GAMMA - A NEW METHOD FOR MODELLING RELATIVISTIC HYDRODYNAMICS AND NON-THERMAL EMISSION ON A MOVING MESH

ArXiv id: 2104.09397
https://github.com/eliotayache/GAMMA

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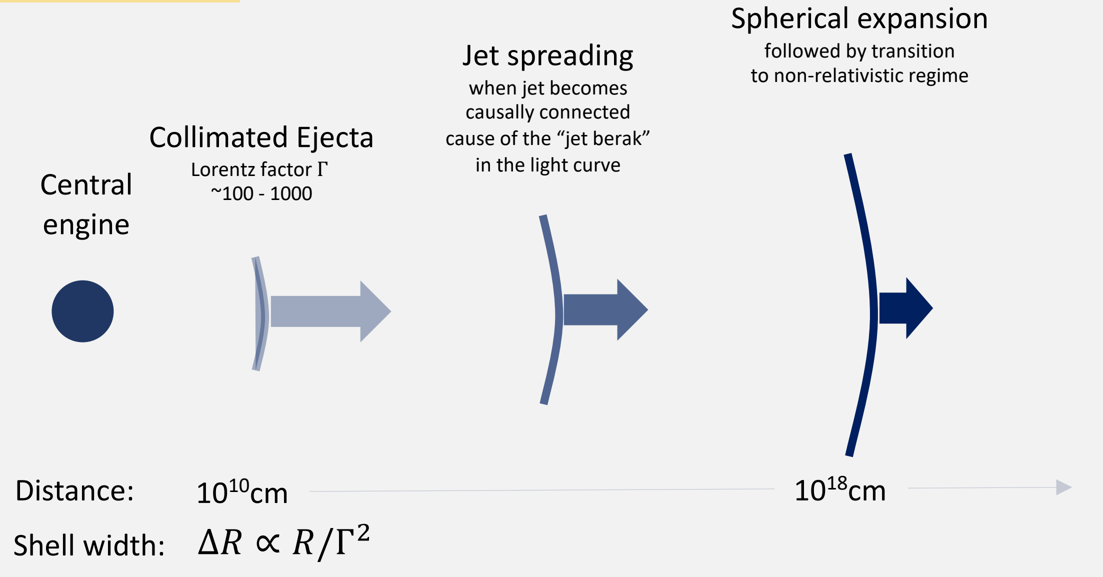
Fig. 1: Artist's impression of a gamma-ray burst

Gamma-ray bursts (GRBs) are produced during the collapse of a massive star or a binary neutron star merger. A collimated jet pointing towards the observer produces the **prompt** gamma-ray emission. The jet interaction with the circumburst medium produces **afterglow** synchrotron emission.

BACKGROUND


Central engine

Collimated Ejecta
Lorentz factor Γ
~100 - 1000

Jet spreading
when jet becomes causally connected
cause of the "jet berak" in the light curve

Spherical expansion
followed by transition to non-relativistic regime

Distance: 10^{10}cm 10^{18}cm

Shell width: $\Delta R \propto R/\Gamma^2$

Fig. 2: Spatial scales covered by GRB jets and the different stages of relativistic jet dynamics. The jet is launched at Lorentz factors of a few hundred and decelerates all the way to the non-relativistic stage. The spatial dynamic range is numerically very challenging.

Dynamical relativistic jet simulation techniques are only just becoming able to numerically resolve gamma-ray burst (GRB) blast-wave evolution across scales.

Current radiative modelling is limited by:

- Resolution requirements
- Approximations in the calculation of radiative losses. (Granot & Sari, 2002; van Eerten et al., 2010; Guidorzi et al, 2014)

Using accurate numerical prescriptions of the emissivity, one can:

- **Simulate observed radiation from multiple emission sites,** (**Ayache** et al., 2020)
- **Understand the trans-relativistic evolution of the jet.**

☞ Implications on our understanding of the jet launching mechanism, the nature and behaviour of the remnant, and the geometry of the various components associated with the explosion.

METHODS

We combine recent developments in moving-mesh relativistic hydrodynamics with a local treatment of non-thermal emission in a new code: GAMMA.

Dynamics

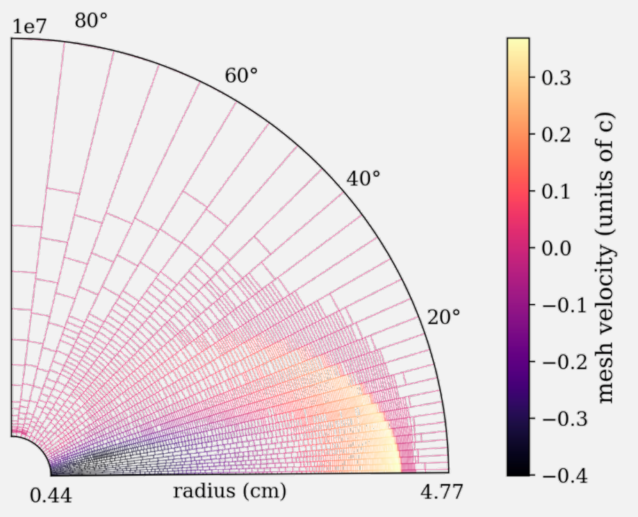


Fig. 3: Low-resolution GRB jet simulation. The mesh moves radially with fluid velocity.

- Finite-volume Arbitrary Lagrangian - Eulerian approach only in the direction of dominant fluid motion:
  ⇒ avoids mesh entanglement and associated computational costs.
  ⇒ increased resolution downstream of shocks. (Duffell & MacFadyen, 2011)
- Shock detection, particle injection and local calculation of their evolution including radiative cooling **done at runtime**.

Radiative transfer

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}z} = \epsilon_\nu - \alpha_\nu I_\nu \longrightarrow F(\nu, t_{\mathrm{obs}}) = \frac{1+z}{2d_L^2}\int_{-1}^{1}\mathrm{d}\mu\int_0^\infty r^2\mathrm{d}r\,\frac{P'_{\nu'}(r, t_{\mathrm{obs}}+r\mu)}{\Gamma^2(1-\beta\mu)^2}.$$

Locally-computed emissivity

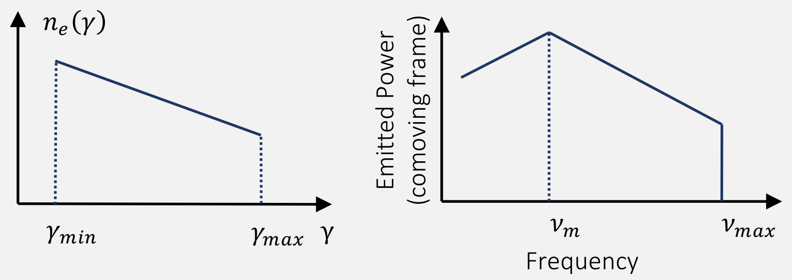


Fig. 4: (left) Power-law distribution of electrons resulting from particle acceleration at shock locations. (right) Corresponding synchrotron emissivity in the co-moving frame.

Electron distribution

$$n'(\gamma'_e) = (\gamma'_e)^{-p}, \gamma_{min} < \gamma_e{}' < \gamma_{max}$$

p can be initialised as a function of shock strength.

Corresponding local emissivity

$$P'_\nu = \begin{cases} P'_{\nu,\max}\left(\frac{\nu}{\nu'_m}\right)^{1/3}, & \nu < \nu'_m, \\ P'_{\nu,\max}\left(\frac{\nu}{\nu'_m}\right)^{-(p-1)/2}, & \nu > \nu'_m, \end{cases}$$

Synchrotron cooling

Advection equation

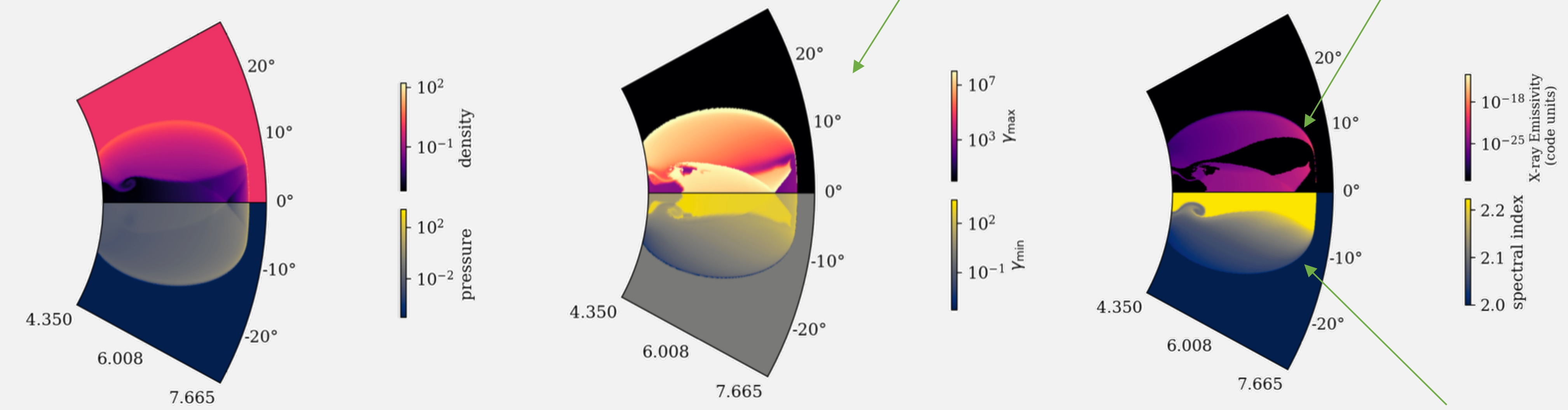
$$\frac{\mathrm{d}\gamma_e}{\mathrm{d}t} = \underbrace{-\frac{\sigma_T (B)^2}{6\pi m_e c}(\gamma_e)^2}_{\text{Radiative losses}} + \underbrace{\frac{\gamma_e}{3\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t}}_{\text{Adiabatic expansion}} \Leftrightarrow \boxed{\frac{\partial}{\partial t}\left(\frac{\Gamma\rho^{4/3}}{\gamma_e}\right) + \frac{\partial}{\partial x^i}\left(\frac{\Gamma\rho^{4/3}}{\gamma_e}v\right) = \frac{\sigma_T}{6\pi m_e c}\rho^{4/3}B^2.}$$

⇒ Passive scalar with a source term.

RESULTS

Local numerical calculation of the particle population evolution

map of emission sites



Variable microphysics: the injection electron power-law index is set as a function of shock strength

Fig. 5 (above): early snapshot a GRB jet simulation. Initial state is the Blandford-Mckee (1976) solution at $\Gamma = 100$, opening angle 0.1 rad. Initial isotropic-equivalent energy 10^{53} erg, lab time 7×10^6s. Radii in light-seconds.

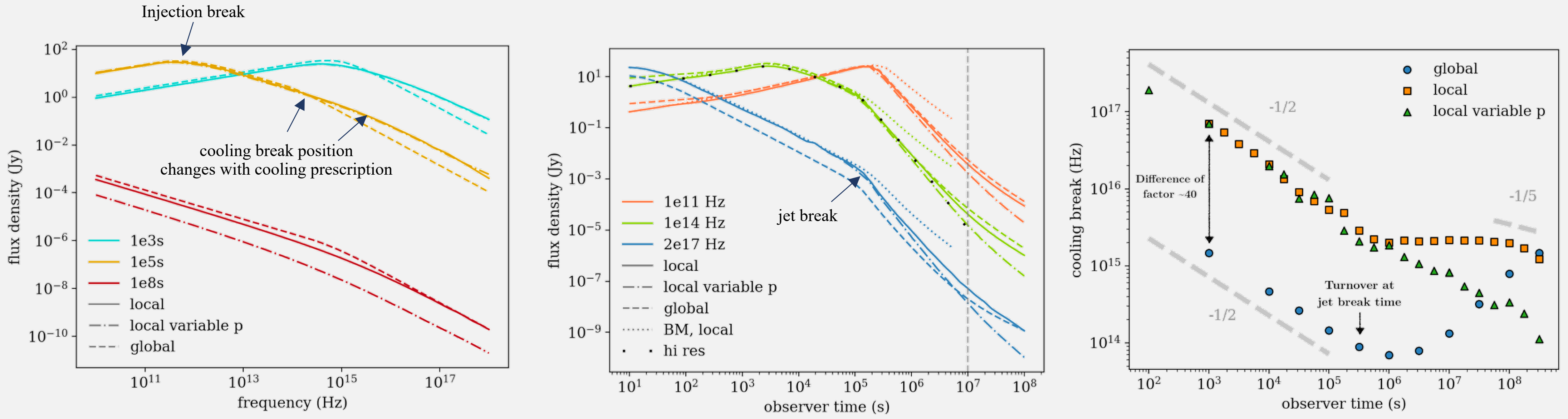


Fig. 6: Afterglow spectral evolution (left), light curves (center), and cooling break position evolution (right), slow-cooling case. "global" refers to the global cooling approximation commonly used in the community. "local" refers to our accurate numerical prescription. In "variable p" we set the injection electron power-law index as a function of shock strength. "BM" is the analytical Blandford-Mckee (1976) solution without jet spreading.

- Position of the cooling break changes significantly when compared to previous prescriptions that over-estimate the radiative contribution to cooling.
- Error is not constant and varies in the trans-relativistic regime (post-jet break) ⇒ **global cooling cannot simply be offset to correct for the error.**
- Variable particle acceleration properties significantly impact the light curve in the trans-relativistic stage.

CONCLUSIONS

- Accurately numerically capturing non-thermal radiative processes is crucial to correctly interpret complex relativistic transient late-time light curve evolution.
- GAMMA can be used as a test-bed for investigating trans-relativistic particle acceleration processes, thanks to the local treatment of particle evolution

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