Compton polarization signatures in gamma-ray burst models

Pieter vd Merwe

July 4, 2023

Introduction

- Since the first detection of Gamma-ray Bursts (GRBs) in 1967, GRBs have been an active subject of study with many questions still left unanswered.
- GRBs are some of the most luminous explosions in the universe with typical isotropic luminosities of $\sim 10^{51} - 10^{53} \boldsymbol{ergs} \cdot \boldsymbol{s}^{-1}$.
- A better understanding of the inner workings of GRBs may be usefull not only in providing additional information on the properties of the ISM and the possible progenitors of GRBs, but also for Cosmological considerations as GRBs are found at a wide range of redshits ($z = 0.0085 - z = 9.4$).

Catagories of GRBs

GRBs are typically divided into two categories depending on the duration of the *prompt emission* phase of the GRB, namely:

- short GRBs ($\lessapprox 2s$)
  - Typically, (but not always) associated with compact object mergers.
- long GRBs ($\gtrapprox 2s$)
  - believed to be associated with the death of massive stars.

Phases of GRBs

The evolution of GRBs are devided into two phases:

- ***Prompt emission***
  - Earliest signal detected from GRBs.
  - Still not well understood (acceleration, emission mechanisms).
- ***Afterglow***
  - Relatively simple physics; well understood.
  - Colimated GRB jet interacting with ambient medium (ISM, Wind)
  - Emission mechanism synchrotron emission.

Classes of GRB models

In literature several different classes of theoretical models have been proposed for GRBs with the most popular models:

- matter dominated Fireball models
- magnetically dominated Poynting-flux dominated jets
- hybrid jets

with less generally accepted alternative models such as

- cannonball models
- fireshell models
- precession models

The prompt emission debate

As shown previously, many diverse models have been proposed for GRBs, this is especially true w.r.t. the prompt emission phase in order to explain the observed non-thermal Band-like spectra with typical emission mechanisms including (and relevant polarization predictions)

- optically thin synchrotron emission (both random and ordered B-field)
  - High polarization degree predicted with distinctions between ordered and random B-Field
- SSC emission
  - Moderate polarization degree
- Compton drag models
  - High polarization degree
- photospheric models
  - Low polarization degree depending on viewing angle

Polarization considerations

- High energy polarimiters such as POLAR and COSI provide additional avenues of probing the various proposed models of GRBs.

- Current polarization measurements for GRBs seem to favour photospheric models.

- In spite of this multiple authors (Kole, 2020; Lan et al, 2021; Burgess et al, 2019) have cautioned against the use of time- and energy- integrated polarization data, showing that time- and energy-resolved polarization observations should be considered in order to discriminate between the various prompt emission mechanisms.

The basic algorithm

- Draw photon energy ϵ from a predefined spectrum.
- Boost photon to the emission region using the model dependant Γ:
  - $\epsilon' = \epsilon\Gamma\left(1 - \beta_\Gamma \cos\theta\right)$
- Calculate polarization vector $\vec{P}$ of photon $\perp$ to propagation direction.
- Draw electron direction and γ.
- Boost photon to electron rest frame:
  - $\epsilon_e = \epsilon'\gamma_e\left(1 - \beta_e \cos\theta_e\right)$

Simulating Inverse Compton scattering

2 The Code

- Easiest to simulate in the electron rest frame.
- Calculate the polarization averaged Klein-Nishina cross section:
  - $\sigma_{KN} = \frac{3}{4}\sigma_T \left[\frac{1+x}{x^3}\left(\frac{2x(1+x)}{1+2x} - \ln(1+2x)\right) + \frac{\ln(1+2x)}{2x} - \frac{1+3x}{(1+2x)^2}\right], x \equiv \frac{\epsilon_e}{m_e c^2}$
- Compare ξ_σ to $\frac{\sigma_{KN}}{\sigma_T}$
- Calculate Θ_{sc}, $\epsilon_e^{sc} = \frac{\epsilon_e}{[1+x(1-\cos\Theta_{sc})]}$ and Φ_{sc}
- Calculate $\Pi = 2\left[\frac{1-\sin^2\Theta^{sc}\cos^2\Phi^{sc}}{\frac{x_e}{x_e^{sc}}+\frac{x_e^{sc}}{x_e}-\sin^2\Theta^{sc}\cos^2\Phi^{sc}}\right]$

Simulating Inverse Compton scattering (*Continued...*)

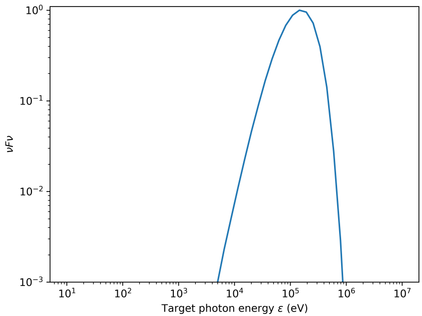
- Compare Π to ξ_{Π}
- If $\xi_{\Pi} > \Pi$:
  - $\vec{P}_e^{sc} =$ random
- If $\xi_{\Pi} \leq \Pi$:
  - $\vec{P}_e^{sc} = \frac{\left(\vec{P}_e \times \vec{D}_e^{sc}\right) \times \vec{D}_e^{sc}}{\left|\vec{P}_e^{sc}\right|}$
- Convert the scattered photon ϵ_e^{sc} back to the emission region and lab frame.
- Calculate the Stokes Q and U from $\vec{P}$
- Boost ϵ_{lab}^{sc} to the observer frame.
- Sum over Q and U in to calculate $\Pi_T = \frac{\sqrt{Q_T^2 + Q_T^2}}{N_{sc}}$ and $\chi = \frac{1}{2} \arctan \frac{U_T}{Q_T}$

Applying the code to a test case

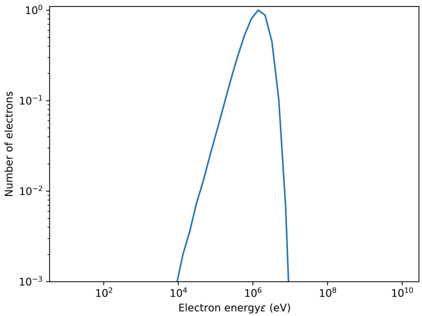
- Photon is drawn from a Planck spectrum and boosted to the emission region with a constant bulk Lorentz factor Γ
- Electron is drawn from a isometric Maxwellian distribution in the emission frame.
- $kT_{rad} = 50keV$
- $kT_e = 500keV$
- $\Gamma = 10$
- $N = 10^6$

Seed spectrums

Drawn target photons for $kT_{rad} = 50keV$

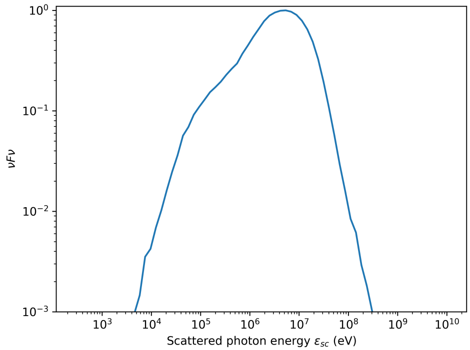


Drawn thermal electrons for $kT_e = 500keV$



Scattered photon spectrum

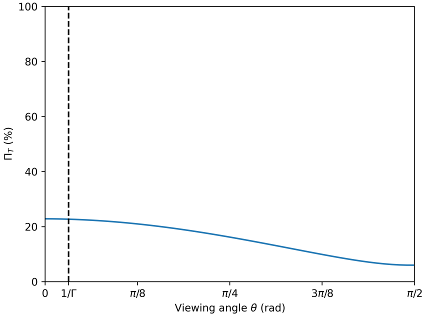
Final spectrum for upscattered photons



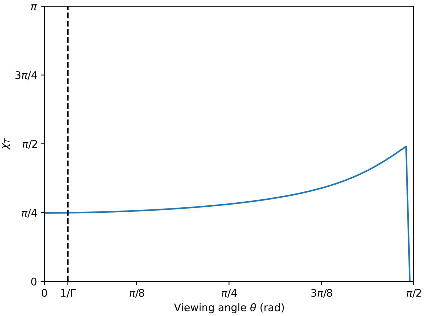
Polarization estimates

Calculated Polarization estimates

Polarization degree Π as a function of viewing angle



Polarization angel χ as a function of viewing angle



Future outlook

- Polarization outputs do not appear to be correct for which the problem needs to be found and fixed.
- Mean free path, multiple scattering and time dependent propagation calculations should be introduced to the code to better describe GRB jets.
- SSC polarization calculations.
- Parallellization (possibly leveraging GPUs) of the code.
- Energy- and time-dependant Polarization.

Acknowledgments

- Thank you to the NRF for funding this research.
- Thank you to the CSR for the oppertunity to attend SAIP 2023.

Compton polarization signatures in gamma-ray burst models

Thank you for listening!

Any questions?