Evolution of an afterglow with a hard electron spectrum

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Abstract. Diffusive shock acceleration theory suggests that the “universal” energy spectrum of electrons with a power-law index $p \approx 2.3$, commonly used to model GRB afterglows, cannot extend below an electron lorentz factor $\gamma_e$ equal to the bulk lorentz factor of the blast wave multiplied by the ratio of proton and electron masses. We suggest that the electron energy distribution has a slope $p < 2$ below this limit, down to an appropriate $\gamma_m$. A two-slope spectrum such as this provides a good model for the afterglow of GRB010222.

1. Introduction

GRB afterglow emission is usually modelled with a single power-law electron energy spectrum:

$$N(\gamma_e) \propto \gamma_e^{-p} \quad \gamma_m < \gamma_e < \infty$$

with the power-law index $p > 2$ and $\gamma_e$ being the lorentz factor of the electron (see Piran 1999 for a review). Relativistic shock acceleration theory predicts an universal $p \approx 2.3$ which fits many afterglow spectra (Waxman 1997; Galama et al 1998; Wijers and Galama 1999).

In some GRB afterglows, harder electron energy spectrum $p < 2$ appears to be needed (Panaitescu and Kumar 2001a; Sagar et al 2001; Cowsik et al 2001; Bhattacharya 2001). Such a spectrum must have an upper cutoff, an injection break $\gamma_i$, beyond which $p$ must exceed 2 in order to keep the total energy in the electron distribution finite. The evolution of the afterglow emission is influenced by the evolution of $\gamma_i$ (Bhattacharya 2001; Panaitescu and Kumar 2001b; Dai and Cheng 2001).

The minimum lorentz factor $\gamma_m$ of the distribution is determined by the fraction $\epsilon_e$ of the postshock thermal energy that is injected into electrons. For $p > 2$ this is given by

$$\gamma_m = \epsilon_e \left( \frac{p - 2}{p - 1} \right) \cdot \left( \frac{m_p}{m_e} \Gamma_{sh} \right)$$

where $\Gamma_{sh}$ is the bulk lorentz factor of the blast wave shock and $m_p$, $m_e$ are proton and electron masses respectively (Sari, Piran and Narayan 1998).
2. An injection break

Relativistic shock acceleration theory predicts that the universal spectrum with \( p \approx 2.3 \) can extend only down to a minimum \( \gamma_{\text{acc}} = (m_p/m_e)\Gamma_{\text{sh}} \). Below this energy the electron Larmor radius becomes smaller than the shock thickness, the shock is no longer perceived as a discontinuity and the acceleration efficiency drops (Hoshino et al 1992; Gallant et al 2000; Kirk 2002). However for a low \( \epsilon_e \) the \( \gamma_m \) estimated from eq. 2, and routinely used in GRB afterglow modelling, works out to be much lower than \( \gamma_{\text{acc}} \). This creates a contradiction.

In the region between \( \gamma_m \) and \( \gamma_{\text{acc}} \), some special pre-acceleration mechanisms are needed (Kirk 2002; Gallant et al 2000). One candidate for this is a variant of the ion magnetosonic wave absorption mechanism proposed for electron-positron-proton plasma (Hoshino et al 1992). This mechanism produces a hard energy spectrum, but has a natural upper cutoff at exactly the \( \gamma_{\text{acc}} \) defined above. We conjecture that for electrons in GRB afterglows, a \( p_2 > 2 \) universal spectrum is valid down to \( \gamma_{\text{acc}} \), and the energy spectrum below this, down to an appropriate \( \gamma_m \), is harder, with a \( p_1 < 2 \). We identify the injection break \( \gamma_i \) with \( \gamma_{\text{acc}} \). This would also introduce a corresponding injection break \( \nu_i \) in the radiation spectrum. Here

\[
\gamma_m = \left[ \frac{\epsilon_e (2 - p_1)(p_2 - 2)}{(p_2 - p_1)(p_1 - 1)} \right]^{1/(p_1-1)} \gamma_i
\]  

3. Evolution of the radiation spectrum

We have calculated the evolution of the afterglow radiation spectrum based on this premise. Writing the flux at a frequency \( \nu \) at time \( t \) as \( F_{\nu}(t) \propto t^{\alpha} \nu^{\beta} \), we find the values of \( \alpha \) and \( \beta \) in different spectral regimes to be as follows:

| \( \nu \) | \( \beta \) | \( \alpha_1 \) | \( \alpha_2 \) |
|---|---|---|---|
| \( \nu < \nu_a \) | 2 | 1/2 | 0 |
| \( \nu_a < \nu < \nu_m \) | 1/3 | 1/2 | -1/3 |
| \( \nu_m < \nu < \nu_c \) | \(-\frac{p_1 - 1}{2}\) | \(-\frac{3(p_1 - 1)}{4}\) | \(-p_1\) |
| \( \nu_c < \nu < \nu_i \) | \(-\frac{p_1}{2}\) | \(-\frac{3(p_1 - 2)}{4}\) | \(-p_1\) |
| \( \nu_i < \nu \) | \(-\frac{p_2}{2}\) | \(-\frac{3(p_2 - 2)}{4}\) | \(-p_2\) |

In the table, the third column gives the light curve slopes after the lateral spreading of the collimated outflow dominates the dynamics, and the second column those before this phase. The transition between them is often called the jet break. The quantity \( \nu_c \) stands for the synchrotron cooling break frequency in the radiation spectrum.
Figure 1. Light curve and spectra of the GRB010222 afterglow compared with the model (solid lines) using a two-slope electron energy spectrum. Optical data taken from the compilation of Sagar et al (2001) and Cowie et al (2001), X-ray data from in’t Zand et al (2001) and Radio data from Frail et al (2002). The model uses $p_1 = 1.32$, $p_2 = 2.1$ and a jet break at 0.4 days. The injection break $\nu_i$ is located at $\sim 10^{18}$ Hz (X-rays) $\sim 1$ day after the burst.

4. GRB010222

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 et al 2001), which cannot explain the early appearance of radio emission; or as a hard electron spectrum afterglow that underwent an early jet break (Sagar et al 2001; Cowie et al 2001; Panaitescu and Kumar 2001a), which had difficulty explaining the spectral slope observed in X-ray bands.

We suggest that this afterglow had an injection break $\nu_i$ in the X-ray band $\sim 1$ 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, as shown in the figures.

5. Summary

We have computed the evolution of a GRB afterglow with a hard electron energy spectrum up to an injection break at $m_p/m_e$ times the bulk lorentz factor of the shock. Above the injection break, relativistic shock acceleration predicts an universal, relatively softer, electron energy spectrum. We obtain good fits to the observed evolution of GRB010222 afterglow using this model. We suggest that hard spectrum emission is more likely to be seen in GRB afterglows that have a relatively low $\epsilon_e$. 
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