Electron Synchrotron Emission in GRB-SN Interaction: First Results

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Outline

- Introduction
- Kinetic equation: numerical solution
- Code testing
- Electron and synchrotron spectra under different initial injection
- Future plans

Introduction

- Long GRBs classified as BdHNe ($E_{iso} > 10^{52}\mathrm{erg}$) show characteristic time power law behaviour in late afterglow phase (Giovanni's talk)
- Synchrotron cooling is proposed as the dominant cooling mechanism
- **Sponge model** $\Rightarrow$ fragmented ejecta with bubbles moving inside
- Kinetic energy losses come from relative drag of bubbles within the ejecta (first approximation $\Rightarrow$ matter collection from surrounding media).

Introduction

Introduction

Bubble regime	Medium regime	Time power law index k
constant	constant	3
free expansion	free expansion	1
Sedov expansion	Sedov expansion	2.2
Sedov expansion	constant size	4.6
constant size	Sedov expansion	1.25
Sedov expansion	free expansion	2.2
free expansion	Sedov expansion	4.6
constant size	free expansion	3
free expansion	constant size	7
Data	*Giovanni's talk*	≈ 1.5

Toy model calculation - more precise MHD approach is necessary but this gives us an general idea.

Introduction

- To reproduce the photon spectra and the light curves it is essential to know the evolution of **electron spectra** under synchrotron cooling $\Rightarrow$ it is necessary to solve **kinetic equation**.

Introduction

Kinetic equation

For a spatially homogeneous source

$$\frac{\partial}{\partial t}\, n(\gamma, t) = -\frac{\partial}{\partial \gamma}(\dot{\gamma}(\gamma, t)\, n(\gamma, t)) - \frac{n(\gamma, t)}{t_{\rm esc}} + q(\gamma, t)$$

Energy losses

Including adiabatic, synchrotron and inverse Compton losses

$$\dot{\gamma} = \frac{v}{R}\gamma + \frac{4\sigma_T\, c}{m\, c^2}\, (u_{\rm B} + u_0 F_{KN})\, \gamma^2 ...$$

Introduction

Solving kinetic equation

In case of time independent injection rate $q(\gamma)$:

$$n(\gamma, t - t_0) = \frac{1}{\dot{\gamma}(\gamma)} \int_{\gamma}^{\gamma_0} q(\gamma') \exp\left(-\int_{\gamma'}^{\gamma_1} \frac{dz}{\dot{\gamma}(z)\tau(z)}\right) d\gamma' , \qquad (1)$$

where γ_0 is defined through

$$t - t_0 = \int_{\gamma}^{\gamma_0} \frac{d\gamma'}{\dot{\gamma}(\gamma')} , \qquad (2)$$

Injection rate and energy losses are expected to be **time dependent!!!**
$\Rightarrow$ we need numerical approach.

Kinetic equation: numerical solution

We use the fully implicit difference scheme proposed by Chang & Cooper (1970) and implemented by Chiaberge & Ghisellini (1999).

- Energy mesh

$$\gamma_j = \gamma_{min} \left(\frac{\gamma_{max}}{\gamma_{min}} \right)^{\frac{j-1}{j_{max}-1}}, \quad \Delta\gamma_j = \gamma_{j+1/2} - \gamma_{j-1/2},$$

- Including the time step Δt we define

$$n_j^i = n(\gamma_j, i\Delta t), \; q_j^i = q(\gamma_j, i\Delta t), \; \dot{\gamma}_j^i = \dot{\gamma}(\gamma_j, i\Delta t).$$

Kinetic equation: numerical solution

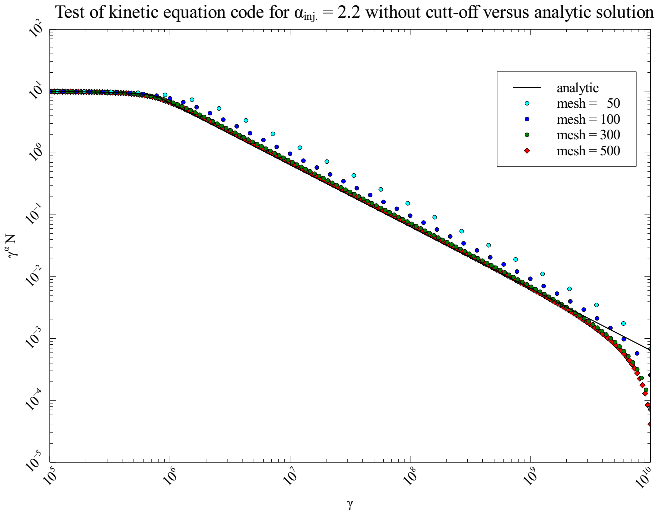
Discretization of kinetic equation

$$V3_j n_{j+1}^{i+1} + V2_j n_j^{i+1} + V1_j n_{j-1}^{i+1} = n_j^i + q_j^i \Delta t,$$

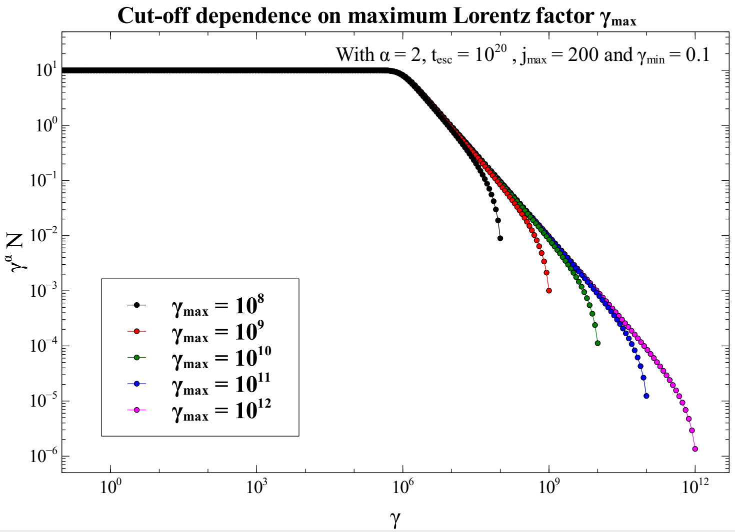
$$V1_j = 0,\ V2_j = 1 + \frac{\Delta t}{t_{\rm esc}} + \frac{\Delta t \dot{\gamma}_{j-1/2}}{\Delta \gamma_j},\ V3_j = -\frac{\Delta t \dot{\gamma}_{j+1/2}}{\Delta \gamma_j}$$

System of equations forms a tridiagonal matrix which can be solved numerically (Press et al., 1989).

Code testing



Code testing



Electron and synchrotron spectra

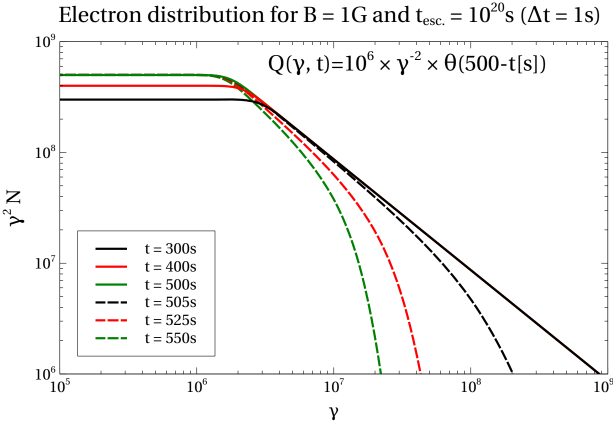


Figure: Evolution of electron spectra for energy power law injection with sudden cut-off time $q = q_0\gamma^{-2}\theta(t_0 - t)$

Electron and synchrotron spectra

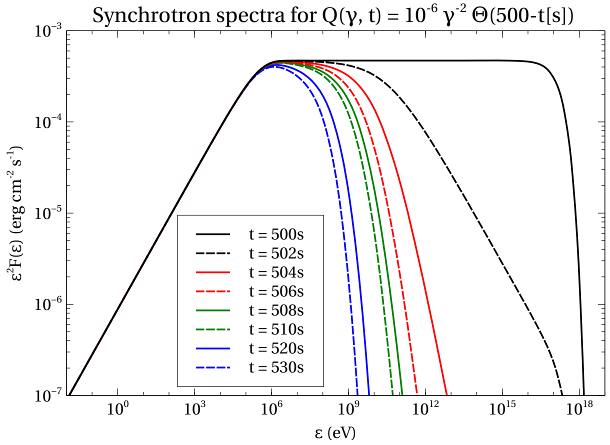
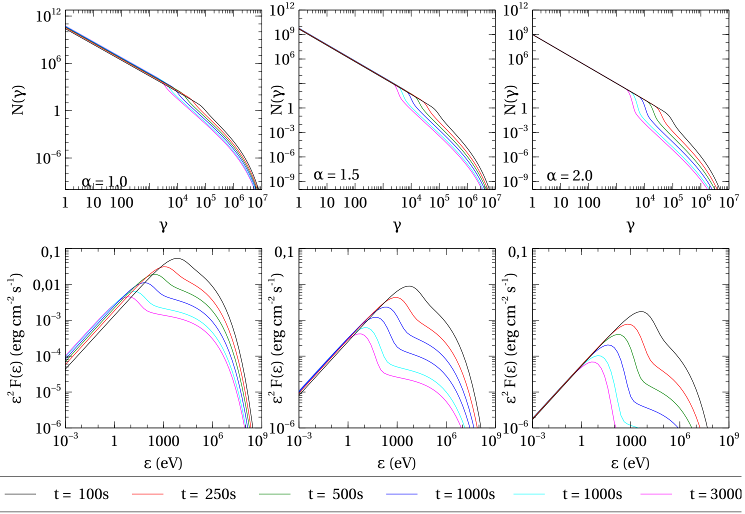


Figure: Synchrotron spectra for energy power law injection with sudden cut-off time $q = q_0 \gamma^{-2} \theta(t_0 - t)$

Figure: Electron and synchrotron spectra for injection with form $q = q_0\gamma^{-2}exp(-\gamma/\gamma_0)(t+t_0)^{-\alpha}$ and magnetic field $B = 1\,\mathrm{G}$.



Electron and synchrotron spectra

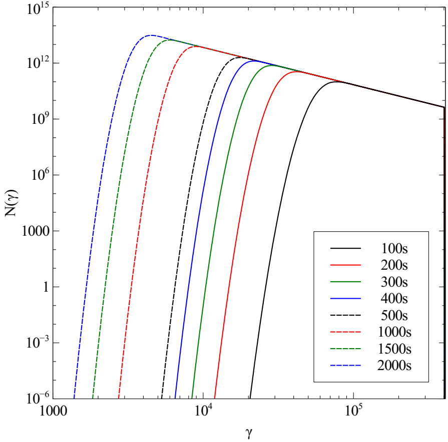
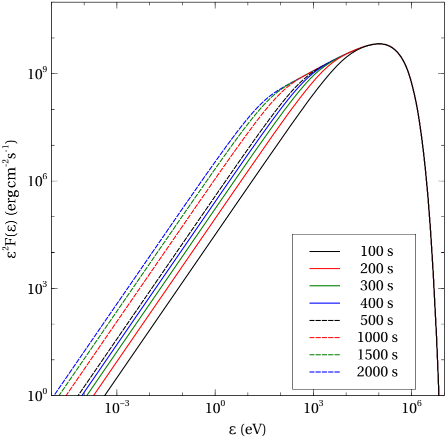


Figure: Electron spectra for constant mono-energetic injection $q = q_0\,\mathrm{rect}(\frac{\gamma-\gamma_0}{\Delta\gamma})$ and magnetic field $B = 10\,\mathrm{G}$.

Electron and synchrotron spectra



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Electron and synchrotron spectra

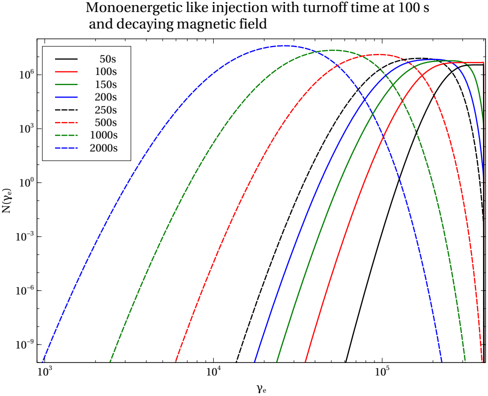
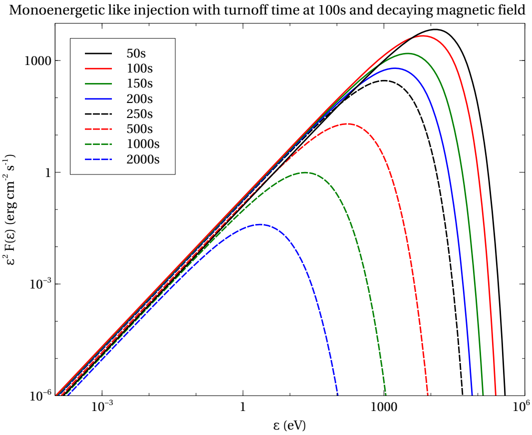


Figure: Electron spectra for mono-energetic injection with time cut-off $q = q_0\,\mathrm{rect}(\frac{\gamma-\gamma_0}{\Delta\gamma})\,\theta(t_0 - t)$ and magnetic field decay $B(t) = B_0\,(R(t)/R_0)^{-1.5}$.

Electron and synchrotron spectra



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Summary and future work

- For certainty code requires calculation in energy range at least one order of magnitude greater then typical electron energies.
- We already managed to explore some interesting scenarios like the turn off of injection and time power law injection with or without time dependence in energy losses
- This code has shown to be quite stable and fast and presents itself as a powerful tool for various astrophysical phenomena.
- Concise understanding of particle acceleration through analytical approach and/or numerical modeling presents itself as a future step.
- Turbulence, magnetic reconnection, diffusive shock acceleration...

Bibliography

- Atoyan, A. M. and Aharonian, F. A. 1999, *MNRAS*, 302: 253–276
- Chang, J.S. and Cooper, G., 1970, *Journal of Computational Physics* 6, 1
- Chiaberge M. and Ghisellini G., 1999, *MNRAS*, 306, 551
- Moderski R. et al., *MNRAS*, 363: 954-966
- Press, W.H. et al., 1989, Numerical Recipes in Fortran, Cambridge University Press