
Multiband Modelling and Radio Observations of Gamma Ray Burst Afterglows

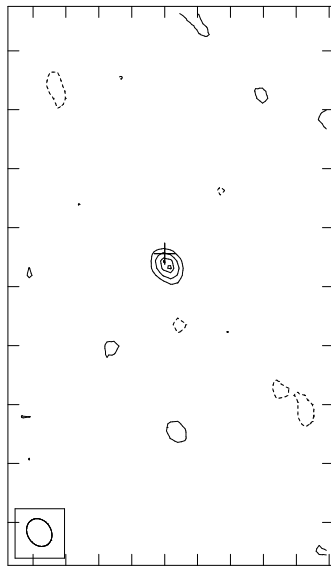
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A Graduate Student's Apology

Dipankar

It was after a friend's wedding reception that I got a ride back home in Dipankar's car. Had it not been for that incident, I would not have gathered the courage to write to him ever, asking for a project.

Five years later, I stand deeply indebted to him, for physics, for research methodology and the approach to science. I must confess that I was often both proud and jealous of his wonderful intuition and insight!

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General

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List of Symbols Used

A_*	Parametrises the normalisation constant for stellar wind driven density profile around the progenitor star
α	Afterglow flux decay index
$\alpha'_{\nu'}, \alpha_{\nu}$	Absorption coefficient, former is in the co-moving frame, while the latter is in the lab frame
B	Magnetic field density in the post-shock medium
β	Bulk velocity of matter in terms of c
c	Velocity of Light
c_s	Velocity of Sound
$d_L, d_{L,Gpc}$	Luminosity distance. Latter is normalised to 1 Gpc
dS'	Thickness of the shocked shell measured in the co-moving frame
δ	Afterglow spectral index
$E_{(B-V)}$	Parametrising the extinction due to dust column
$E_{\text{tot}}, \mathcal{E}_{\text{iso}} \ \& \ \mathcal{E}_{\text{iso},52}$	Total energy in explosion, isotropic equivalent energy and the same normalised to 10^{52} ergs respectively
E_{γ}	Energy in the prompt phase, emitted as γ -radiation
ϵ	Parameter characterising the radiative losses from the shocked medium, $\epsilon = 0$ implies the fireball dynamics is adiabatic and $\epsilon = 1$ implies it is radiative.
ϵ_e	Fraction of shock created thermal energy in the accelerated electrons
ϵ_B	Fractional shock thermal energy in the downstream magnetic field
$F(x)$	Functional form of mono-energetic synchrotron power spectrum
f_{γ}	Fluence, energy received per unit area per unit frequency
f_{ν_m}	Synchrotron flux at $\nu = \nu_m$
f_p	Function of p_1 and p_2 , the indices describing the double powerlaw, $f_p = \frac{(2-p_1)(p_2-2)}{(p_1-1)(p_2-p_1)}$
ϕ_p	Function of the power law index p , used in evaluation of f_{ν_m}
g_p	Function of p_1 and p_2 , $g_p = f_p(p_1 - 1)$
Γ	Gamma function
Γ	Bulk lorentz factor of the shock front
γ	Single electron lorentz factor
γ_c	Lorentz factor above which synchrotron cooling is effective
γ_i	Injection break, above which a double power-law steepens to γ^{-p_2}
γ_m	Minimum lorentz factor for the electron energy spectrum
γ_u	Upper cut-off lorentz factor for hard electron energy spectrum

$\hat{\gamma}$	Ratio of specific heats of a gas
Jy	Unit of flux density, equals 10^{-26} Watt m ⁻² Hz ⁻¹
k_B	Boltzmann constant, 1.381×10^{-23} Joules/Kelvin
K_e	Normalisation constant of the power-law distribution of shocked electrons
K_j	Modified Bessel function of order j
M, dM	Total mass (rest mass and the equivalent of thermal energy) in the shock downstream
m, dm	Ambient matter swept up by the shock
m_1	Single particle rest mass
m_p, m_e	Rest mass of proton and electron respectively
N_H	Hydrogen column density along the line of sight
$N(\gamma)$	Number density of shocked electrons as function of γ
$n, n(r)$	Number density of the ambient medium, which can be a function of radius (r)
ν, ν'	Frequency of radiation, measured in the lab frame and the co-moving frame of the shock wave respectively
ν_a	Synchrotron self absorption frequency
ν_c	Cooling frequency, beyond which the synchrotron spectrum steepens
ν_i	Injection break, corresponding to the lorentz factor γ_i
ν_m	Characteristic synchrotron frequency corresponding to the minimum lorentz factor γ_m of the electron distribution
Ω	Solid angle of the jet, given as $(1 - \cos \theta_j)$
$P(\gamma), P(\gamma, \nu)$	Single electron power, total and specific
p	Power law index describing a non-thermal, single slope, electron distribution
p_1	Power law index for the flat part of the double slope electron spectrum
p_2	Same for the steep part
P, V, T	Pressure, Volume and Temperature
q	Index which parametrises the dependence of the injection break, γ_i on Γ
r, r_{17}	Radius of the shock front from the center of explosion, the latter is normalised to 10^{17} cm
r_0	Radius normalisation for wind driven density profile, equated to 10^{10} cm in the document
r_{dec}	Deceleration radius of a fireball, beyond which the Blandford-McKee profile applies
r_j	Radius corresponding to the jet break time, t_j
ρ	Total mass density
ρ_0	Normalisation parameter for ambient medium density profile
s	Index characterising the radius dependence of ambient medium density profile $s = 0$ for a constant density medium
t	Time elapsed after explosion, measured in the lab frame
t_{co}	Time elapsed since explosion measured in the comoving frame of the shock wave

t_d	Time since burst in days
t_j	Jet break time : time beyond which lateral expansion of the jet becomes dominant
t_{NR}	Non-relativistic transition time of fireball, usually approximated to the time when $\Gamma \rightarrow 1$
τ	Optical depth
θ_0	Initial half opening angle of the ejecta
θ_j	Half opening angle of the ejecta at any given time
σ_T	Thompson cross-section, $6.6524 \times 10^{-25} \text{ cm}^2$
U, u	Thermal energy density of gas/plasma
x_p	Function of power law index p used in evaluation of ν_m
ξ	Constant of proportionality for the upper cut-off lorentz factor (γ_i) to Γ
z	Redshift

Synopsis

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 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.

Multiband modelling of GRB afterglow (AG) 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_{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 (but unfortunately poor in x-rays) which enabled detailed and well constrained modelling attempts. The rigorous monitoring campaign revealed an unexpected behaviour of the radio flux, for which one explanation was that that the early optical emission and the late radio emission arose in two different jets. However, our detailed modelling using the rich data set allowed us to propose a new mechanism in which the initial outflux of energy is ‘refreshed’ by a later episode of injection.

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. 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.

Apart from multiband modelling, this thesis also presents late time observations of the GRB030329 afterglow in low frequency radio bands. 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 Meterwave Radio Telescope (GMRT). The follow-up campaign is still continuing thanks to the slow evolution in low radio frequencies. This afterglow has hence become the longest (~ 1000 days) observed, beating the earlier record of ~ 500 day long observations of Radio afterglow of GRB970508. It also is the only one which is seen in frequencies below 1 GHz.

This thesis is organized in the following manner:

Chapter 1 gives a general introduction to GRBs and their afterglows. After describing the properties of the burst and the afterglow, we proceed to explain the standard fireball model in detail. The dynamics of the external shock and the profile of the bulk lorentz factor (Γ) vs. r is described. We explain the jet break (t_j) and non-relativistic transition (t_{nr}), two major developments in the life of the fireball. We then give a detailed description of the synchrotron radiation mechanism, which is the source of afterglow radiation. The spectral breaks (ν_a , ν_m and ν_c) and their time evolution is explained. We conclude this chapter by listing a few unanswered questions relevant to this thesis.

In Chapter 2, 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. 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. In chapter 3, 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.

Chapter 4 and 5 are devoted to GRB030329, one of the best monitored afterglows till date. The 4th Chapter focuses on the radio observations of the afterglow done with the GMRT at low frequencies. To begin with, we give a brief introduction to the interferometric techniques and the instrument. GMRT, an interferometric array with 30 elements, each of diameter 45 meters has an excellent sensitivity at low frequencies which allowed it to detect and monitor the afterglow for a long time. We then 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.

Chapter 5 describes the multiband modelling of this afterglow. 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 ~ 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. 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.

The contribution of this thesis lies in presenting a consistent modelling platform for ‘hard’ electron energy spectra as well as in the low frequency campaign of GRB030329 afterglow and the interpretation of its evolution. Chapter 6 concludes the thesis along with a few suggestions for future directions.

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