An Investigation of Gamma Ray Burst Collimation

by

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Certificate

This is to certify that the thesis entitled **"An Investigation of Gamma Ray Burst Collimation"** submitted by Atish P. Kamble for the award of the degree of Doctor of Philosophy of Jawaharlal Nehru University, New Delhi is his original work. This has not been published or submitted to any other University for any other Degree or Diploma.

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Declaration

I hereby declare that the work reported in this thesis is entirely original. This thesis is composed independently by me at the Raman Research Institute, Bangalore under the supervision of Prof. Dipankar Bhattacharya. I further declare that the subject matter presented in the thesis has not previously formed the basis for the award of any degree, diploma, membership, associateship, fellowship or any other similar title of any University or Institution.

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Dedicated to my dear Mother...

Acknowledgement

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In retrospect, this thesis has received helps from so many quarters that it hardly looks mine ! One sets out on this long journey with the thesis being a prime destination in mind. However, the experiences I had during the course and the lessons they taught me are of such importance in life that the thesis appears as only a milestone, and not the destination. And if there is one lesson that I have to pick up, from this lot, for the journey ahead, then it would be :
"*Oh traveller, there are no paths. Paths are made by walking !*"[1]

[1] attributed to Antonio Machado.

Synopsis

GRBs are usually classified into two groups, Long ($>$ 2s) GRBs with relatively soft spectrum that are thought to originate in the collapse of massive stars and Short ($<$ 2s) GRBs with relatively hard spectrum that are thought to originate in coalescing compact binary stars. This thesis deals with bursts of the first type, and we refer to them simply as "GRBs".

The discovery of redshift associated with a GRB afterglow (GRB 970508) put an end to a long standing debate about the extragalactic or galactic origin of GRBs and for the first time gave a direct estimate of the amount of energy released, ($E_{\gamma,iso}$), during the explosion in the form of Gamma-rays, assuming that the explosion was isotropic. The subsequent estimates of the isotropic equivalent energies indicated alarmingly high values ($\sim 10^{54}$ erg) for a few GRBs. It was then suggested that the GRBs could be collimated and hence $E_{\gamma,iso}$ might not be a good representation of the actual energy released during the explosion.

If GRBs were indeed collimated then effects of collimation are expected to be seen in the evolution of their afterglow light curves. The origin and evolution of GRB afterglows is described by a widely popular model, called the Fireball Model, in which a fireball is created by release of a large amount of energy ($\sim 10^{51}$ erg) possibly due to collapse of a massive star. The gravitational energy released in the process drives a relativistic shock wave which propagates into the circum-burst medium. The relativistic shock wave sweeps up the surrounding material, heating it to high temperatures. The shocked electrons are accelerated to high energies and the post-shock magnetic field is amplified to a fraction of a gauss. The relativistic electrons gyrating in this magnetic field radiate synchrotron radiation which is seen as an afterglow of the GRB in x-ray, optical and radio wavelengths. A significant deceleration of the shock wave in the radial direction due to sweeping up of a substantial amount of circum-burst material causes the lateral expansion to eventually dominate over the radial expansion. This consequent drop in the Lorentz factor of forward expansion results in a faster rate of decay of the afterglow light curve. Being of dynamical origin, this should show up at all wavebands simultaneously, causing an "achromatic break" in the afterglow light curve.

Breaks that are achromatic within the available wavelength coverage have indeed been seen in many GRB afterglows, and have been interpreted as the jet break i.e. a break due to sideways expansion of the initially collimated outflow. The time of the observed achromatic break since the GRB can be used to estimate the degree of collimation of the outflow. By taking into account this collimation, the estimates of the energy released during the GRBs, E_γ, came down by a factor of $(\frac{\Omega}{4\pi})$ where Ω is the solid angle of the GRB outflow collimation. The distribution of solid angle corrected E_γ was found to be tightly clustered around $\sim 10^{51}$ erg. This distribution is considered to be one of the most important results since the discovery of GRB afterglows. A near similar amount of energy release during every GRB is considered to be a strong evidence for a similar progenitor for all GRBs.

It is important to note here that the existence of collimation, i.e. jet, in GRBs is inferred from the interpretation of the achromatic breaks observed in the light curves. The jets in GRBs are not directly observed (imaged) as in the radio galaxies and quasars. Various other effects of collimation in the GRBs, apart from the achromatic breaks, have been investigated. The evolution of polarization angle and the degree of polarization of the GRB afterglow, if observed, could be an important tool to establish or to rule out the existence of jets in GRBs. Unfortunately, this is a very difficult exercise for transients in general and especially for GRB afterglows given the faintness of the afterglows. An interesting corollary of GRB collimation is an Orphan afterglow, i.e. an afterglow for which the GRB is not detected.

If GRBs are indeed collimated then the GRBs and initially their afterglows would be visible only to *on-axis* observers which fall within the opening angle from the jet axis of the GRBs. As the collimated outflow decelerates and starts expanding sideways the opening angle of collimation widens and the afterglow becomes visible to *off-axis* observers outside the initial opening angle from the jet axis. Thus the *off-axis* observers will see the afterglow even after having missed the GRB. Such orphan afterglows would be faint, difficult to detect and more importantly very hard to identify. Not surprisingly, none of them have been detected so far.

Given this situation, the achromatic breaks remain the only practical tool to understand GRB collimation.

Apart from the achromatic breaks observed, the afterglow light curves also show presence of a few other chromatic breaks. The Fireball model assumes the Fermi acceleration of electrons across the shock which ensures the power-law distribution of electron energies and the power law synchrotron spectrum of the afterglows. The observed synchrotron spectrum of GRB afterglows generally is not a simple power-law and it exhibits breaks which arise due to various reasons. The synchrotron self absorption changes the spectrum below frequency $\nu_{\rm a}$. The peak of the spectrum corresponds to a frequency $\nu_{\rm m}$ which is a characteristic frequency corresponding to the electrons at the lower cut-off of the Lorentz factor distribution of the accelerated electrons. At higher energies where the synchrotron radiation loss becomes significant the electron distribution steepens. Thus the energy distribution of accumulated electrons is in fact a broken power-law with two segments. The break in the electron distribution results in a break in the afterglow spectrum at a frequency called the ‘electron cooling frequency’ $\nu_{\rm c}$. The temporal evolution of these spectral breaks and of the peak flux is governed by the evolution of the Fireball itself which results in different shapes of the afterglow light curves at different frequencies. The effect of a natural transition of the shock wave from relativistic to non-relativistic expansion phase, after about a few tens of days, is also expected to be seen as an achromatic break in the afterglow light curves.

A multifrequncy coverage of GRB afterglows can be used to extract important information about GRBs and their environments. By sampling the three spectral breaks and the peak flux mentioned above, which requires a very good multi-frequency coverage of the afterglow light curves over a wide temporal baseline, it is possible to estimate the total energy content of the Fireball (E), the average density of the ambient medium (n), and the fraction of total energy content in the electrons ($\epsilon_{\rm e}$), and in the post-shock magnetic field ($\epsilon_{\rm B}$). A good multi-frequency coverage of the afterglow light curve is a must for inferring the existence of achromatic breaks, the epochs of which can be used to estimate opening angles of the outflows.

Swift, a satellite devoted to GRB detection and follow up, which was launched in Nov. 2004, has since discovered $\sim$ 200 GRBs. A sensitive x-ray telescope onboard *Swift* and its quick follow up capabilities combined with ground-based optical telescopes, especially the robotic optical telescopes, has provided us with a wide multi-frequency coverage of GRB afterglows and has resulted in a rich diversity of afterglow light curves with multiple breaks. It has also been seen that for many afterglows the achromatic break did not occur even after a few weeks. This raises a possibility that the collimation in GRBs, which is inferred from the existence of achromatic breaks, is not a generic feature of all GRBs. Alternatively, it raises doubts over the interpretation of achromatic breaks as an effect due to GRB collimation. It is also true that there is, so far, no single model which can explain the multiple breaks observed in afterglow light curves. Thus, it is important to understand every observed break in order to search for evidence of collimation. The work presented in this thesis consists of multi-frequency observations and modeling of a few GRB afterglows to understand various breaks seen in their light curves, and to search for and investigate the collimation in GRBs.

The afterglow of GRB 050401 presents several novel and interesting features which are difficult to explain using the standard fireball model described above. A break in the x-ray light curve above $\sim$ 0.05 day with an unusual slope after the break which is not accompanied by a simultaneous break in the optical and the large extinction inferred from the x-ray afterglow which is inconsistent with the detection of the optical afterglow makes this afterglow intriguing. We have modeled the observed multi-band evolution of the afterglow of GRB 050401 as one originating in a Two Component Jet, interpreting the break in the x-ray light curve as being due to lateral expansion of a narrow collimated outflow which dominates the x-ray emission. The majority of optical emission is attributed to a wider jet component. Our model reproduces all the observed features of multi-band afterglow of GRB 050401. GRB 030329 is a previous example where the existence of a two-component jet was inferred.

We have followed up the radio afterglow of GRB 030329 using the Giant Metrewave Radio Telescope (GMRT) for more than $\sim$ 1400 days. The afterglow of this GRB has been observed the longest, and also at the lowest frequency, among all afterglows so far. Our observations provide the deepest probe into the non-relativistic evolution of a GRB fireball. Using the observations of this afterglow from Westerbork Synthesis Radio Telescope (WSRT) and Very Large Array (VLA) we have modeled the evolution of the afterglow and conclude that the fireball evolved from the relativistic to the non-relativistic regime at $\sim$ 60 days. The energy content of the fireball estimated independently from the non-relativistic regime indicates that the energy inferred from the relativistic regime was an under-estimate. This could be due to uncertainties involved in the assumed degree of collimation in the relativistic phase or a residual anisotropy in emission during the non-relativistic phase.

A very interesting and unique case of afterglow evolution is provided by the GRB050319 afterglow. Optical light curves of the afterglow show an unusual transition from steep to flat decay with a break at ~ 0.02 day after the burst onset. This break is absent in the x-ray light curve. We present a model for the multiband afterglow of GRB050319 where we show that the break seen in the optical light curve at ~ 0.02 day is possibly due to transition of the circum-burst medium from wind to homogeneous interstellar medium. To our knowledge, this is the first ever detection of such a transition. This can also serve as a confirmation of massive star collapse scenario for GRB progenitors, independent of Supernova signatures.

The organisation of the thesis is as follows. Chapter 1 provides an introduction to the subject of Gamma Ray Bursts and their Afterglows. In Chapter 2 we describe in detail the computer codes we have built to semi-numerically model the multi-band afterglow light curves. In Chapter 3 we describe our observations of the afterglows and the telescopes and the detector systems used. The method of data analysis is elaborated in this chapter. During the course of this work, we have tried to detect the afterglows of various GRBs but not every attempt met with a success. A complete list of GRBs for which we attempted to detect the afterglows is given in this chapter with the detailed log of observations as well as the upper limits obtained. Apart from this, the observations of the afterglows which were detected and followed up are listed in the corresponding chapters. The radio afterglow of GRB 030329 and our understanding of the non-relativistic phase of GRB fireball based on it is discussed in Chapter 4. Chapter 5 discusses the interesting case of GRB

050401 whose faint afterglow was detected in optical. Observations and modeling of GRB 050319 afterglow as being due to wind to ISM transition of the circum-burst medium is discussed in Chapter 6. We present our conclusions and lessons learnt about the collimation in GRBs from the above mentioned studies, in Chapter 7.

Contents