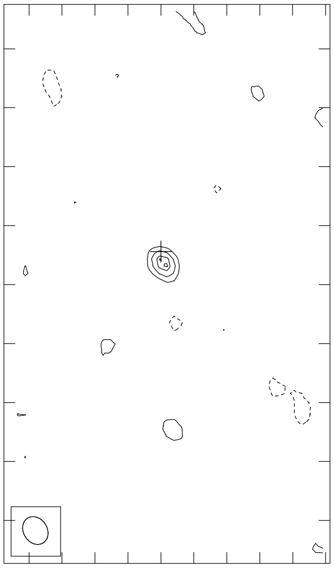
Multiband Modelling and Radio Observations of Gamma Ray Burst Afterglows



Resmi L

A thesis submitted for the degree of

Doctor of Philosophy

in the

Faculty of Science

Department of Physics
Indian Institute of Science
Bangalore-560 012
India

September 2006

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!

I have no words to thank him for his understanding, the enormous patience he has shown towards me and his care in many difficult situations.

I heartily thank you Dipankar, for showing me the beauty of the art of science! In fact, I am sorry too, I wish I could do better. Hope this thesis is not the end, but only the start of a collaboration between us.

Collaborators

I am obliged to Ramsagarji for giving me a shelter at ARIES, at a time when this thesis was about to vanish into thin air. I thank him for the care he has taken during the three months of my stay there, where this document started taking its shape.

GRB collaborations are multi-wavelength affairs. Thanks to Ramsagarji, Anupama, D K Sahu, Shashi and Kuntal for the optical part of our team, Pramesh Ishwar and Atish for the radio and Alberto and his group for the millimeter part.

Many thanks to Ishwar for patiently training me in interferometric data analysis.

I must say I learnt a lot during my discussions with Kuntal. Thank you Kuntal, and hope we will continue working together!

Other Academics & Administration

Chanda was my nominal guide in the JAP programme. Whenever we met in the campus, she used to earnestly inquire about my progress. Thanks Ma'am for all your good wishes and concern.

My sincere gratitudes to my advisory committee at RRI, Dipankar, Sam and Shukre, for the annual review, comments and suggestions (most of which I never in fact could not execute, apologies added!)

Thanks to the JAP course work instructors.

The administrative staff at the Physics Dept. especially Meena and Rakma for handling my 'complicated fellowships' and other official processes properly.

Gratitudes to Krishna for his special ability in sorting out complicated matters, I largely benefited from it during my foreign trip.

Other administrative staffs of RRI, Radha, Marisa and others for all the efforts they have taken to make my life simple and comfortable there.

Council for Scientific and Industrial Research (CSIR) for financial support, making it a mess with a competent support from me, and the no-support of the final year.

Confidants

There are two friends of mine, without whom I wonder what course my life here would have taken. I met Chaitra during my interview time itself, as the would-be-senior, later she became my closest confident. On enormous number of situations, it was to her that I ran to, for help, advice, support, encouragement.... She played a major role in developing my views and attitude. Arun cracked his head on almost all problems of mine, be it academic, personal, academico-personal... and came up with suggestions and consolation, whichever was required. He used to be the first to express delight on all apparent successes of mine, how small they were. Chaitra, Arun, I am at loss of words to thank you two.

IISc

Some souls prefer to graduate leisurely, and I remember one of them mentioning, 'one does not feel like leaving even after eight years'. IISc is the home, no question.

Thanks to all of you whom I befriended during my six year stay on the campus. My MSc batchmates Manju and Santo, Jayanthi and Smitha who joined with me and formed a good company, thanks a lot for our 'childhood days' and its paranoias. Manoj for the best intellectual friendship I ever had, and for several mails and gchats about almost everything in the universe. Was nice to have your company Manoj! Sameen for an intimate friendship, for our movie collections. It was a pleasure to have Deeps' cheerful company. Thanks Deeps for the company you gave me at IISc, in 'looking around' in the C-mess, in watching complan uncle's walking style and other similar oddities which were easily available in the campus. RM is fondly remembered for a chat on Russian literature, Aug-24, BT, and Nexito. Sunil for several discussions over cups of tea in the tea-board, which mostly centered on research methodology and the like, Murali for joining towards the end. Cheryl for our 'race' in publishing papers, which never started or ended since both parties preferred to be rabbits. Randhir, Dileep, Hemanth, Prasanth, Ajith, Dr. Sarada ... for conversations. Jayanthi and Ashwathi for training me to ride the bicycle, for the bi-wheeled friend later on became my trusty companion to RRI and back. Thanks to Kanak for astrophysics discussions and tea-board trips.

I bought both my cameras at IISc, the first one, the simple P&S, KB10 hopefully still survives somewhere in the mythic land of the Hellenic republic. The second, Vivitar 3800N in my room, in a similar forgotten fashion. Anyhow, thanks Ayash and raoar for introducing the art of photography to me for I really plan to do it sometime in my life, and thanks Raghu for joining in the team later. The trio for all the fun through e-mails.

Thanks to IISc filmsoc, CC and MMB for keeping me entertained by some sensible cinema. Apratim, Sriparna and Tirtha for a nice friendship which came through the filmsoc. Thanks to other filmsoc friends like Ayan, Anindita, Samridhi ....

Joby for introducing me the wonderworld of avifauna. Maddy, Vivek and others for chats about the chirpy friends.

Teaboard for tea and the environment. A, B and C mess for being available after every couple of months.

Brachistochrone for helping me with the 1.5kms every day. It was perhaps one of the saddest memmories I will have, to find my favourite bicycle stolen one fine evening.

RRI

RRI is a place where everyone knows everyone else, and I found it rather uncomfortable to be known so much.

Gratitudes to the Astro faculties. I always enjoyed Srini's attention. It was nice to have discussions with him, of astrophysical topics and of a science-career. Thanks Sirni! Biman encouraged me always, his suggestion of the 'newsflash' indeed proved useful and helpful to me. I saw his door always open to discussions regarding various academic things. Thanks Biman! Thanks to Dwaraka and Anish for Radio Astronomy lectures, Shiv for some GRB conversations. I've learned quite a bit of general Astrophysics by being in a 'floor' which has varied interests. Thanks to the astro floor.

Amit and I shared a nice friendship, thanks Ami. Thank to the rest of the g-7 for all the enjoyment in the form of tours and several outings to 'strictly vegetarian restaurants'. It was fun to watch the bewildered faces at the noise we created in the eatery, most of it belongs to a divya's laughing capacity!

Chandreeye is one of the nicest people I have seen. Thanks for the company especially in the beginning and end of my Ph.D days. I wish I never made you to go till IISc, with the sole aim of waking me up.

Sunita and I seem to have shared a mysterious resemblance, it will be difficult to count the number of people who misidentified us, or assumed a relation between us, other than that of guide's wife – husband's student. Overall it was fun! Sunita, many thanks for letting me to 'generally' walk down to your room and converse in long, be it any silly matter or any serious thing. And also for the several useful tips you kindly provided for my profession.

Ravishankar and me had several similarities. We talked about many things, be it gossip or philosophy, with the same involvement and seriousness. Thanks Ravi!

Madhavan, thanks for the ‘cartoon’ by the ‘cartoon’

More than a secretary, Vidya was like a friend to all of us. Thanks Vidya for patiently dealing with all the issues concerning the daily life in RRI.

Thanks to Nirvikar for conversations regarding research in general.

My astro seniors and juniors are thanked.

Lakshmanamma for (light and sweet) tea, made for my taste, before the pantry service was stopped and we became self-reliable in that matter.

Thanks to Kanak for astrophysics discussions and tea-board trips.

The transport service is acknowledged for responding to all my calls from IISc at odd hours to pick me up from this or that gate.

General

During the span of this thesis, I have spent some time as a migrant researcher at various places inside and outside India.

Friends at NCRA, Ananda, Subhashish and others and staff at GMRT are thanked for the warm atmosphere, Subhashis especially for several discussions about the academic life.

ARIES people are thanked, especially Jessy and Kuntal for taking care of the non-hindi speaking alien in the Kumaon hills.

Alberto, Martin and Gorosabel are thanked for taking care of me during my stay in Granada. Ralph and his students for extending a warm welcome at the Astronomical Institue, Amsterdam.

Niruj, Mr. & Mrs. Dharam for their care during my Amsterdam visit.

Sudip Bhattacharyya, my senior, for giving me several useful tips and directions from which I got largely benefited.

My course work batchmates, Manas, Kaustuv and Suparna is thanked for their company.

Gopika for friendship.

Photoclub friends, (raoar, Ayash, Raghu, Sid, Girish et. al.) for all treks, Anish and the group for the rain trek of Bababudanagiri, Motta and Luke for the

Hessarghatta camping.

People from Past

Vikraman Sir and Venu Sir for Physics, encouragement, care. Valsamma Teacher for the charm of Mathematics. VCK for Mathematical Physics, RBT for Statistical Physics and Classical Mechanics. And all my other teachers for their constant encouragement, which is still boosting my confidence to a large extent.

Dr. Somak Raychaudhury was my mentor in research. I was a little too excited when I got a chance to do summer project in astro-physics, under the JNC fellowship, because I never expected it. That changed my plans – the idea of research became more vivid than a crazy dream, under the exciting guidance of Somak Sir. Before the project ended, I decided what to do next : an astrophysics Ph.D. Somak Sir, thanks for helping me out in selecting my supervisor too. Dipankar, as you said, indeed is an excellent supervisor.

Many thanks to Minu and Viva for giving the crucial support for me to take my first step to research. Had they not been accompanied me (with no particular reason) to IUCAA, my trajectory could have perhaps been something else.

Thanks to Sandhya for our intimate friendship, which extended from MSc days, and for her good wishes.

Home

It was never in the dream of Chechiamma, Amma and Pappachi that I will go away when they expected me to finish my studies and get a job. That too to stay away for so long. They would have never dreamt that I remain unsettled for three decades! My apologies, for having to shatter all your expectations that I will follow a conventional path, and I have to say it once again, because I do not plan to do it even now either. Hope you will accept my odd ways, and will give that unconditional support and love forever! Many many thanks, for all the strength. Let me dedicate this thesis to you three.

List of Symbols Used

$A_\star$	Parametrises the normalisation constant for stellar wind driven density profile around the progenitor star
α	Afterglow flux decay index
$\alpha'_{\nu'}$, α_ν	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
$E_{\rm tot}$,$\mathcal{E}_{\rm iso}$ & $\mathcal{E}_{\rm iso,52}$	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, $g_p = f_p(p_1 - 1)$
$\mathsf{\Gamma}$	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 $10^{-26}\,\mathrm{Watt\,m^{-2}\,Hz^{-1}}$
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, 6.6524×10^{-25} 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 ($E_{\rm tot}$) 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 (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 ($\sim$ 1000 days) observed, beating the earlier record of $\sim$ 500 day long observtions 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 ($t_{\rm nr}$), 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 $\sim$ 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. 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.

Contents

List of Figures

List of Tables