Paramo: PArticle and RAdiation MOnitor for Relativistic Outflows

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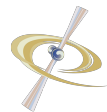
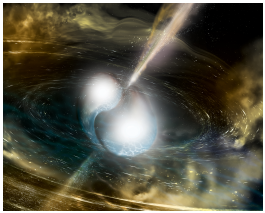


Outline

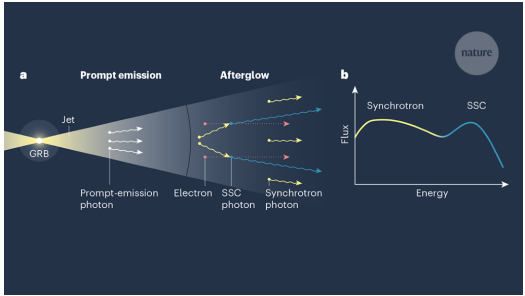
1. Introduction
2. Numerical Approach
3. Astrophysical Application
4. Summary & Conclusions

Introduction

- Gamma-ray bursts (GRBs) are highly energetic events
  - Long: Collapsar
  - Short: Compact binary mergers
- GRBs show different phases in their light curves since the outburst
  - Prompt phase
  - Afterglow
- Inverse Compton (IC) scattering is a radiative process in which an ultrarelativistic electron transfers part of its energy to the photon, giving way to a photon with higher frequency.



Credit: NSF/LIGO/Sonoma State University/A. Simonnet



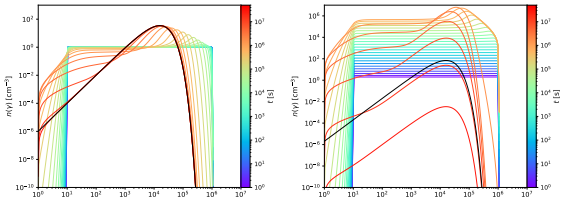
Kinetic equation

The evolution of a distribution of relativistic particles $n'(\gamma', t')$, where γ' is the particle Lorentz factor and t' the time variable, is given by:

$$\frac{\partial n'(\gamma', t')}{\partial t'} = \frac{1}{2}\frac{\partial^2}{\partial \gamma'^2}\left[D'(\gamma', t')n'(\gamma', t')\right] - \frac{\partial}{\partial \gamma'}\left[\dot{\gamma}'(\gamma', t')n'(\gamma', t')\right] + Q'(\gamma', t') - \frac{n'(\gamma', t')}{t'_{\rm esc}}, \quad (1)$$

better known as the *Fokker-Planck* equation, D' is the diffusion coefficient, $\dot{\gamma}'$ the particle energy gains/losses, Q' the source term, and $t'_{\rm esc}$ the average time particles take to escape from the domain.

- The solution will give us the particle energy distribution profile at a given time t'.
- A numerical code, named `Paramo`, has been developed to solve eq. (1) with robust numerical solver (Park & Petrosian 1996)



Radiation processes

- Sophisticated and efficient numerical integration techniques have been developed to calculate, for arbitrary particle distributions (see, JMRB, Mimica & Aloy 2014, 2017; JMRB 2017):
  - Synchrotron
  - Synchrotron self-absorption (SSA)
  - Inverse Compton scattering (IC)
- `Paramo` is capable of calculating the emission and absorption of a dynamic distribution of particles and photons (JMRB, Harrison & Giannios 2021)
  - Radiative Transfer
  - Kompaneets Equation

Radiative cooling

- The energy loss rate due to radiative IC interactions (Rybicki & Lightman 1979):

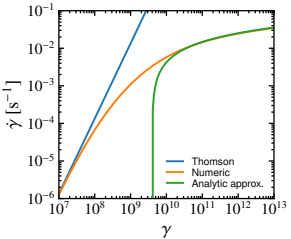
$$\dot{\gamma}' = \frac{4c\beta'^2\gamma'^2 u'_0}{3m_e c^2}\sigma' \qquad (2)$$

where u'_0 is the radiation field energy density.

- In the classical regime σ' is the Thomson cross-section σ_T
- If $\gamma' h\nu'_0 > m_e c^2$ we enter into the *Klein-Nishina* regime

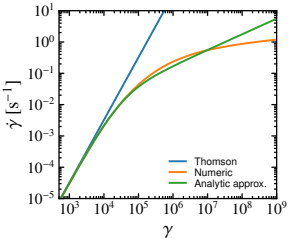
- Using sophisticated numerical techniques, eq. (2) can be estimated for arbitrary incoming photon fields (JMRB 2021; JMRB in preparation)

Blackbody



Analytic: Dermer & Menon 2009

Monochromatic



Analytic: Moderski et al. 2005

- Charged particles accelerated at the shock front of relativistic blast waves.
- The evolution of the bulk Lorentz factor is given by (Petropoulou & Mastichiadis 2009):

$$\Gamma(r) = \frac{\lambda\left(x^3-1\right)+\Gamma_0}{\left(1+2\Gamma_0\lambda\left(x^3-1\right)+\lambda^2\left(x^3-1\right)^2\right)^{1/2}},$$

where $\lambda \equiv 4\pi m_{\rm p} n_{\rm ext} r_0^3/3M_0$, $x \equiv r/r_0$ and $M_0 \equiv E_{\rm iso}/\Gamma_0 c^2$

- Continuous injection of particles $\propto \gamma'^{-p}$
- In the comoving frame

$$t' = \int_{r_0}^{r} \frac{dr}{\Gamma\beta c},$$

with $\beta \equiv \sqrt{1-\Gamma^{-2}}$

- Cosmologically distant observer

$$t_{\rm obs} = (1+z)\int_{r_0}^{r} \frac{dr}{\mathcal{D}\Gamma\beta c},$$

where $\mathcal{D} \equiv 1/(1-\beta\cos\theta_{\rm obs})\Gamma$ is the Doppler factor.

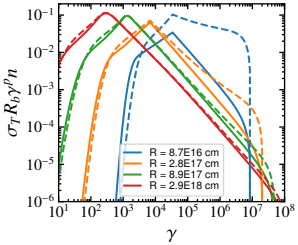
Astrophysical Application

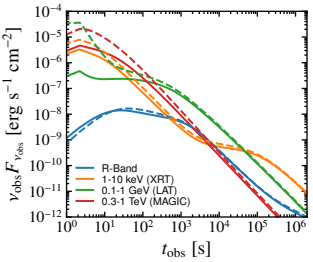
GRB190114C

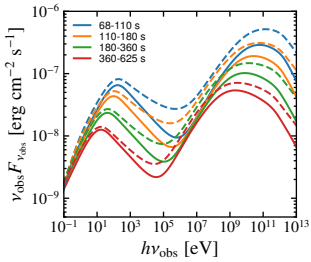
Parameter	Value
$d_{\rm L}$	2.3×10^9 pc
z	0.4245
p	2.6
ϵ_B	8×10^{-5}
ϵ_e	0.07
$E_{\rm iso}$	8×10^{53} erg
Γ_0	700
$n_{\rm ext}$	0.5 cm^{-3}
$u_{\rm ph}$[a]	7.5×10^{-9} erg cm^{-3}
$\nu_{\rm ph}$[a]	0.02 eV/h

[a] From Zhang+ JMRB (2020).

Solid lines: simulation with radiative cooling in the Thomson regime. **Dashed lines:** simulation with the numerical Klein-Nishina.

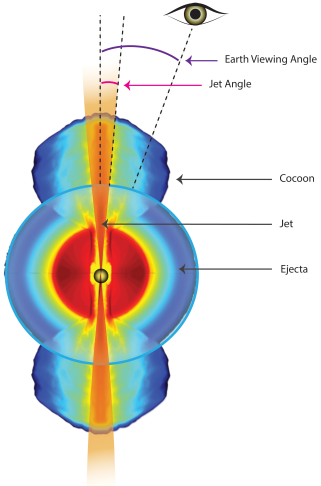






Summary and Conclusions

- Particle acceleration is ubiquitous in high-energy astrophysical outflows like relativistic jets.
- A numerical code, `Paramo`, has been developed with several tools capable of evolving energy distributions of particles, the evolution of their spectral signature, and the dynamical interaction between them.
- `Paramo` is able to simulate the evolution of a distribution of particles and the spectral evolution in, e.g., relativistic jets.
- Ready to be implemented into structured outflows, e.g., BNS post-merger jets (work in progress).



Credit: Sophia Dagnello, NRAO/AUI/NSF

¡Gracias!