Neutrino and cosmic ray production in an evolving GRB fireball

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Abstract

Neutrino astronomy is currently presenting us a fascinating new addition to multi-messenger astrophysics and allows for ever better constraints on astrophysical source models such as those for gamma-ray bursts (GRBs). The non-detection of neutrinos from GRBs so far is challenging the concept of GRBs as sources of ultra-high energy cosmic rays (UHECR). We therefore reconsider the particle emission from internal shocks inside a GRB under the premise of an evolving fireball. By combining an approach for the calculation of synthetic light-curves from the collision of several shells with our treatment of photohadronic interactions, we are able to model neutrinos, UHECR, and the maximal energy of the escaping photons on basis of individual collisions. We show that the neutrino production, the maximal UHECR energies, and the maximal photon energies all peak at different collision radii. Moreover, we test how this affects neutrino flux predictions compared to the commonly used models using a fixed collision radius.

Motivation

Gamma-Ray Bursts (GRBs) are considered to be one of the prime candidates for the **acceleration of ultra-high energy cosmic rays (UHECR)**.

- **"Smoking gun"** signature for UHECR acceleration: detection of **high-energy neutrinos** produced in the interactions of high energy protons with gamma-ray photons inside the source.
- GRB neutrino flux predictions possible based on the particle physics involved and the observational data of individual GRBs possible, but need (simple) source model. Commonly used model: **internal shock fireball model**.
- **Current GRB neutrino searches** by the IceCube [1] and ANTARES [2] **challenge UHECR acceleration** in GRBs.
- However, one **key assumption** for the calculations is the use of **static parameters** such as the collision radius.

Idea: *How do results change, when we take into account that a GRB evolves and is the result of several similar, but not identical collisions?*

Approach

Combination of approaches:

- Approach for synthetic light-curves (temporal structure) by Aoi et al. [3]
- Neutrino (and UHECR) production based on NeuCosmA-code ("Neutrinos from Cosmic Accelerators") [4]

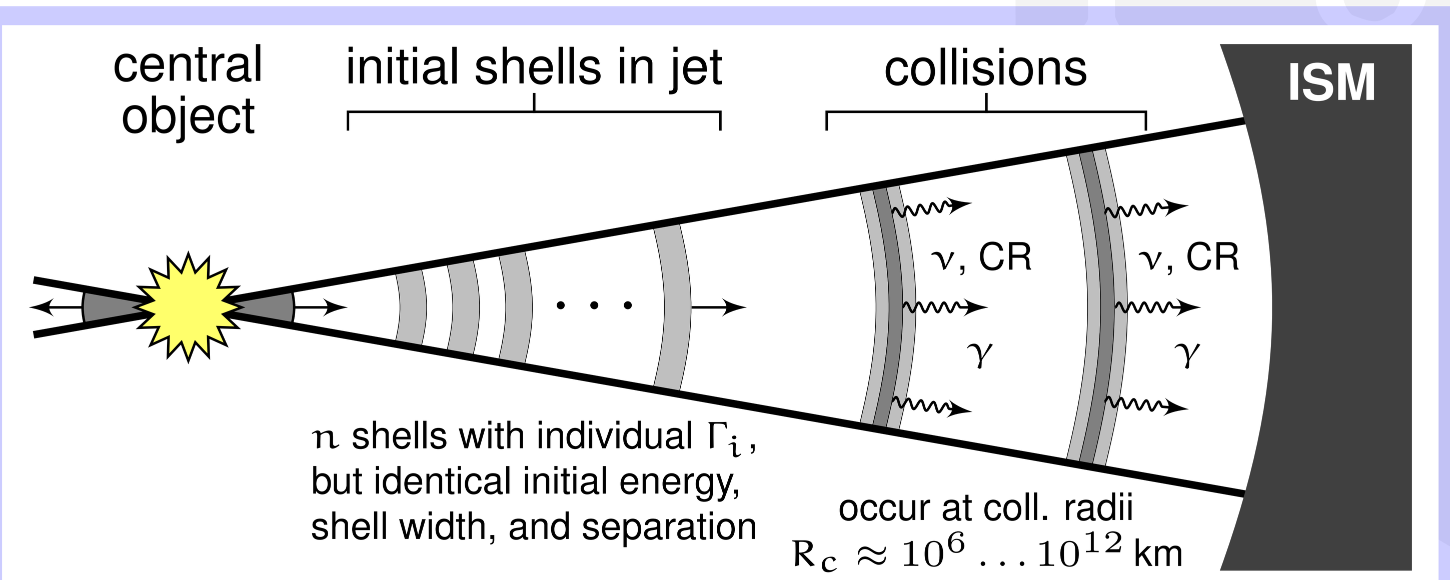

Figure 1: Schematic of evolving fireball (not to scale).

Monte-Carlo-algorithm

- n shells with same energy, but slightly different Lorentz factor Γ_i
- Propagation of shells tracked till ISM (incl. merged shells)
- Parameters of collisions calculated such as freed energy

Collision parameters passed on →

NeuCosmA-code

- Magnetic field and normalization of photon and proton spectra calculated based on energy density in each collision
- Neutrino and UHECR production simulated based on derived values
- Maximal (theoretical) escaping photon energy estimated

Results

1. Main contribution to the **prompt neutrinos** comes from the **innermost collisions** due high particle densities. These collisions are considered to be optically thick to neutron escape.
2. Neutrino production continuously decreases with collision radius since fireball expands (with some fluctuations due to variation of parameters).
3. Maximal **cosmic ray** (proton) energies reached at **intermediate collision radius** range in which cosmic ray emission changes from (optically thick) neutron escape to direct proton escape.
4. Maximal (theoretical) **escaping photon energy** is highest at the **largest radii**.
5. Neutrinos, UHECR, and highest energy photons come from different stages of evolving fireball.
6. Low radius collisions **shift peak of prompt neutrino flux** prediction **to lower energies**.

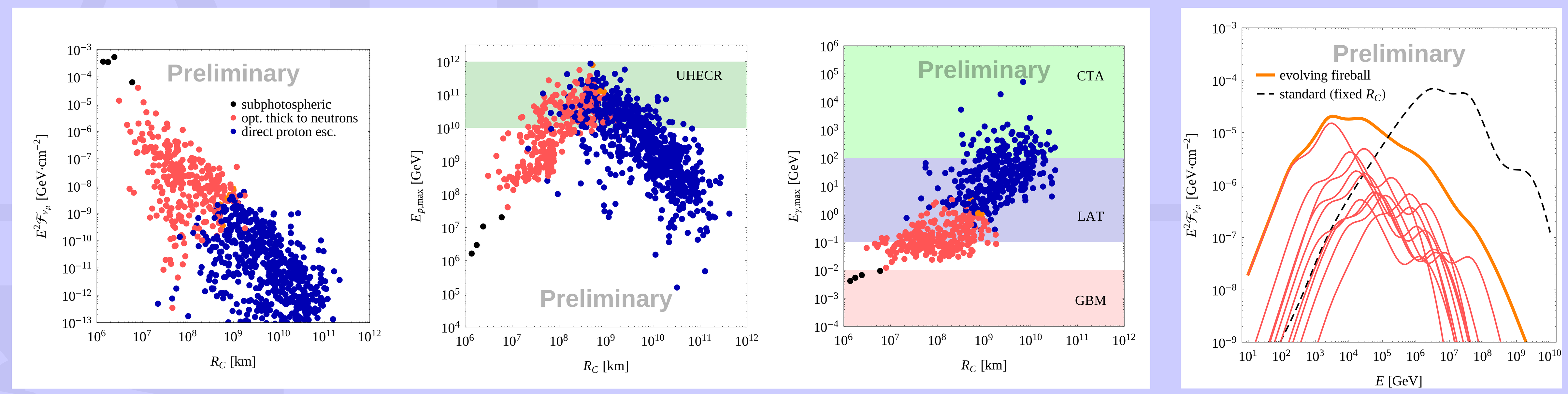

Figure 2: *Left:* The integrated neutrino fluence (left plot), the maximal energy of escaping cosmic ray protons (middle plot), and the theoretical maximal energy of escaping photons (right plot) for burst with about 1000 individual collisions, all as function of the collision radius. Different colors indicate different escape regimes (see labels in left plot). *Right:* The total neutrino fluence (thick orange curve) as function of energy in the evolving GRB model is result of stacking the results of the individual collisions; the ten individual collisions producing most neutrinos shown as thin solid curves (excluding subphotospheric collisions). The black dashed curve represents the result of obtained from the standard calculation using fixed parameters and identical collisions.

Summary and Outlook

We have shown that the particle flux predictions in the internal shock model for GRB fireballs are significantly altered as soon as we include the evolution of the colliding shells as well as that collisions occur over a range of radii. Our simulations, based on standard photon and proton spectra, indicate that the main contribution to the prompt neutrino flux comes from the innermost collisions while the highest energy cosmic rays come from higher collision radii. Moreover, we could show that the (theoretical) maximal energy for escaping photons grows with collision radius due to the decreasing particle densities. This means that the highest energy photons probably originate from a different stage of the GRB fireball than the UHECR and the neutrinos since the production of these quantities is favored by different conditions. However, the shown simulations are very sensitive to the chosen parameters and an extensive discussion of these effects will be presented elsewhere [5]. Nonetheless, the GRB neutrino flux predictions for an evolving fireball peak at different energies compared to standard calculations, which might require a change in the search strategy for GRB neutrinos.

References

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