Monte Carlo Simulations of Relativistic Shock Breakout

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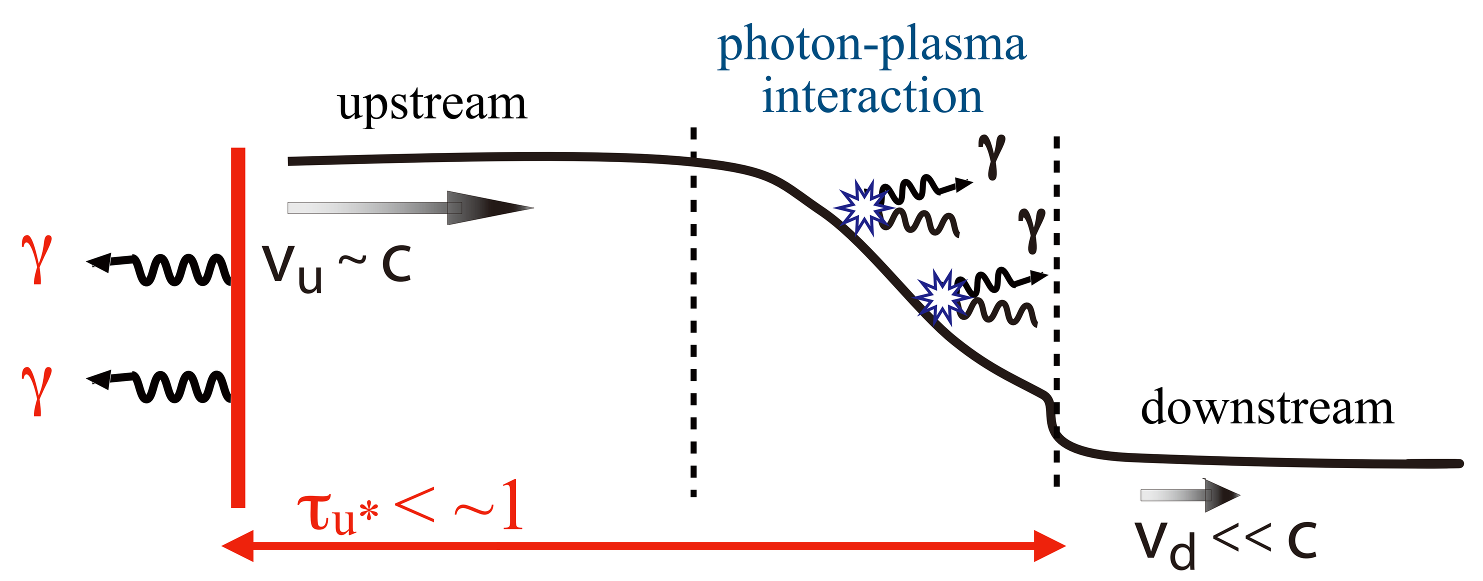
Abstract

We explore the phenomenon of relativistic shock breakout emanating from an envelope with a gradually decaying density profile. To evaluate the breakout signal, we calculate the steady-state structure of relativistic radiation mediated shocks, incorporating photon escape at the upstream boundary, characterized by the fraction of shock energy in escaping photons, f_{esc}. We present the shock structure and the spectra of the escaping photons for shock velocities of Γ_u = 2, 6, and 10. Compared to the analytical model of Granot et al. (2018), our findings reveal a significantly narrower shock width, which may be attributed to the presence of a subshock whose strength increases with f_{esc}. This suggests that relativistic breakout emission is more prolonged and energetic than previously estimated. The escaping photons exhibit a spectral peak around Ep ≈ 300 to 600 keV, largely independent of f_{esc} and Γ_u, due to temperature regulation in the immediate downstream region by the pairs. In all cases, the escaping photon spectrum below the spectral peak shows a nearly flat component ($f_\nu \propto \nu^0$), while above the peak, a high-energy extension emerges.

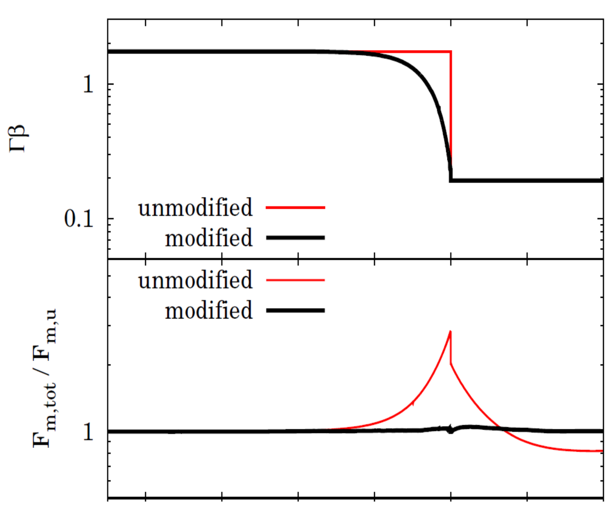
Introduction

Shock breakout shapes the early electromagnetic signals from cosmic explosions like supernovae and gamma-ray bursts. During breakouts, photons are released as the shock transitions from a radiation mediated shock (RMS) to a collisionless shock (e.g., Levinson & Nakar 2020). This study focuses on relativistic shock breakouts ($\Gamma_u \geq 2$) occurring in gradually decaying density profiles, such as energetic or anisotropic explosions of a star surrounded by a wind. Assuming the shock evolves gradually and maintains a quasi-steady state governed by local conditions, we compute the shock structure during the breakout phase using Monte Carlo simulations. These simulations solve the steady-state structure of relativistic RMSs (RRMSs) which takes into account the effect of photon escape from the upstream boundary, following the method developed by Ito, Levinson & Nakar (2020).



Numerical Method

Our numerical code employs an iterative method that seeks a steady shock structure which conserves the energy-momentum flux throughout the flow. In the infinite shock calculations conducted in Ito, Levinson & Nagataki (2020), a large imposed value of the pair-loaded optical depth τ_{u*} prevented the photons produced in the shock from diffusing back to the upstream boundary. In contrast, in the current simulations, the smaller values of τ_{u*} invoked allow a fraction of counterstreaming photons to escape through the upstream boundary.



Give plasma profile (n,T,Γ)

↓

Solve radiation transfer using Monte-Carlo Method

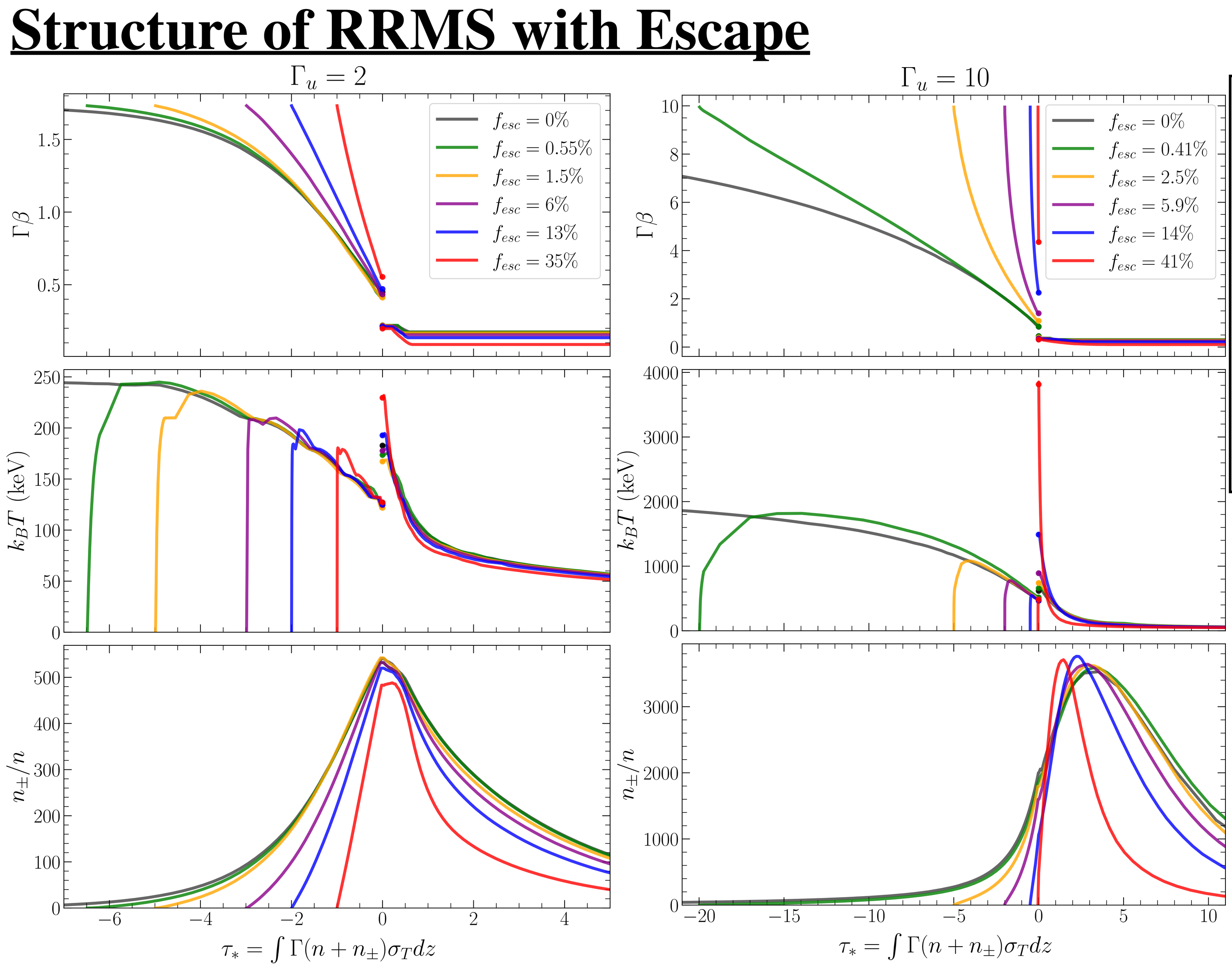
↓

Evaluate deviation from energy-momentum conservation

feedback

Iterate until convergence is achieved

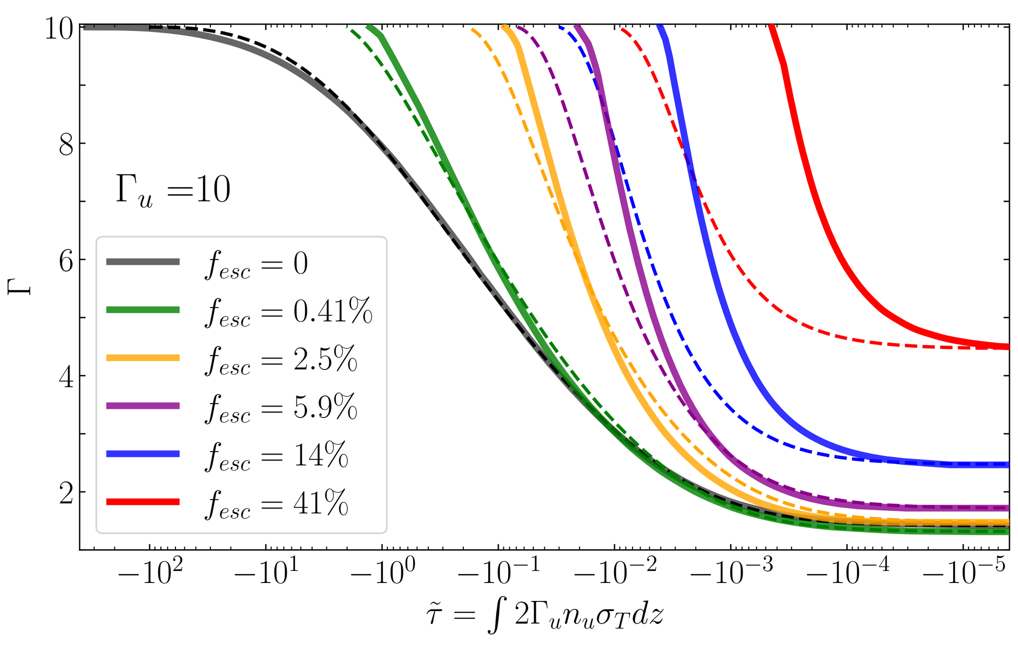
Structure of RRMS with Escape



$f_{esc} = -\frac{F_{esc}}{F_b}$ Ratio of the energy flux carried by escaping photons to the incoming energy flux of the far upstream baryons

As f_{esc} increases, the shock width narrows, and the subshock becomes stronger.

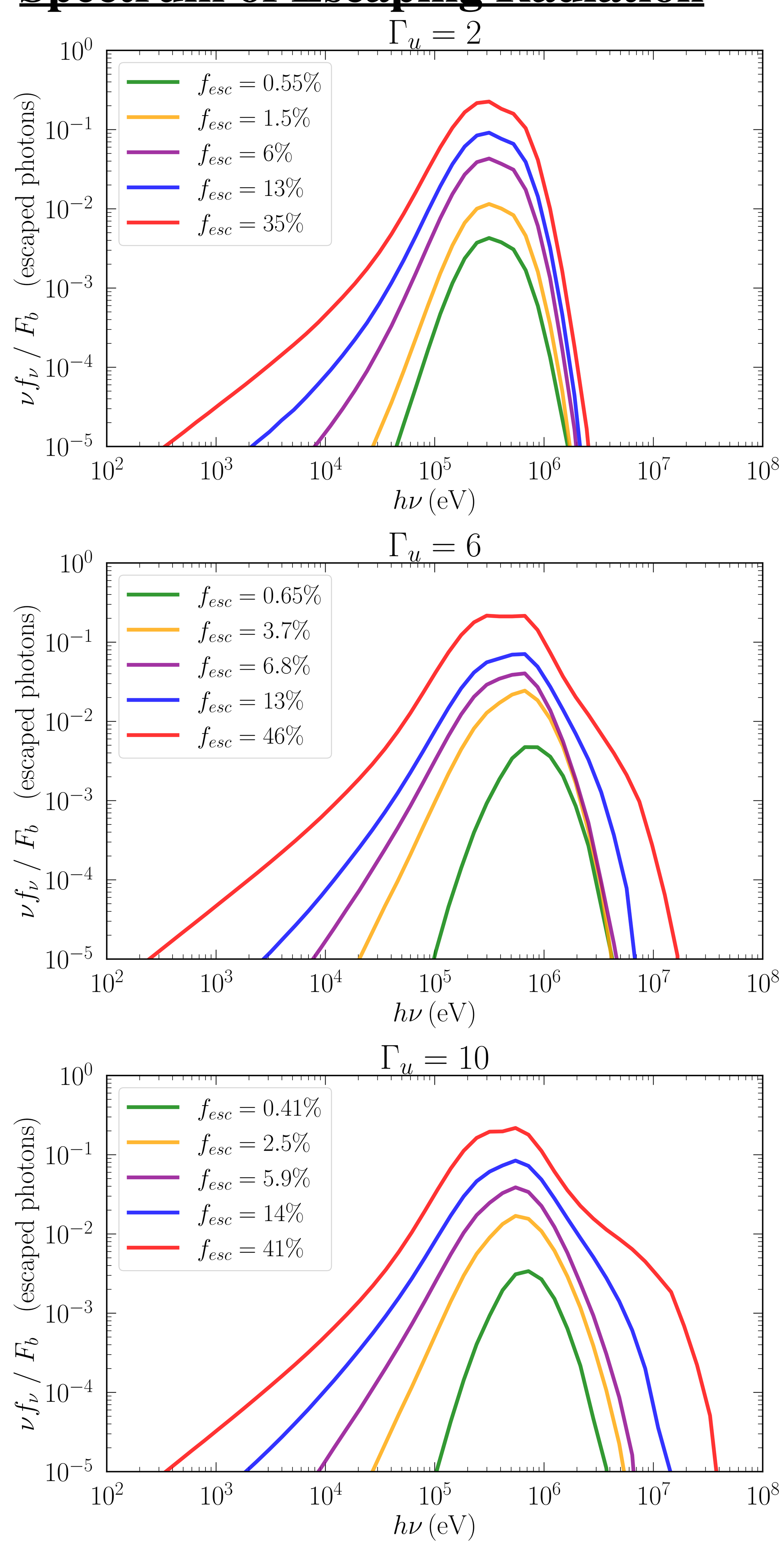
Comparison with Analytical Model (Granot et al. 2018)



Lorentz factor profile as a function of pair unloaded optical depth for Γ_u = 10. The solid and dashed lines are the numerical and analytical solutions, repectively.

For f_{esc} = 41 %, the simulation exhibits a shock width narrower than that of the analytical model by a factor of ~ 20. Assuming that this scaling continues up to f_{esc} ≈100 %, the result indicates that the complete breakout takes place at an optical smaller by a factor ~ 40.

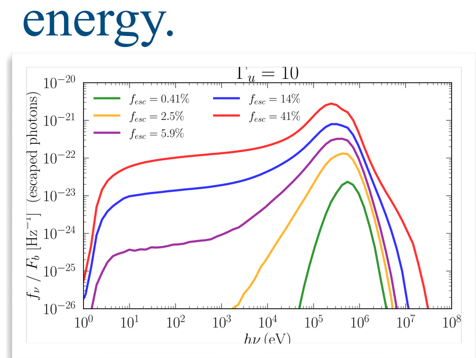
Spectrum of Escaping Radiation



The spectral peak energy lies within the range of E_p ≈ 300 to 600 keV, irrespective of and Γ_u and f_{esc}, due to the stabilization of the downstream temperature by pair production.

Below E_p, the spectra exhibit a soft extension characterized by a slope that asymptotically approaches $f_\nu \propto \nu^0$, which is attributed to free-free emission.

The excess above E_p is generated by the effect of the subshock, wherein high temperature pairs at the post-subshock region up-scatter a fraction of photons, immediately transferring their energy.



References

1. Granot A., Nakar E., Levinson A., 2018, MNRAS, 476, 5453
2. Levinson A., Nakar E., 2020, Phys. Rep., 866, 1
3. Ito H., Levinson A., Nagataki S., 2020, MNRAS, 492, 1902
4. Ito H., Levinson A., Nakar E., 2020, MNRAS, 499, 4961