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Multiband modelling and radio observations of GRB afterglows

L Resmi[1,2*]
[1] *Raman Research Institute, Bangalore 560080, India*
[2] *Institut d'Astrophysique de Paris, 98-bis, Bd-Arago, Paris-750014*

Abstract. Gamma Ray Bursts (GRBs) are the most energetic explosions in the Universe. Most of our knowledge about GRBs have come from multiband modelling of afterglows associated with the bursts. Afterglow emission is believed to be synchrotron radiation from electrons which are accelerated to high energies, by the shocks created in the explosion. Here we present a modification for the standard modelling paradigm to accommodate electron distributions which are harder than usual, and make multiband studies of afterglows arising from such distributions. We also present the low frequency campaign of GRB 030329 radio afterglow done with the Giant Metrewave Radio Telescope, and interpret the evolution of this afterglow.

Keywords : gamma rays : bursts

1. Introduction

The widely popular and successful standard fireball model for Gamma Ray Burst (GRB) afterglows is based on ultra-relativistic external shocks sweeping up matter around the explosion site to accelerate electrons upto GeV energies and boost the magnetic field to values close a few Gauss in its downstream. According to the model, the afterglow radiation is the synchrotron emission from these electrons gyrating around the enhanced magnetic field. A contribution from inverse compton scattering may also appear in the total flux at higher frequencies.

The synchrotron spectrum is characterised by 'breaks' which arise due to various

*e-mail: resmi@iap.fr

physical processes. The spectral slope changes due to the synchrotron self absorption below a frequency ν_a. The synchrotron peak frequency (ν_m) corresponds to the emission by electrons at the lower limit of the power law distribution of energies and the cooling break ν_c corresponds to the electron energy above which synchrotron radiation loss becomes very significant. Apart from these, the lightcurves exhibit achromatic slope changes due to dynamical processes within the fireball. The ejected matter is collimated and initially undergoes a radial expansion. Later, the lateral expansion of the jet takes over and this is reflected as an achromatic break (jet break) in the lightcurve. The next achromatic change of slope marks the transition of the fireball into the non-relativistic regime.

The spectrum of afterglow radiation itself evolves with time, reflecting the expansion of the fireball, hence a data set well sampled in both spectral and in temporal domain is essential for useful study.

2. GRB 030329

Multiband modelling of GRB afterglow lightcurves is at present the best available tool to understand the true nature of the explosion and its surroundings. Apart from that, detailed modelling also holds the key to the secrets of particle acceleration processes in collisionless shocks.

By modelling the well-sampled data set of an afterglow, the energy content ($E_{\rm tot}$) of the jet, its angle of collimation (θ_0), the density profile of the ambient medium ($n(r)$ where r is the distance from the site of the explosion) and some relevant parameters of shock microphysics (p, the power law index of the distribution of electrons which are radiating via synchrotron mechanism, ϵ_e, the fraction of energy in those electrons and ϵ_B that in downstream magnetic field) can be obtained.

Afterglow data of the nearby ($z = 0.16$, one of the nearest GRBs) GRB 030329 was unprecedentedly rich in both optical and radio bands which enabled detailed and well constrained modelling attempts. The evolution of the afterglow was complex. While the afterglow flux in optical as well as in x-ray exhibited a jet break around half a day, the radio flux past 0.5 days did not follow the expectations from a jet which has already entered the lateral expansion regime. Instead, it showed an achromatic steepening around $\sim$ 10 days. Hence, a novel suggestion of two co-aligned jets, one narrow and one wide, together giving rise to the observed flux has emerged (Berger et al. 2003). We test the predictions of this conjecture and get a refined set of parameters, prompted primarily by the additional data from GMRT. We then proceed to suggest a different scenario in which the initial jet which gave rise to the x-ray and optical flux is re-energized by the central engine during its lateral expansion that makes it once again collimated, now to a wider opening angle (Resmi et al. 2005). This new jet enters a lateral expansion phase around 10 days, resulting in the jet break seen in radio bands. One peculiarity of this

GRB was its association with a supernova (SN2003dh) which dominated the optical flux beyond a week. The refined afterglow flux calculation allowed us to subtract the afterglow contribution from the total optical flux and compare the resulting supernova contribution with the stereotype SN1998bw. While being similar in lightcurve, SN2003dh is fainter compared to a redshifted SN1998bw.

2.1 Radio afterglow

Radio observations have always been special since they allow the estimation of the self absorption frequency, thus giving a direct clue to the size of the fireball. Afterglows are long lived in low radio frequencies (< 1 GHz) while they quickly decay below visibility in all other bands, even at high radio frequencies (say 15 GHz). Hence monitoring at low radio frequencies is the only way to study the late time evolution including the transition from relativistic to non-relativistic dynamics.

GRB030329 had one such rare bright radio afterglow and we followed it up in low frequencies (1280 MHz and 610 MHz) using the Giant Metrewave Radio Telescope (GMRT). We present observations in 1280 MHz and 610 MHz bands during the second year of the afterglow. Thanks to this long coverage, we were able to pin-point the location of ν_a and the transition of the fireball to the Newtonian regime. The follow-up campaign is still continuing thanks to the slow evolution in low radio frequencies. This afterglow has hence become the longest observed. It also is the only one which is seen in frequencies below 1 GHz.

3. Hard electron energy spectrum

The standard fireball model uses certain simplistic assumptions owing to our lack of knowledge of the shock acceleration process. One common assumption is that of a *universal spectrum* of the accelerated electrons, a steep non-thermal energy distribution with power law of index ~ 2.2. It owes its origin to theoretical simulations of shock acceleration which often produce a steep ($p > 2$) spectrum (for eg., Achterberg et al. 2001). This also fits many observed cases of such energy distributions. Further, this assumption leads to a simplification in theoretical models, since the upper cut off energy of the distribution plays virtually no role.

The presence of harder, $p < 2$ spectrum, in a minority of cases, has hence not received a fair share of attention. Calculations to derive the physical parameters of the burst in such cases are often not done consistently. Early attempts to model GRB afterglows with *hard* electron energy spectrum had several loop holes. In this thesis, we have done these calculations consistently and applied them to a few afterglows with fairly good temporal and spectral coverage (Bhattacharya & Resmi 2004; Misra et al. 2005).

We present the theoretical modifications required for the standard model to accommodate electron energy spectra with power-law indices less than 2. The energy spectrum requires a new parameter γ_i, which is the Lorentz factor corresponding to the upper cut-off of the hard energy distribution. Above γ_i, the distribution either terminates or steepens (double-slope electron distribution) to a value of p larger than 2. The functional form of this cut-off is decided by the particle acceleration processes, which are at present poorly understood. We therefore parametrised the temporal evolution of γ_i, in terms of the bulk lorentz factor of the shock (Bhattacharya 2001). We discuss two possible origins for the cut-off. As a result of this cut-off in the energy spectrum, a new break ν_i is introduced in the radiation spectrum, which is the synchrotron frequency corresponding to γ_i. Apart from that, the expressions for ν_m and ν_a differ from the standard scenario. We have calculated the shock dynamics using the method adopted by Huang et al. (2000), which allows a smooth transition from ultra-relativistic to non-relativistic regime of the fireball. Using this profile of Γ vs. observed time, we calculated the synchrotron spectral evolution from a double slope electron energy distribution semi-analytically. The self compton emission also is calculated. For ultra-relativistic and non-relativistic regimes, analytical solutions are presented for both ISM $[n(r) \propto r^0]$ and stellar wind driven $[n(r) \propto r^{-2}]$ ambient medium density profiles.

The way one identifies potential candidates which could have an underlying hard electron energy spectrum, is ~~by~~ looking at the lightcurve decay index past the jet break. The choice is confirmed by the optical and x-ray spectral indices. According to the standard model, the flux in higher frequencies, past jet break, decay as a power-law of index p; the spectrum below ν_c should have a slope of $(p-1)/2$ and above it should fall as $p/2$. The value of p one thus obtains from all these methods is expected to be consistent. We chose three such afterglows (GRB010222, GRB020813 and GRB041006), which show shallow decay of fluxes in the optical as well as in x-ray bands and relatively flat spectra. Out of a dozen such afterglows, these three have well sampled multi-band lightcurves. We fitted the data set with the model and estimated the physical parameters. For GRB041006, we have estimated the contribution of the associated supernova by subtracting the afterglow model from the total emission. We found the contribution from compton emission to be negligible in all these cases. Interestingly, all these afterglows had relatively low cooling frequency, which could perhaps be due to some unknown relation to the acceleration mechanism itself.

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