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Energy and Radiation Spectrum of Electrons in Ultra-relativistic Shocks of GRB Afterglows

L. Resmi[1,2], D. Bhattacharya[1]
[1] *Raman Research Institute, Bangalore – 560 080, India.*
[2] *Joint Astronomy Programme, Indian Institute of Science, Bangalore – 560 012, India.*

Abstract. We consider particle acceleration near ultra relativistic shocks ($\Gamma_{\rm shock} \gg 1$) and the distribution of accelerated particles in the shock downstream. We suggest that the electron energy spectrum will settle into an "universal" power law with index $p \approx 2.2$ above an "injection break" at $\gamma_e = \gamma_i \equiv \frac{m_p}{m_e}\Gamma_{\rm shock}$, and will be flatter at lower energies.The synchrotron radiation spectrum arising from these electrons is computed for a decelerating relativistic fireball. We show that this model can account well for the observed spectra and lightcurves of Gamma Ray Burst Afterglows.

Keywords : GRB Afterglow – Spectral index – Particle acceleration

1. Introduction

Gamma Ray Burst Afterglow emission is believed to be synchrotron radiation from shocked relativistic electrons (Piran 1999). The standard fireball model assumes these electrons to be produced by Diffusive Shock Acceleration (DSA). The main feature of DSA is the 'universal powerlaw' of particle energy distribution it produces. The accelerated particles will follow a distribution,

$$N(\gamma_e) \propto \gamma_e^{-p} \qquad (1)$$

where γ_e is the lorentz factor of the electron, and the value of p is predicted to be ~2.3. Many afterglow models are well fitted by a p very close to this universal value (Waxman 1997, Galama et.al 1998) .

2. A Modified Energy Spectrum

Fermi Acceleration theory predicts that DSA would be effective only when the particle sees the shock as a sharp discontinuity, which requires that the electron larmor radius be larger than the shock thickness. This limits the DSA operating range to an electron energy larger than $\gamma_{acc} \sim (m_p/m_e)\Gamma_{sh}$. Here m_p and m_e are the proton and electron masses respectively, and Γ_{sh} is the shock lorentz factor (Ostrowski et al, 2000). However, the standard model spectrum is often used in the literature for $\gamma_e \ll \gamma_{acc}$, contrary to theoretical predictions.

On the other hand, detailed modelling of some of the afterglows reveal the presence of a flatter ($p < 2$) or a double slope electron energy distribution (Panaitescu & Kumar 2001, Sagar, R. et al, 2001, Cowsik, R. et al, 2001, Bhattacharya, D., 2001).

We conjecture that for electrons in GRB afterglows, a $p_2 > 2$ universal spectrum is valid down to γ_{acc}, and the energy spectrum below this down to an appropriate γ_m is harder with a $p_1 < 2$. We denote γ_{acc} as an "injection break" γ_i, where the electron energy spectrum starts steepening. This would introduce a corresponding injection break ν_i in the radiation spectrum.

3. GRB 010222

The afterglow of GRB010222 has been modelled previously as a burst in a very high density medium undergoing a transition to a non-relativistic expansion (Masetti, N., et al, 2001), which cannot explain the early appearance of radio emission; or as a hard electron spectrum afterglow that underwent a early jet break (Sagar R., et al, 2001), which had difficulty explaining the spectral slope observed in X-ray bands.

We suggest that this afterglow had an injection break ν_i in the X-ray band ~1 day after the burst, had a jet break transition at $t_j \sim 0.5$ day, and evolved in a normal ISM. With an assumed $p_1 = 1.3$, $p_2 = 2.1$, and a smooth joining of the power-law segments, we are able to obtain good fits to the spectrum and the light curve of this afterglow.

4. Origin of the Flatter Spectrum

Possible pre-acceleration mechanisms to inject electrons at the lower DSA cutoff of γ_i have been discussed by many authors. Hoshino et al (Hoshino, M., et al, 2001) describe resonant ion-cyclotron wave absorption mechanism in a three component (electron, positron and proton) magnetized plasma, which operates in the range $\gamma_{sh} \leq \gamma_e \leq (m_p/m_e)\Gamma_{sh}$, and produces a hard electron spectrum. Leptons absorb the elliptically polarized magnetosonic waves emitted by the protons and undergo 'non-thermal heating'. Electrons and positrons will be eventually distributed in a maxwellian with a suprathermal power law tail extending precisely till γ_i. This suprathermal tail is expressed by a flatter power law where the index p could be as low as 1.5. The mechanism requires protons to be the major contributors to the upstream flow energy while the $e^{\pm}$ component should dominate the downstream number density.

In a GRB blast wave, we estimate that the total pair production due to high-energy bremsstrahlung as well as synchrotron photons is insignificant. The total lepton number density is therefore only slightly larger than the number density of ions. The applicability of the resonant wave absorption mechanism to this regime is unclear. We plan to investigate this in further detail.

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