Prompt Emission of Gamma Ray Bursts

A Summary of scientific work constituting the thesis written by Rupal Basak

Gamma-ray bursts (GRBs) are the most violent astrophysical explosions produced either during the collapse of massive *Wolf-Rayet* stars ('long GRBs') or via merging of binary compact objects ('short GRBs') to form *stellar mass black holes*. During this process a highly relativistic bipolar jet is launched. The explosion releases an enormous energy comparable to the total energy produced by our entire Galaxy over a few years. Moreover, most of this energy is produced within a few seconds to a few minutes, known as the prompt emission phase. The surrounding medium, heated by the jet then glows as burning amber for days to months (the afterglow). As the prompt emission occurs close to the burst, it carries the most valuable information on the geometry and composition of the ejecta and the nature of the central engine. In addition, the prompt emission is so bright that a GRB is detectable up to a very high redshift corresponding to an epoch when the universe just started to form the first structures. Hence, GRBs are considered to be the most important tracers to study the universe at high redshift. My PhD thesis involves two very important aspects, namely, a detailed study of the timing and spectral properties of the prompt emission and using GRBs to study the Cosmology at high redshift. For our purpose, we primarily use data from *Swift*/Burst Alert Telescope (BAT), *Swift*/X-ray Telescope (XRT), *Fermi*/Gamma-ray Burst Monitor (GBM) and *Fermi*/Large Area Telescope (LAT). In the following we summarize the main findings of my thesis.

■ Pulse-wise emission during prompt emission phase:

The prompt emission spectrum of a GRB can be roughly described by a model having two smoothly joined powerlaws (Band et al. 1993). The lighcurve, on the other hand, generally shows multiple pulses. We have found that the spectrum evolves within the individual pulses such that a pulse can be considered as an independent entity, and the spectral evolution can be parametrized within a pulse. In Basak & Rao (2012b), we use this fact to describe the individual GRB pulses simultaneously in the time and energy domain. We generate the individual pulses of GRB 090618, and after adding the pulses we successfully retrieve the lightcurve, spectrum and pulse properties, like width, spectral delay of the prompt emission phase. Hence, study of the prompt emission boils down to the study of the individual pulses.

■ A new GRB correlation within the pulses:

One of the most important discovery in modern cosmology is the finding of accelerated expansion of the universe using Type Ia supernovae (SN Ia) as standard candles (Nobel Prize in Physics, 2011). However, due to the absorption of optical light SN Ia cannot be seen beyond a redshift of ~ 1.5. GRBs, on the other hand, being very bright in gamma rays are detected out to the furthest redshifts ($\sim 8-9$) among all astrophysical objects. Hence, GRBs can be used to measure the cosmological expansion from distant past. To this end, we study GRB correlation between a measurable quantity e.g., the peak of the spectrum and a physical quantity e.g., the energy. Then the luminosity distance can be measured using the correlation. In Basak & Rao (2012a), we find this correlation within the GRB pulses. It has a Pearson correlation coefficient of 0.96, highest among all such correlations. In Basak & Rao (2013c), we study the redshift evolution of the pulse-wise correlation for a larger sample and find that the correlation remains stable. We suggest that the pulse-wise GRB correlation should be used to explore GRBs for cosmological purpose.

■ Emission mechanism – evidence of thermal component:

The Band function, which is used to describe the GRB spectrum, is a phenomenological model. It is widely believed that the GRB emission occurs via synchrotron mechanism. But, then the photon index must be lower than -1.5, known as the 'synchrotron line of death'. In Basak & Rao (2014), we have shown that this limit is frequently violated. On the other hand, there is now growing evidence for an underlying thermal emission in time-resolved spectra of GRBs (e.g., Ryde & Pe'er 2009). The major challenge in the time-resolved spectroscopy is the poor statistics of fine temporal bins, while a broader bin may not capture the spectral evolution. In recent works (Basak & Rao 2013b; Rao et al. 2014), we have compared

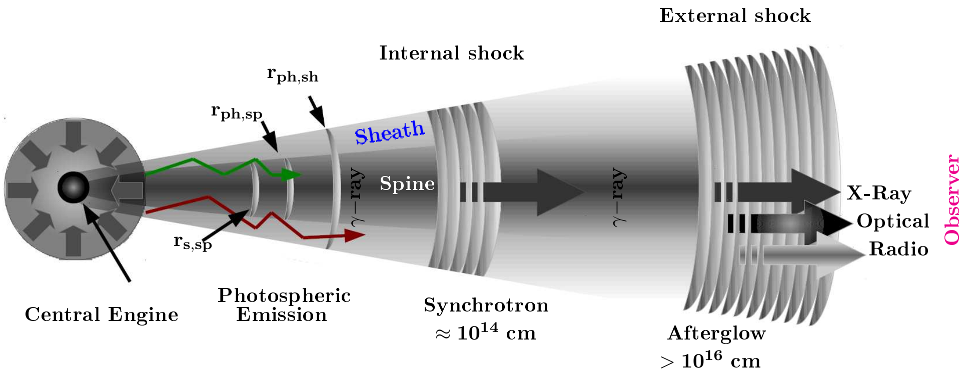

Figure 1: A schematic view of the spine-sheath jet in GRBs. Two blackbodies arise from the photospheres of the two components (marked as $r_{\rm ph,sp}$ and $r_{\rm pn,sh}$). Photons crossing the boundary layer (zigzag path) can effectively form a powerlaw with a cutoff. Additional non-thermal (synchrotron) emission can occur at larger radius via 'internal shocks'. Finally, afterglow emission occurs due to 'external shocks at much higher latitude. Figure from Basak & Rao (2015a).

various spectral models by parameterizing the corresponding spectral evolution. This new method, named "parametrized joint fit", considerably reduces the number of free parameters of time-resolved spectroscopy, making the analysis more tractable. Using this technique for the individual pulses of bright GRBs, we surprisingly find that a model consisting of two blackbodies and a power-law (2BBPL) is the preferred spectral model. Our finding is recently supported by an independent group (Iyyani et al. 2015).

■ **Connection with high energy (GeV) emission:**

In addition to kelo – mega electronvolt (keV–MeV) emission some GRBs emit photons at gigaelectronvolt (GeV) energies. This emission is delayed compared to the prompt keV–MeV emission by a few seconds. It is well known that the Band function cannot capture the wider spectrum from keV to GeV. Also, the GeV flux is found to be uncorrelated with the prompt keV–MeV flux. It is interesting to fit the keV–MeV data with the 2BBPL model and then compare with the flux at GeV energies. Analyzing a set GRBs detected by the LAT, we find significant correlation of the GeV photon fluence with that of the non-thermal (powerlaw) component of the 2BBPL model fitted to the keV–MeV data (Basak & Rao 2013a). Also, the powerlaw flux of GRBs with high GeV emission tend to have a delayed onset, and this component lingers at the final phase of the prompt emission. Remembering that the GeV emission is delayed and long lasting than the keV–MeV emission, we strongly suggest that the powerlaw component of the prompt emission shares a common origin with the GeV emission. In addition, this result validates the 2BBPL model.

■ **A physical picture – Spine-sheath jet structure:**

Recently, we have started looking for spectral data in detectors having high spectral resolution. We have found such data for GRB 090618 (Basak & Rao 2015a) and GRB 130925A (Basak & Rao 2015b). For the former, we have used the XRT data contemporaneous with the BAT data, while for the later we have obtained high resolution data from *NuSTAR* and *Chandra*. In both cases, we have clearly shown that the 2BBPL model captures the spectrum and shows smooth evolution in the falling part of the pulse.

We suggest a spine-sheath jet structure to explain our observations (e.g., Ramirez-Ruiz et al. 2002; Zhang et al. 2004; see Fig 1). Such a structure is theoretically expected as the GRB jet pierces through the envelop of the progenitor. The two blackbodies are produced at the two photospheres, while the photons crossing the boundary layer of the spine and sheath are inverse-Compotonized and form a cutoff powerlaw (see Fig 1). In addition, internal shocks produced at larger radius will also contribute to the non-thermal emission. We will develop a spine-sheath jet model and use it to fit the data. Our analysis will provide direct estimates on the physical parameters of the jet.

■ **Scientific impact:**

The thesis involves a comprehensive study of GRB particularly the radiation mechanism and application to high redshift universe. The research is fundamental for GRB science, an ever growing research field which continues to bring important results since its discovery about fifty years ago, and still eludes us with many puzzling phenomena. Despite an enormous advancement in dedicated GRB satellites, our understanding about the nature of the central engine, the jet launching mechanism etc. remains unclear. In the absence of a detection of the gravitational wave, it is the electromagnetic radiation, most importantly that of the prompt emission phase has the potential to probe the physical mechanism of a GRB. Some of the most striking observations made in the past couple of years have challenged our basic understanding of the radiation mechanism. These include e.g., finding thermal emission spanning the early prompt emission till the late afterglow, presence of flares in the X-ray afterglow, both of which require a late time activity of the central engine and a high efficiency of gamma-ray production which the standard GRB models do not provide. The thesis aims to understand the radiation mechanism by combining observational data and interpretation, particularly in the framework of structure in GRB jets. As jets are ubiquitous in various astrophysical objects, and particularly the structured jet is also suggested for the powerful Blazars, our study will shed light on the mechanism of jet launching in general. In addition, based on our improved understanding and larger statistics of GRB correlations we shall be able to probe the expansion history of the universe out to high redshifts. The astrophysical community is eagerly waiting to witness the first detection of gravitational wave with advanced LIGO and VIRGO. As GRBs are considered as the prime targets of these experiments, the results obtained in this study will be invaluable providing an important and complementary view of the GRB phenomenon in the electromagnetic sector.

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