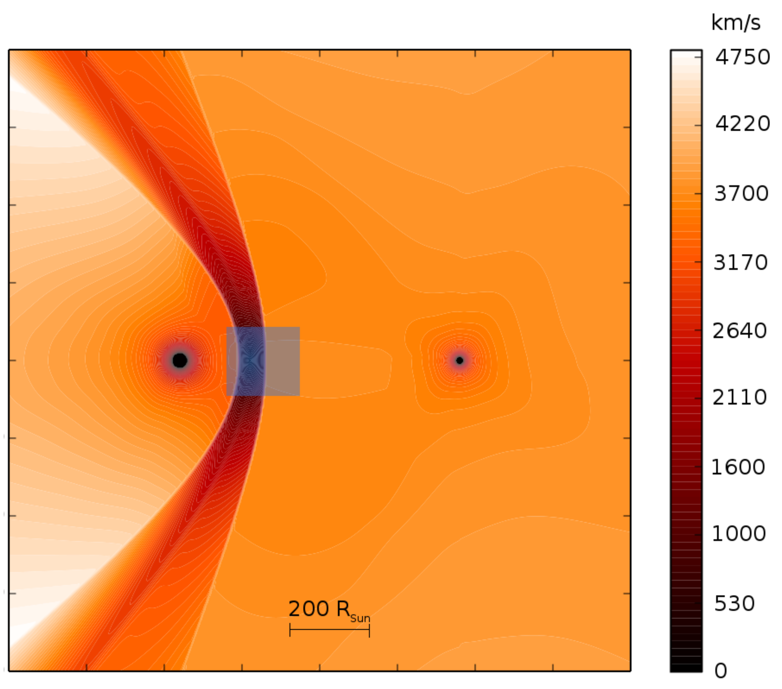
Particles accelerated at the shocks forming at the wind collision region of a binary system of massive stars are expected to produce γ-rays predominantly either through inverse Compton scattering of electrons in the stellar radiation fields, or through the decay of neutral pions produced in proton-proton collisions. Up to now, the only colliding wind binary system associated with γ-ray emission is η Carinae, where two components seem to be present. So far, there is no evidence for γ-ray emission from other binary massive star systems, such as WR 140 or WR 147, which were expected to be detected with comparable or even higher fluxes.

Method

Monte Carlo simulations of diffusive shock acceleration combined with hydrodynamic (HD) simulations:

- **Background** plasma conditions **from HD simulations**, using CRONOS [1]
- Test particle approach
- Guiding centre approximation
- Large angle scattering
- Mean time between scatterings: $t_c = \eta r_g / v$
  - r_g gyroradius
  - v particle speed
  - $\eta = 3$ proportionality factor (highly turbulent medium) [2]
- Background magnetic field aligned with plasma flow velocity
- Particles injected at the shocks on B- and WR-side of WCR
- Spectra recorded at corresponding shock front

System



- **B star** (left) and **WR star** (right)
- Stellar separation:
  $$R = 720 R_\odot$$
- **Two shock fronts** delimit the wind collision region (WCR)
- Compression ratios r:
  $$r_{WR} > r_B > 4$$
- Blue square: region used for Monte Carlo shock acceleration simulation

Stellar parameters [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]
B	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

Results

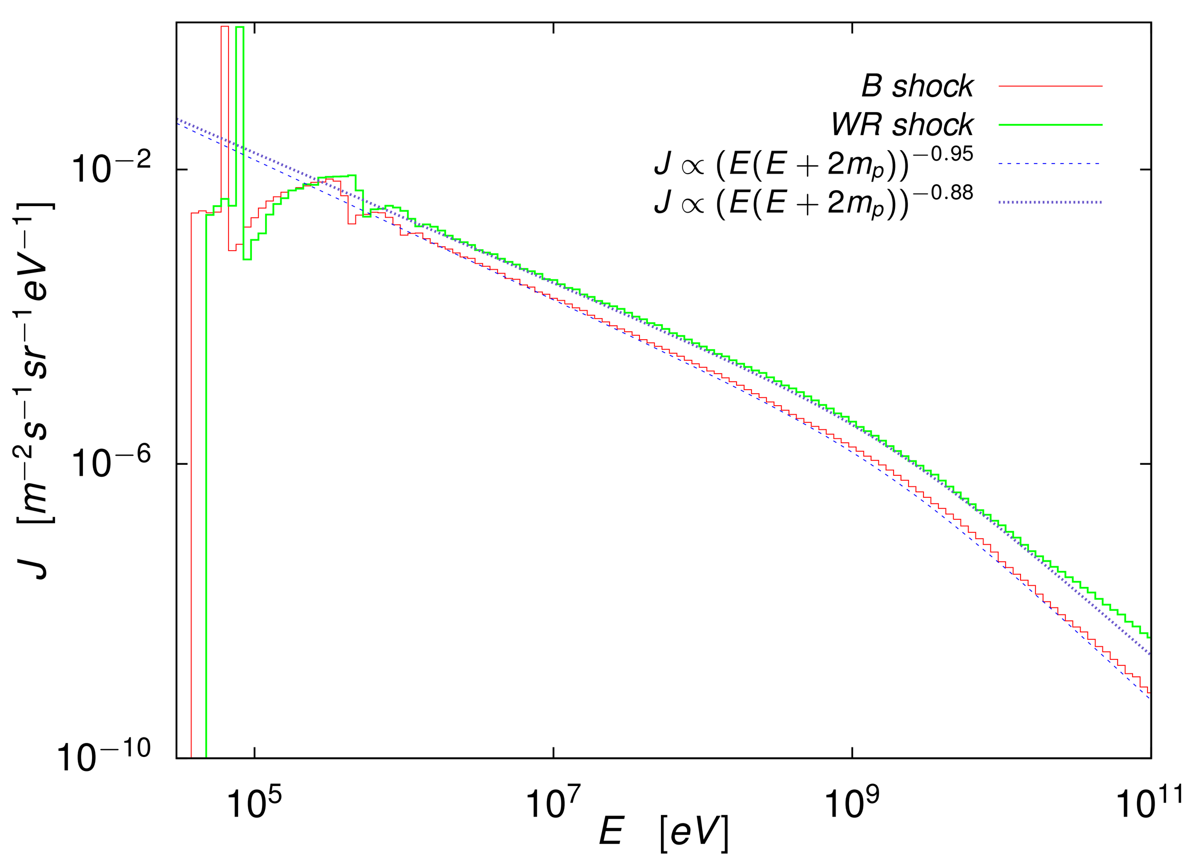


Figure : Fluxes of protons at the shock fronts of the wind collision region.

- Analytical treatment of acceleration process [4] would give:
  $$J \propto (E(E + 2m_p c^2))^{-\frac{\sigma}{2}}$$
  - E kinetic energy
  - m_p proton mass
  - $\sigma = (r+2)/(r-1)$ spectral index
- Monte Carlo simulations give:

Star	Spectral index σ	Injection efficiency ε
B	1.90 ± 0.02	$\approx 11\%$
WR	1.76 ± 0.02	$\approx 14\%$

Conclusions

Caused by different compression ratios of shocks:
- Slightly different spectral indices on the two sides of the WCR
- Slightly different injection efficiencies on the two sides of the WCR

With parameters used and in the considered energy range:
- No effect of double-shock structure on resulting spectra of accelerated protons
- Further studies needed to understand two components in γ-ray spectrum

References:

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- [3] K. Reitberger et al., *ApJ* **782** (2014) 96
- [4] M. G. Baring, D. C. Ellison and F. C. Jones, *ApJ* **409** (1993) 327-332

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