PROJECT REPORT

ON

SHORT DURATION GAMMA-RAY BURSTS AND ITS IMPLICATIONS

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AIM

The aim of this study is to understand the mechanism of prompt emission and afterglow properties of Short Gamma-ray bursts and their implications in astrophysical context.

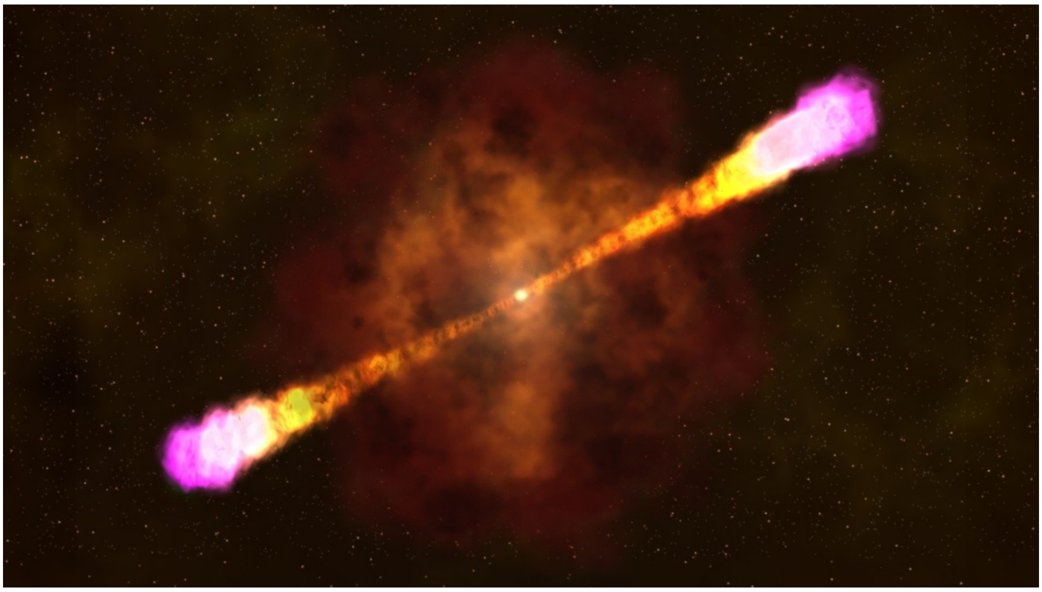
ACKNOWLEDGEMENTS

Firstly I would like to acknowledge the support of my project supervisor **Dr. Shashi Bhushan Pandey (ARIES, NAINITAL)**, who gave me this opportunity to work in this field. He being a veteran in Gamma-ray/Optical astronomy, with his immense knowledge about the field guided me with perfection. I would also like to give certain credit to my college **IISER-Pune** for building my basics in physics and motivating me to take the field of Astronomy and Astrophysics as my career.

CONTENTS

ABSTRACT

This report provides an introductory study towards one of the most energetic explosions in the universe, known as Gamma-ray bursts. It introduces the physical properties of these relativistic jets such as progenitor models and afterglow theory of both Long gamma-ray bursts and Short gamma-ray bursts. Later this report talks about Short duration Gamma-ray bursts in much detail and its non association with Supernovae. Also we differentiate Long GRBs from Short GRBs on the basis of comparative studies of their prompt emission and afterglow phases with data collected by various ground bases telescopes and space based telescopes (SWIFT , FERMI, HST etc). It touches upon the compact merger theory of origins of these Short GRBs.



1. INTRODUCTION

Gamma-ray bursts are brief sudden intense flashes of gamma-ray radiation that were discovered in the late sixties (1967) by the VELA satellites (Klebesadel et al., 1973), which were operated by the United States to keep a check on nuclear weapon test a consequence of a peace treaty. While not going on the history too much, these flashes were irregular pulses with non thermal radiation. The energy scale scale of these bursts was detected to be of the order of $\sim 10^{52}$ ergs

(Kulkarni et al., 1999a) which is almost the energy released by the sun in its entire lifetime.

Figure Artist's depiction of Long GRB : source Wikipedia

It was a watershed time for the theoreticians at that time. Various models were being proposed to predict these bizarre explosions in the universe which according to a study were seen a few times a day at random locations in the sky. At first basically the data collected by the Burst and Transient Source Experiment (BATSE) on-board the Compton Gamma-Ray Observatory suggested that GRBs can be generally divided into two groups based on their duration and spectral hardness.

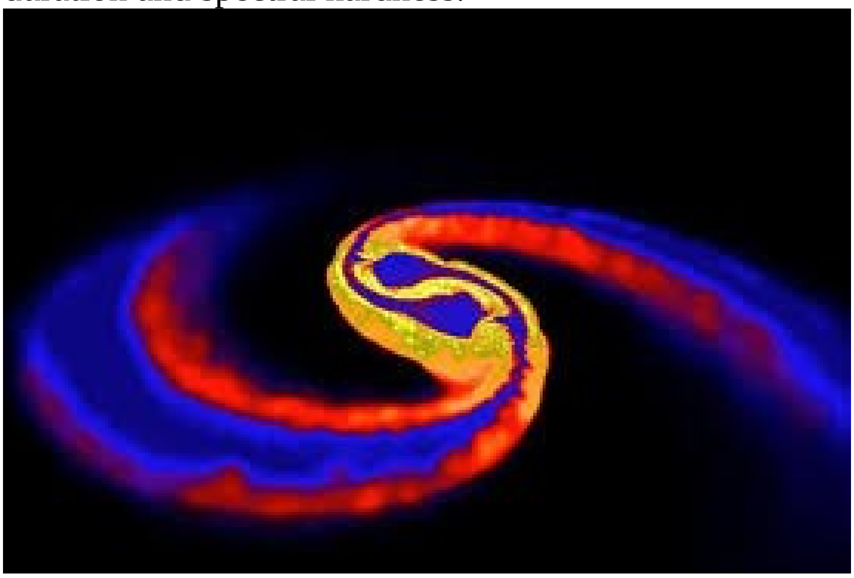


Figure Simulation depicting NS-NS merger leading to SGRBs: source Wikipedia

With the advent of CGRO distances of these bursts were determined. It also concluded that these bursts are isotropically distributed in the sky. This led to a realisation that these bursts are not only some process in the local galactic environment but millions of light years away as well. Beppo-SAX satellite allowed researchers to search for the radio and optical counterparts of the bursts. Their redshift and flux data were collected which gives the estimation of energy of these bursts.

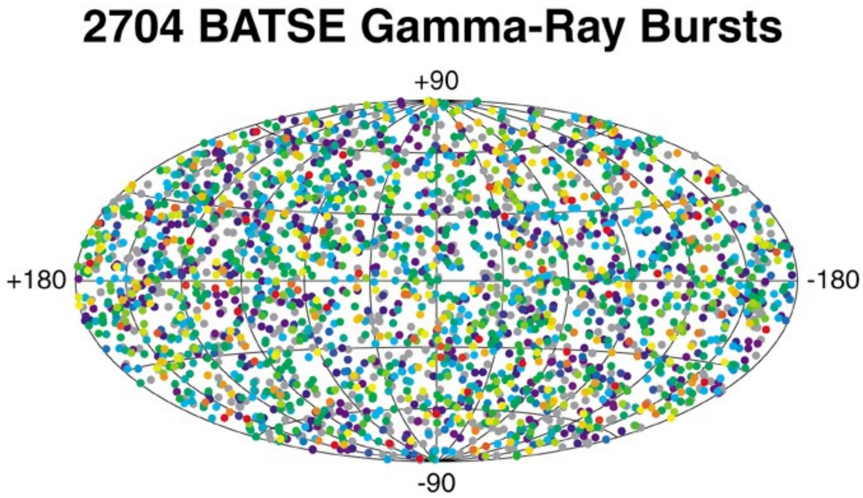


Figure isotrophic distribution of GRBs :source wikipedia

Slowly fading bursts then emitted in longer wavelengths. Later these bursts were tracked in X-ray and optical regions of the spectrum which showed that there is steepness in X-ray afterglow light curve which led to the conclusion that these bursts are collimated as narrow jets. As the ejecta is decelerated and the strength of the relativistic beaming diminishes, the edge of the jet becomes visible to the observer. The finite angular extent of the ejecta leads to an achromatic faster decay of optical & X-ray light curves. This Achromatic Transition from a slower to a faster decay of light curves is called ‘”jet-break".

1.1 Long gamma-ray burst

The long gamma ray-bursts were shown to be bursts with duration of more than 2 secs by the bimodal distribution of the study conducted. The peak of this distribution of Long gamma-ray bursts was 30s. A long gamma- ray bursts can last upto hundreds of seconds. These bursts usually have higher redshift than Short gamma-ray bursts. The median redshift of the Long gamma-ray bursts was observed to be $<z>=2$ (a study by Edo berger).These bursts have a high correlation with supernova explosions mainly supernova type Ic. There are also some other properties and further differences with short gamma ray bursts which will be discussed in detail in later sections.

1.2 Short gamma-ray bursts

Short gamma-ray bursts were classified as the bursts with duration less than 2s in Bimodal distribution. These bursts have a duration peak at 0.3s. There were several anomalies with bursts of more than 2s. Short gamma-ray bursts in comparison to Long gamma-ray bursts occur a lower redshift with median $<z>=0.5$ (Edo Berger study). They had properties different than that of Long gamma-ray bursts and supernovae. Due to these differences in properties it was inferred that both these type of bursts have different progenitors. So, different models regarding them were proposed. One such widely accepted model is compact merger model. Short GRBs were proposed to be originated from compact binary mergers such as a Neutron star-Neutron star or a Neutron star-Black hole binary. With technological advancements there were studies conducted on these bursts properties like Peak energy, Spectral shape, variability time scale etc.

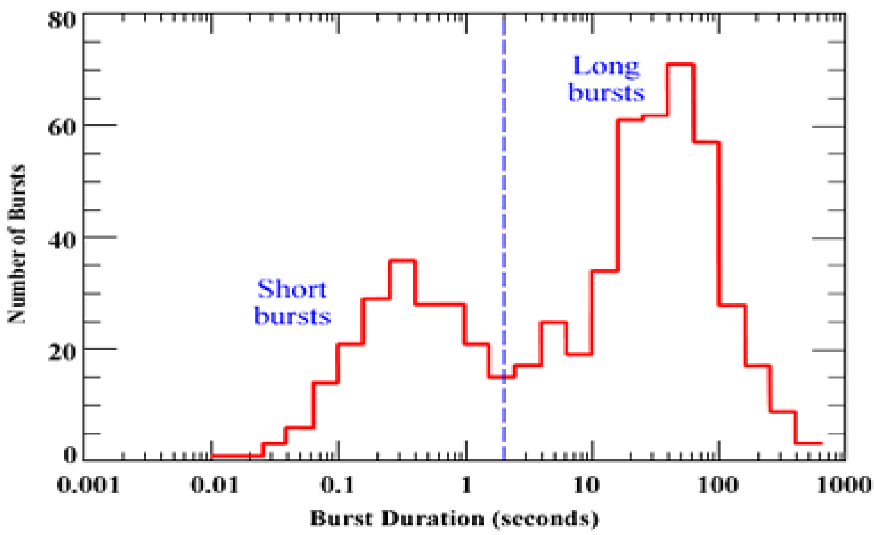


Figure Bimodal distribution on gamma ray bursts on the basis of their duration which shows a peak for SGRBs at 0.3s and 30s for LGRBs. Also the plot sjows the divide between the two GRBs at 2s.: source wikipedia

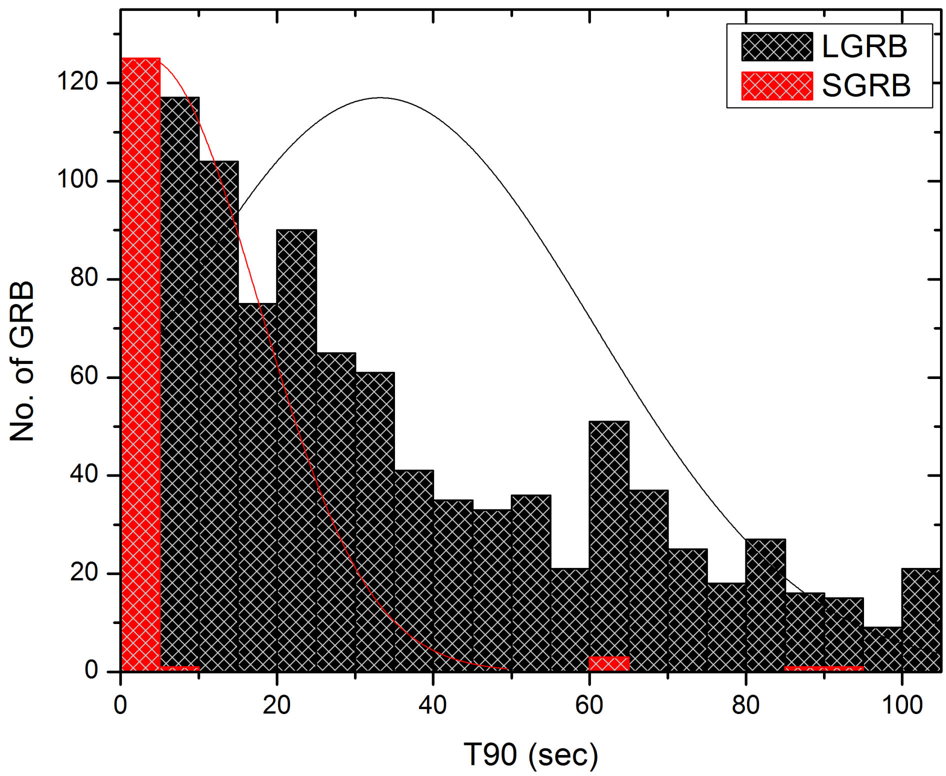


Figure T90 Distribution comparison of 1011 LGRBs vs 131 SGRBs data by leading satellite sources plotted under this project ; source GRBOX. It shows that the average T90 distribution of LGRBs is greater than SGRBs.

2. RADIATIVE PROCESSES

Gamma-ray bursts have numerous properties in itself. One such property of a typical Gamma-ray burst is the radiative process.

2.1 SYNCHROTON RADIATION

Synchroton radiation is the electromagnetic radiation emitted by an electron moving at relativistic speed in given magnetic field. This radiation will occur when relativistically charged particles have a component of their velocity perpendicular to a local magnetic field.

PROPERTIES OF SYNCHROTON RADIATIONS:

1. The spectrum of the radiation spans from X-ray to microwaves.
2. Highly collimated photon released

3. High intensity photons are emitted in the process leading to high flux.
4. Highly stable and have a far reach before disintegration.

During the process apart from the electron frequency there are 2 more frequencies associated i.e. self absorption frequency and cooling frequency.

2.2 INVERSE-COMPTON RADIATION

The simplest interaction between photons and free electrons is scattering. When the energy of the incoming photons (as seen in the comoving frame of the electron) is small with respect to the electron rest mass–energy, the process is called Inverse-Compton scattering or Thomson scattering.

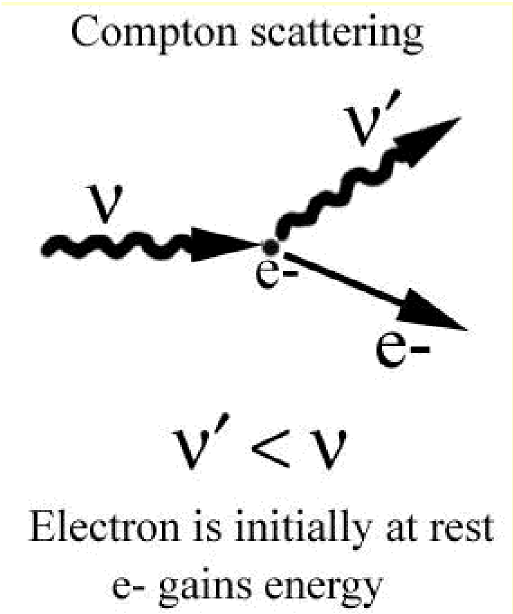


Figure Compton scattering ; source Wikipedia

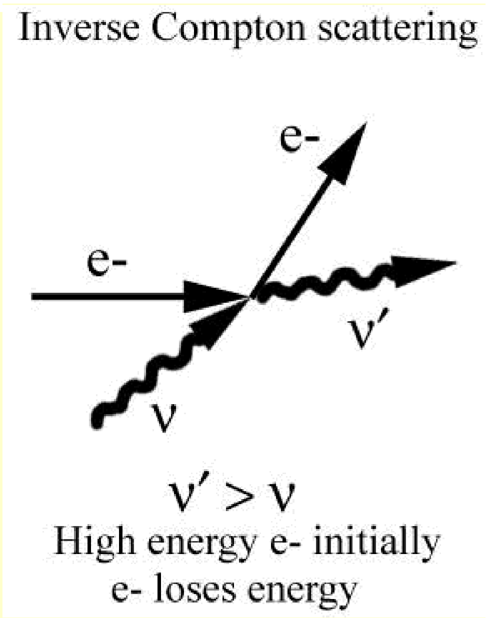


Figure Inverse compton sacttering ; source wikipedia

KLIEN-NISHINA REGIME

During Inverse Compton scattering of soft photons injected from external sources into the jet because of the large bulk Lorentz factor of the jet, the energy of soft photons is Doppler shifted in the comoving frame of the jet, and the scattering is likely to occur in the Klein-Nishina regime. So we can say that as the energy of the incoming photons increases and becomes comparable or greater than $m_e c^2$, a quantum treatment is necessary (Klein–Nishina regime).

3. SHORT GAMMA-RAY BURSTS

3.1 INTODUCTION

Short Gamma-ray bursts (SGRBs) are the explosions with duration less than 2s (Li, L.-X., Paczynski, B.,). These were bursts were observed to be of comparatively lower redshifts than Long gamma-ray bursts in general. Due to lack of associations of these bursts with the supernova collapse, studies were conducted to probe their origins and a new model called compact binary merger model was proposed with higher acceptance as compared to several other models. This model says that the Short gamma-ray bursts are generated when two compact celestial bodies such as a Neutron star- Neutron star or a Neutron star- Black hole merges to release intense flashes of energetic gamma rays.

Details of these models will be discussed in further sections. However there is no observed proof of this model, still being the most consistent with the data recorded, it is the closest model we know. The energy released during a typical Short gamma-ray burst is $\geq 10^{50}$ ergs. The merger is accompanied by a relativistic outflow of ejecta called as baryonic matter in two opposite collimated jets. The luminosity of a Short gamma-ray bursts is less than that of a typical Long gamma-ray burst because of the less dense interstellar medium of the short gamma-ray bursts environment. Compared to Long gamma-ray bursts, the study of Short gamma-ray bursts have been challenging till date. It has been a tougher task to deal with the merger models than the supernova collapse.

Studies have been conducted to track the prompt emissions and record the afterglows of these bursts to find out the distance and properties of the galaxies in which they occur. One of the most interesting aspect regarding these bursts is the model suggesting electromagnetic counterpart of the gravitational waves produced during the Neutron star- Neutron star or a Neutron star- Black hole merger.

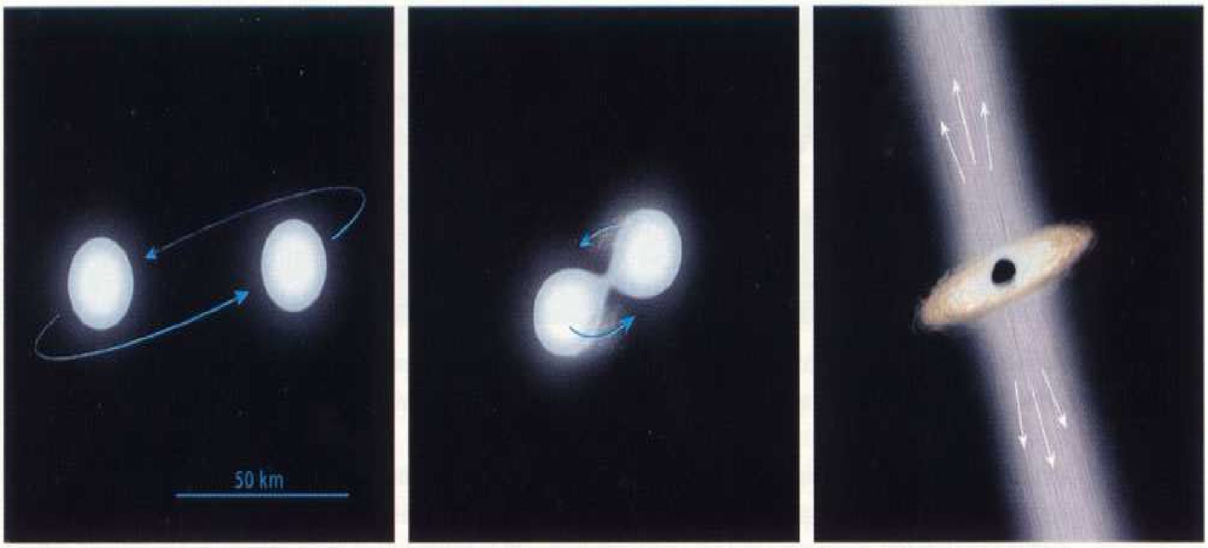


Figure Artistic depiction of NS-NS merger model: source Narayan, Paczynski, & Piran 1992

4. SGRB BURST PROPERTIES

4.1 PROMPT EMISSION

The phenomenon of prompt emission basically revolved around the central engine which is the black hole. The black hole with its intense gravitational pull distorts the Neutron star and forms an accreting disk of the mass of the rotating neutron star. This mass is then ejected as relativistic jets along the axis of rotation of the black hole. During this jets collimation when the Slower moving blob of baryonic matter collides with the fast moving blob, corresponding energy(gamma-ray) of radiations are emitted.

The prompt emission of a typical burst releases intense energy. One such energy parameter associated with it known as isotropic equivalent gamma-ray energy is studied to relate the energy spectrum of these bursts. Also E_P known as peak energy of the burst spectrum is plotted with $E_{iso-\gamma}$ to observe some differences. The spectra of a typical short gamma ray bursts is hard and the spectra of a long gamma-ray burst is comparatively soft. In astrophysical contexts, a hard spectrum is one relatively rich in higher-energy photons, so it is a comparative term. It may be associated with an index of a power-law spectral shape, or derived more crudely from the ratio of photons detected in various energy ranges.

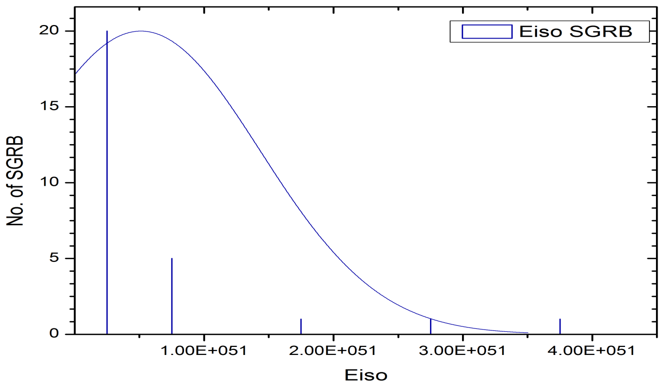


Figure Isotropic energy count plotted under this project shows the range of energies in which the SGRBs exists. Mostlt the range is from 10^{48}-10^{52} ergs.; data source Berger 2014

So we can say that the spectra of Short gamma-ray bursts has peaks mainly towards higher energies as compared to those found in the spectra of long gamma-ray bursts. In terms of data of the prompt emission spectra the short gamma-ray bursts have a shallower low energy spectral slope α=-0.4 in comparison to long gamma-ray bursts with slope α=-0.9. Also short gamma-ray bursts have higher spectral peak E_p=400 KeV whereas long gamma-ray bursts have lower spectral peak, E_p=200 KeV. (Paciesas et al. 2003).

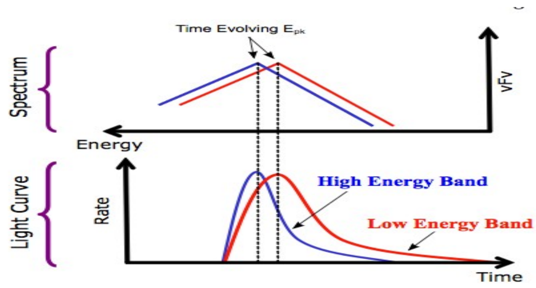
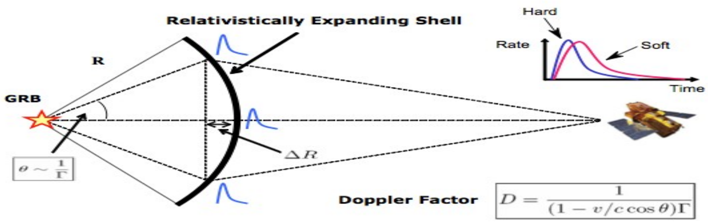


Figure 5. The time evolution of the $E_{\rm pk}$ across energy bands may cause the observed spectral lags in GRBs.



There is also spectral lag observed in plots short gamma-ray bursts and long gamma-ray bursts as shown in the figure below. The key significance of these spectral lags and harder spectra of short gamma-ray bursts is that it gives new dimension of classification of gamma-ray bursts on basis of their prompt emission properties.

4.2 <u>EXTENDED EMISSION</u>

The phenomenon of a burst has a prompt emission phase with an initial spike of gamma-rays called the prompt spike. After this there is emission of softer gamma-rays with peak less than the prompt spike. This phase of emission after the initial prompt spike is called extended emission. Extended emission on contrary to prompt emission lasts much longer, about 10-100s.

Not all short gamma-ray bursts show extended emission. The extended emission led to the discovery of the afterglows later on. The period of extended emission is taken to be the onset of afterglow (x-ray, optical, radio). The interesting part is that the extended emission has higher fluence than the prompt emission by a factor of 2 - 40. For eg GRB 050709 (Villasenor et al. 2005) and GRB 050724 (Barthelmy et al. 2005) showed the similar nature of extended emission.

Various theories have been proposed to explain this phenomenon of extended emission. One such model by Bucciantini et al. (2012) uses the magnetar model in a different way, in which the delay in the onset of extended emission is due to a breakout of the relativistic outflow through a baryon-loaded wind from the proto-magnetar. Metzger et al. (2010) predicts instead that the gap between the prompt spike and extended emission may be due to heating from *r*-process nucleosynthesis, which momentarily halts fall-back accretion onto the central object. In this scenario, events lacking extended emission are due to a timescale for the *r*-process heating of ∼ > 1 s, which leads to a complete cut-off in fallback accretion, while those with extended emission resume fall-back accretion after a delay.

4.3 X-RAY FLARES

X-ray flares are the radiation emitted by the bursts after the phase of gamma-ray radiation has faded. X-ray flares can be detected in bursts with or without extended emissions as in some cases the offset of gamma-ray prompt region marks the onset of X-ray region (X-ray flares). In certain plots it was observed that there was an increase in the flux with respect to time at the instant of x-ray flares which eventually falls.

These x-ray flares have been understood broadly in terms of late time central engine activity. One or more X-ray ares can be found in nearly half of GRB X-ray afterglows. These ares share many properties with prompt emission pulses (Ioka et al., 2005; Burrows et al., 2005b; Fan andWei, 2005; Zhang et al., 2006; Liang et al., 2006a; Lazzati and Perna, 2007; Chincarini et al., 2007; Maxham and Zhang, 2009; Margutti et al., 2010).

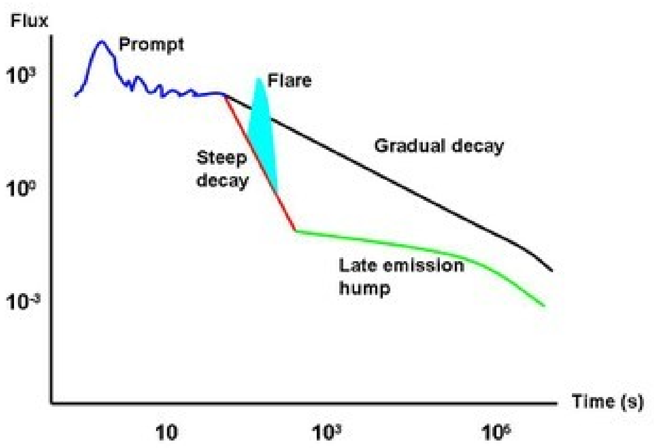


Figure mechanism of a bursts indicating x-ray flares :source wikipedia

Several X-ray light curves plotted under this project showing x-ray flares at early epochs at 0.3-10 KeV using Swift data.

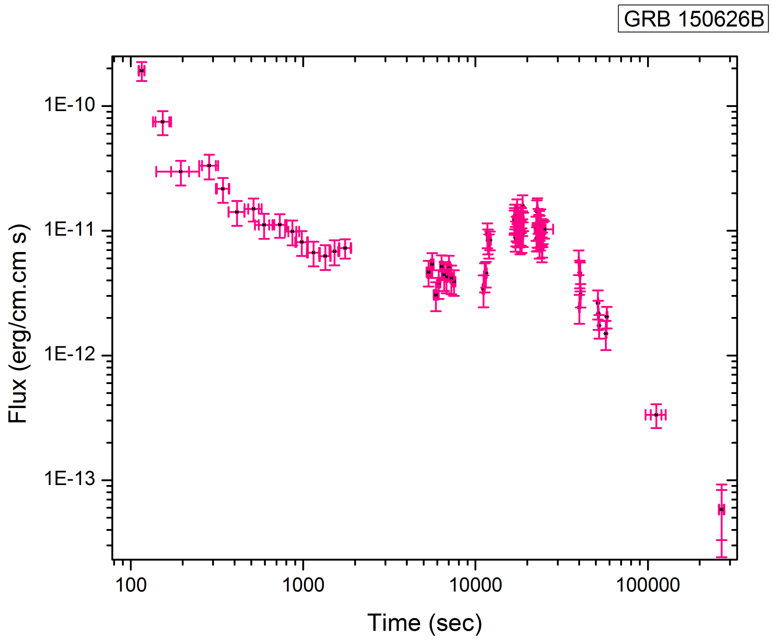


Figure GRB 150626B light curve showing x-ray flares in the early afterglow phases as a late type central engine : data source www.swift.ac.uk

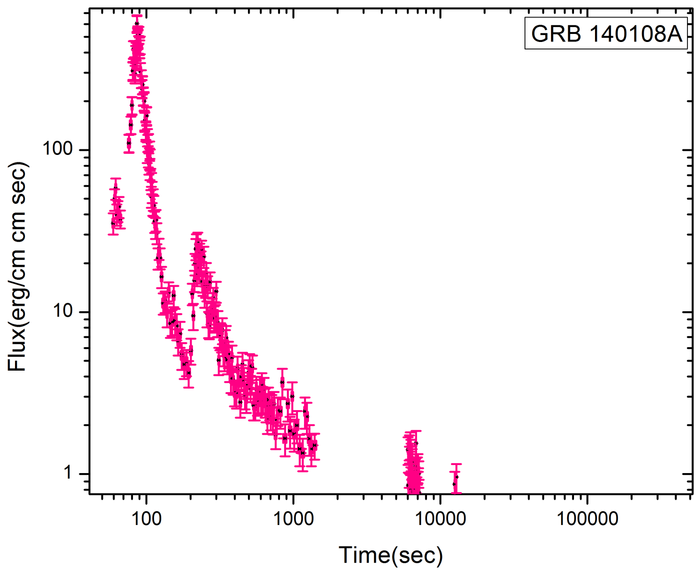


Figure 140108A light curve showing x-ray flares flares in the early afterglow phases as a late type central engine: data source www.swift.ac.uk

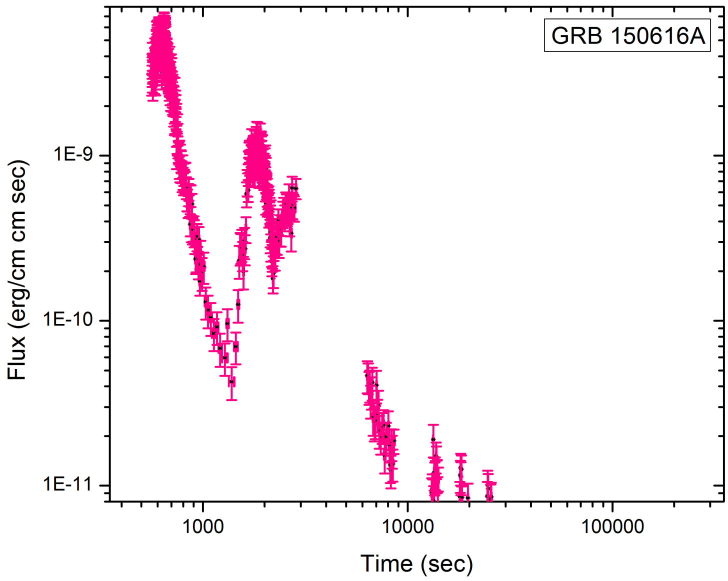


Figure 150616A light curve showing x-ray flares flares in the early afterglow phases as a late type central engine: data source www.swift.ac.uk

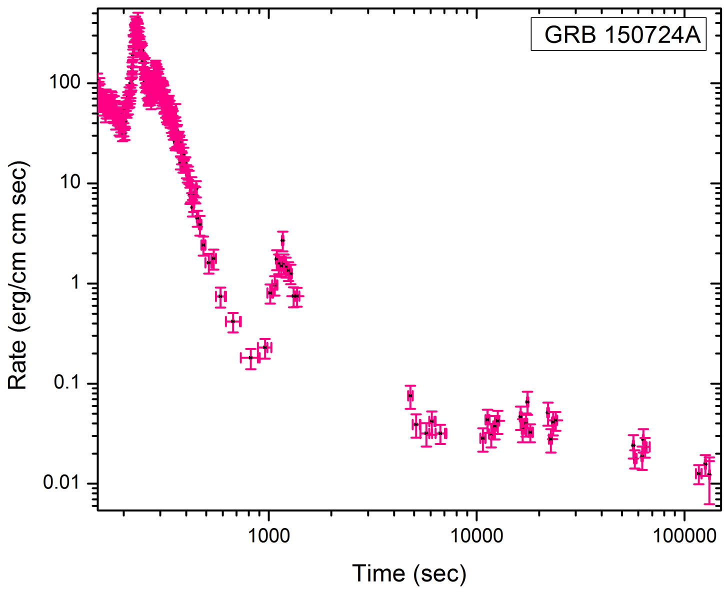


Figure 150724A light curve showing x-ray flares flares in the early afterglow phases as a late type central engine: data source www.swift.ac.uk

Various models have been proposed to predict the mechanism of these X-ray flares. There are some accretion based model such the one by Perna, Armitage & Zhang (2006) which says that these flares are produced by large amplitude variations in the central engine of the bursts when gravitational instabilities causes the fragmentation of the outer accretion disk. One more model by

Giannios (2006) propose that the X-ray flares are produced when the strongly magnetised outflow decelerates while passing throw circumburst medium leading to delayed magnetic reconnection.

5. AFTERGLOW THEORY

After the initial burst, a slow fading radiation emission was recorded at higher wavelengths. The proposed reason of the observation was the collision of the gamma-ray bursts ejecta with the interstellar medium. Such a phenomenon was named afterglow. An afterglow can last from hours to days or even month

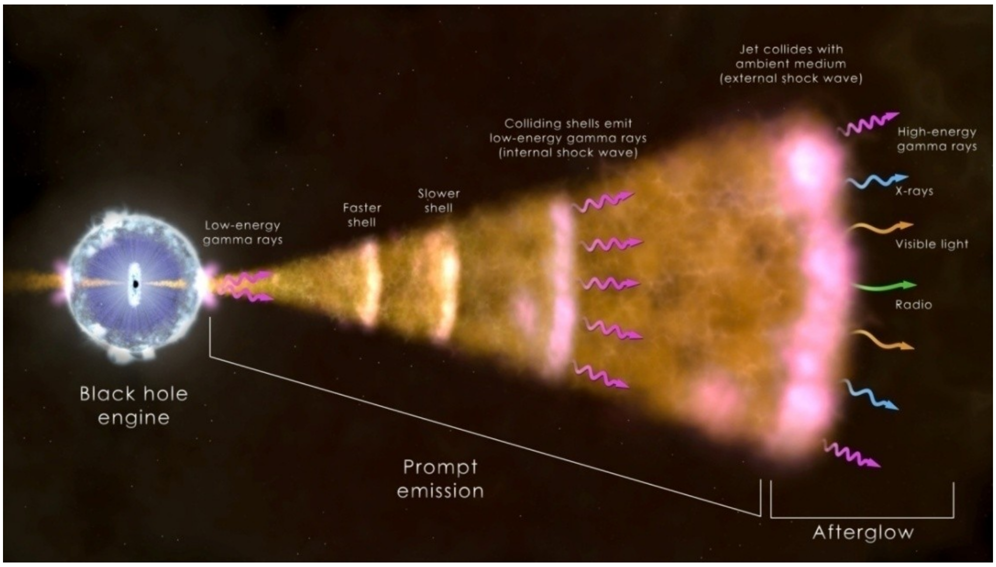


Figure afterglow mechanism : source Wikipedia

Earlier it was difficult to record an afterglow due to their faint luminosity and less advanced telescopes. But with the launch of BeppoSAX, Fermi, SWIFT, etc scientists were able to pinpoint the location of the afterglow. For example BeppoSAX recorded the afterglow of GRB970508 whose spectrum was redshifted to z=0.835.

The significance of recording this afterglow is to locate the galaxy scale environments of these bursts to be in order to distinguish them properly on the basis of their stellar mass, stellar population age, star forming rates etc.

5.1 RELATIVISTIC SHOCKS

This section basically deals with the relativistic blastwave and its interaction with circumburst medium (CMB). This relativistic shock theory was developed by Blandford and McKee (1976)for Active Galactic Nuclei (AGN) jets which turned out to be well suited for interpreting GRB afterglows in X-ray, optical and radio bands when they were discovered in 1997 (Costa et al., 1997; van Paradijs et al., 1997; Frail et al., 1997).

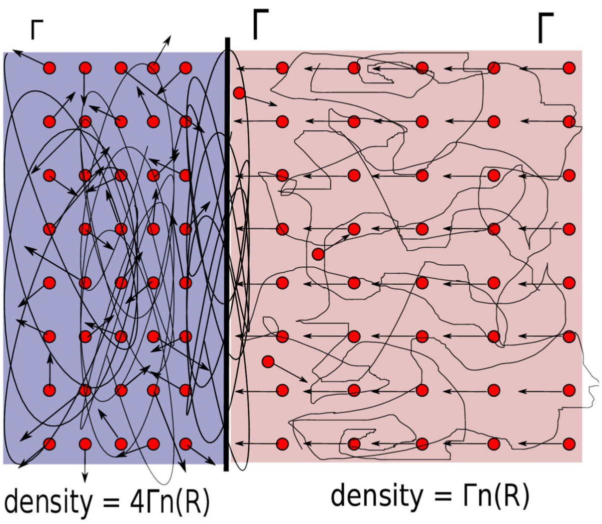


Figure sketch of highly relativistic shock as viewed from the mean : source Bin Zhang and Pawan Kumar 2014

This figure above explains the theory very well. Here in this figure lines represent magnetic fields, and arrows show particle velocity with respect to the shocked plasma. The cold upstream particles with Lorentz factor moves towards the shocked plasma and compresses it by a factor of 4 in the plasma frame and increases the magnetic field to accelerate the particles.

These are the basic requirements one needs to follow to theoretically calculate the afterglow radiation from the blastwave interaction with the interstellar medium.

5.2 SYNCHROTON SPECTRUM & LIGHT CURVE

The spectrum of a gamma-ray burst is a crucial element in understanding the nature of the event. Hence one important feature of the afterglow is its recorded synchrotron spectrum. There are three main frequencies associated with synchrotron spectrum i.e. self absorption frequency, cooling frequency and synchrotron frequency.

While the electron decelerates through the medium it starts cooling and a frequency along with synchrotron frequency called colling frequency is attached to the electron which is shown in the spectrum below.

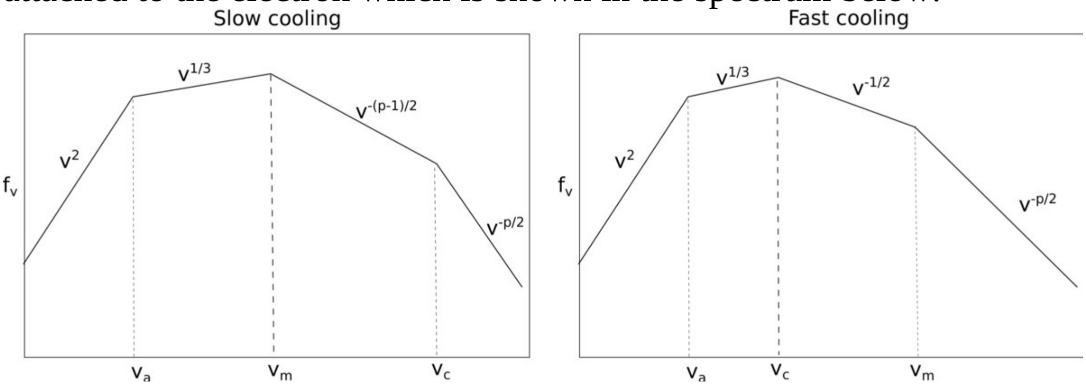


Figure Synchrotron afterglow spectrum for the case where $V_a < V_m < V_c$ is shown in the left and the case where $v_a<v_c<v_m$ is in the right : source (Sari et. Al 1998)

Various different kinds of light curves are obtained from the data where the flux of the burst is plotted with time. This light curve will show various properties of the bursts such as prompt emission, extended emission, x-ray flares, jet breaks, afterglow emissions (recorded at different wavelengths).

Unlike the extreme variation in the light curves, the spectra of gamma-ray bursts are fairly homogeneous.

Figure Radio, optical, and X-ray model light-curves for eight GRB afterglow; source (Panaitescu & Kumar2001)

Light curves of some GRBs plotted under this project to have a clear picture of the afterglow phases such as extended emission, x-ray flares, jet-breaks etc.

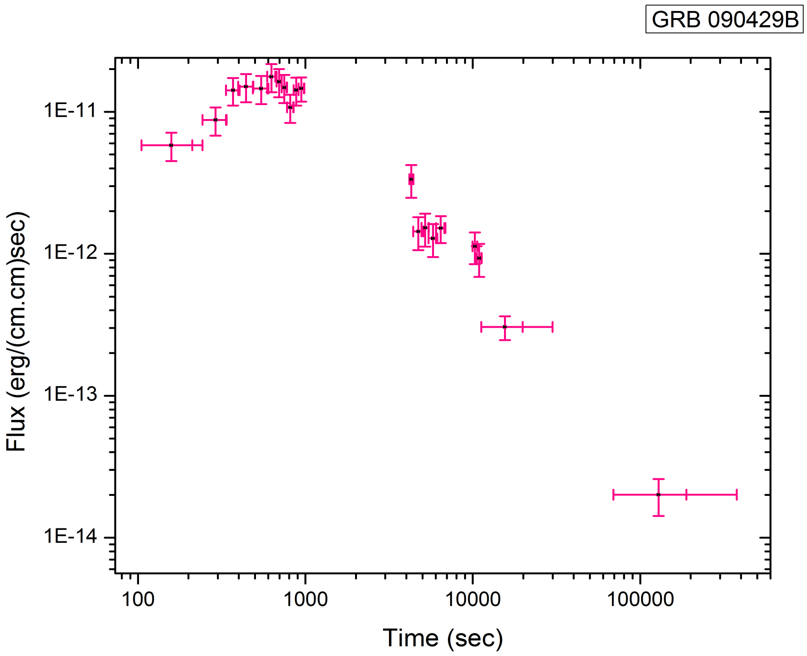


Figure GRB 090429B light curve: data source www.swift.ac.uk

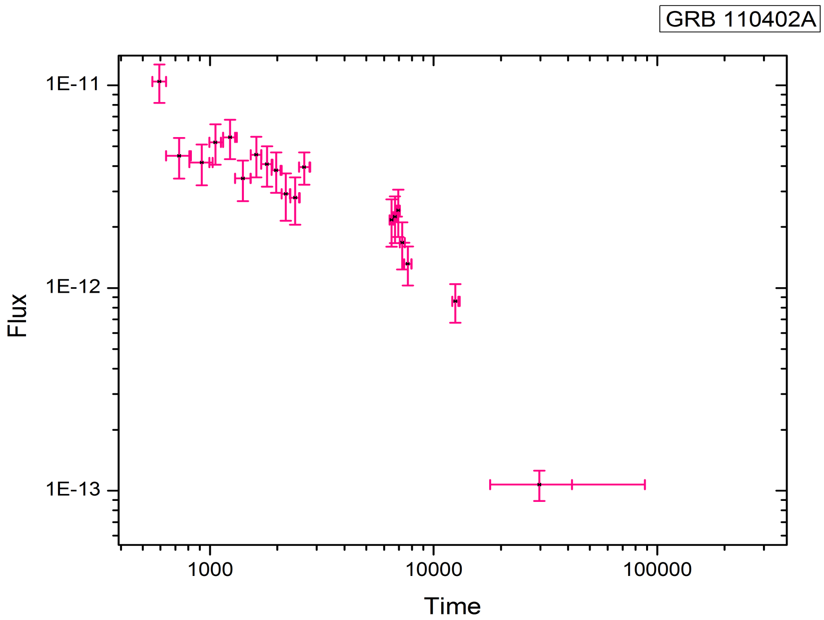


Figure GRB 110402A light curve: data source www.swift.ac.uk

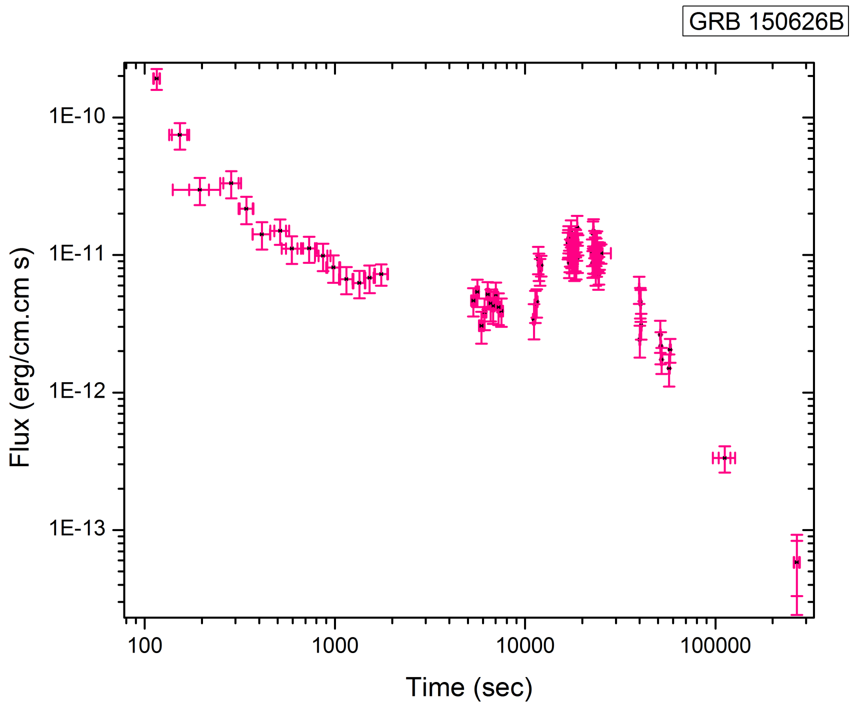


Figure GRB 150626B light curve: data source www.swift.ac.uk

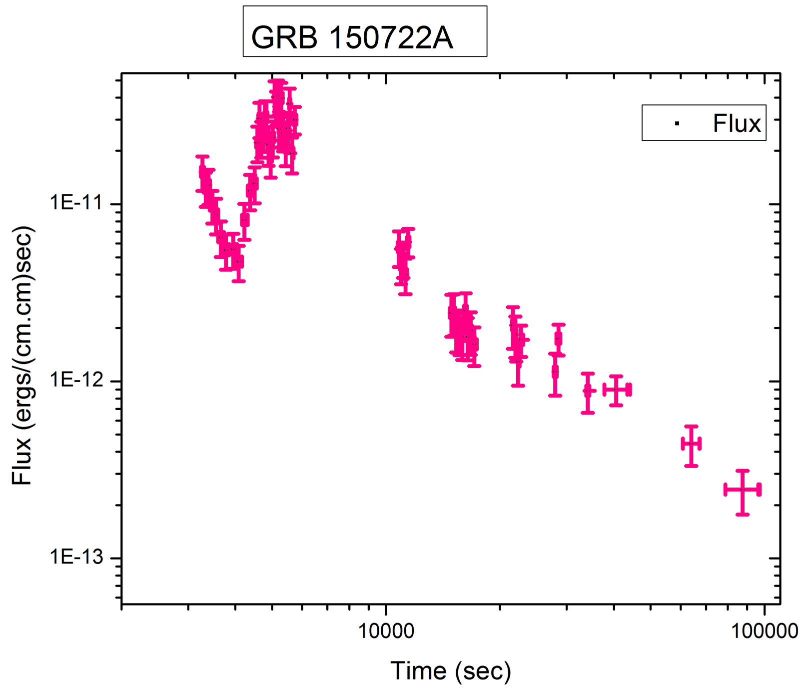


Figure GRB 150722A light curve: data source www.swift.ac.uk

5.3 JET BREAKS

Gamma-ray burst emissions are released in jets and not spherical shells (Sari, R.; Piran, T.; Halpern, J. P. 1999).The achromatic breaks seen in the light curve of the afterglows led to the discovery of jet breaks. The conclusion made out of this break in the light curve was that it the jets are collimated (Rhoads 1997).

Also there was the steepening of the light curve after the jet breaks. The reason for this was firstly the edge effects (Meszaros and Rees, 1999; Panaitescu and Meszaros, 1999; Rhoads, 1999; Sari et al., 1999).
Secondly, relativistic beaming effects subside, and once Earth observers see the entire jet, the widening of the relativistic beam is no longer compensated by the fact that a larger emitting region is seen. Many GRB afterglows do not display jet breaks, especially in the X-ray, but they are more common in the optical light curves (Wikipedia)

6. AFTERGLOW PROPERTIES OF SHORT GAMMA-RAY BURSTS

After the prompt emission phase comes the afterglow phase. The key mechanism for the afterglow is the ejecta mass of baryonic matter colliding with interstellar medium. An afterglow can lasts from days to months spanning the x-ray, optical, IR and radio wavelength range. On a comparison basis the afterglow of a typical short gamma-ray bursts is fainter in luminosity than a long gamma-ray bursts and the reason predicted is the less denser interstellar medium of the short gamma-ray burst environment.

When we study an afterglow, we need to take account of several parameters such as the energy scale in γ-rays (E_γ) and in the blastwave powering the afterglow(E_K), the geometry of the outflow (characterized by a jet half opening angle, (θ_j), and the density of the ambient medium (n).

The significance of studying the afterglow is to firstly locate the galaxy environments and on energy scale is to find the beaming corrected energy which requires the jet opening angle value so that we can understand certain properties of the central engine such as the event rates.

6.1 X-RAY AFTERGLOW EMISSION

X-ray afterglow is the emission region which largely dominates the afterglow phase. Sometimes the x-ray afterglow lasts for 1000s. As compared to X-ray afterglow, the optical and radio emission fades quickly.

To study the properties of X-ray afterglow we plot both long and short gamma-ray bursts in the isotropic-equivalent luminosity at a fiducial rest-frame time of 11 hr in a rest-frame band of 0.3 − 10 keV (L_X,11) and isotropic-equivalent γ-ray energy (Eγ,iso) phase space.

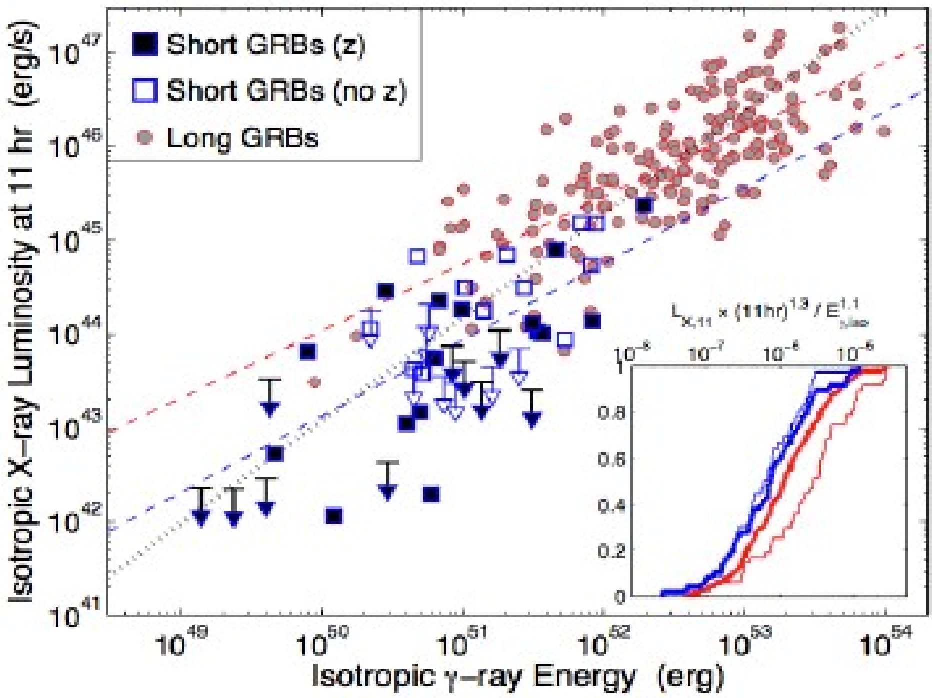


Figure x-ray afterglow correlation with $E_{iso\text{-}gamma}$: source Berger et al.

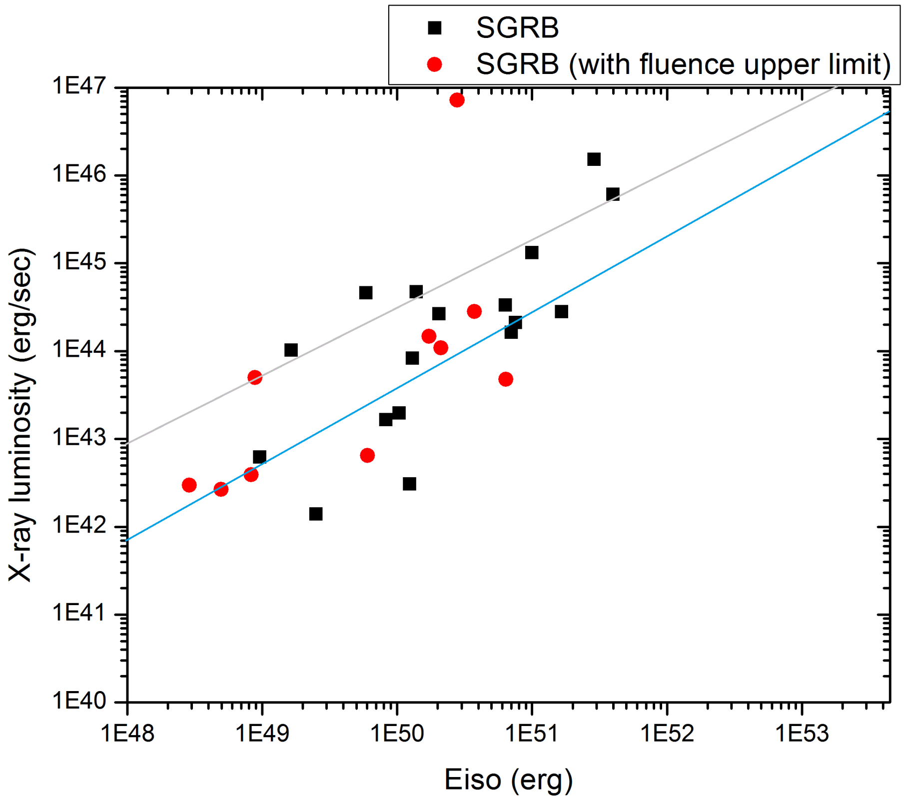


Figure x-ray afterglow correlation with Eiso-gamma 27 SGRBs plotted under this project : data source Berger et al. This comparison shows the difference in slope of LGRBs(gray) and that of SGRBs(blue). Hence it shows SGRBs are fainter than LGRBs.

What we observed from this plot was that there was a similar trend in both long and short gamma-ray bursts. From calculating the actual values of the slope it was observed that the slope of long gamma-ray bursts was 7 times higher than the slope of short gamma-ray bursts.

6.2 OPTICAL AFTERGLOW EMISSION

After the x-ray afterglow comes the optical afterglow emission. The emission lasts for about an hour to a day or so. The median r-band brightness of the short gamma-ray burst optical afterglow emission at a fiducial time of 7 hours is approximately 23.2 AB mag (Edo Berger et al.). Whereas the same median r-band brightness at the same fiducial time of 7 hours for a long gamma-ray burst is approximately 20.8 AB mag (Kann et al 2011).

For studying the nature of this emission we plot the isotropic-equivalent optical luminosity in the rest-frame *r*-band at a fiducial rest-frame time of 7 hours ($L_{opt,7}$) as a function of E_γ,iso.

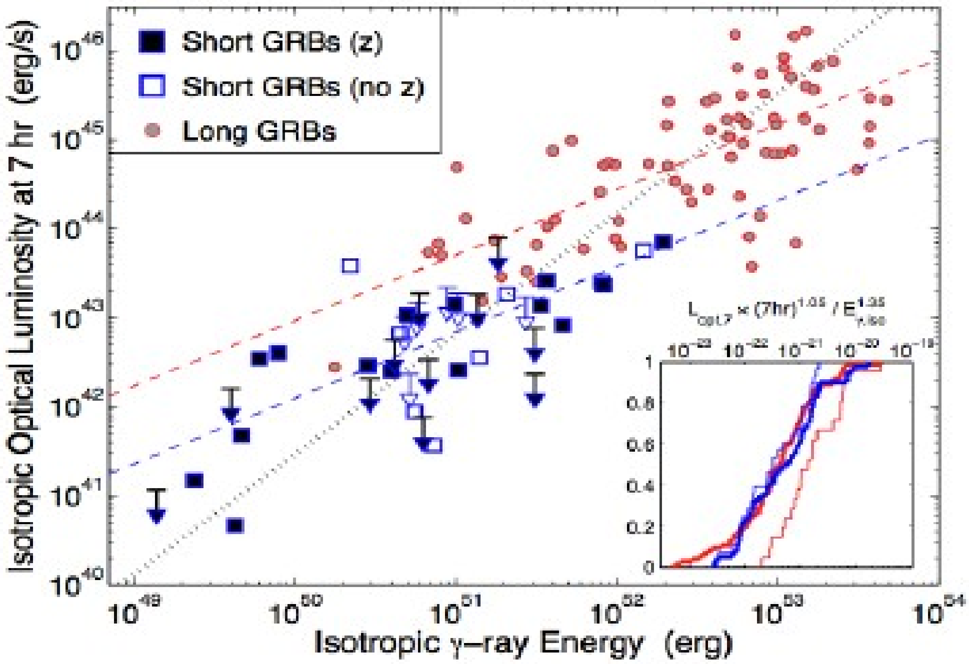


Figure optical afterglow correlation with $E_{iso\text{-}gamma}$: source Berger et al.

The results of the plot shows that there is a clear correlation between the two given parameters i.e. the isotropic-equivalent optical luminosity in the rest-frame *r*-band at a fiducial rest-frame time of 7 hours ($L_{opt,7}$) and E_{γ},iso. The calculation of the slope of both short and long bursts show that the magnitude of the slope of long gamma-ray bursts is almost 7 times higher than the slope of short gamma-ray bursts. This means the optical afterglow emission of long gamma ray burst is brighter than short gamma-ray burst.

6.3 RADIO AFTERGLOW EMISSION

At last there is radio afterglow emission. This afterglow emission is at comparatively higher wavelengths and is very rarely observed. There were 28 observations out of which only 3 have showed detectable radio afterglow (GRBs 050724, 051221A, and 130603B; Berger et al. 2005b, Soderberg et al. 2006b, Fong et al).

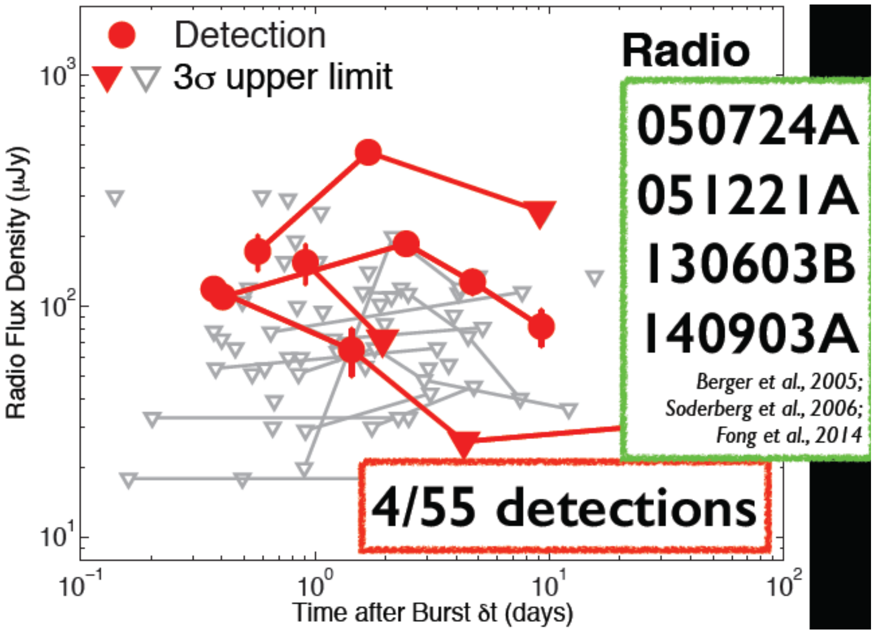


Figure Rasio afterglow depiction

6.5 RELATIVISTIC JETS

As we know till now that the event of a gamma-ray burst is marked by two bipolar relativistic jets. These jets have a very important implication on energy scaling and event rates. By determining the collimated angle of the jets using theoretical assumptions we not even can calculate the energy of the prompt emission but also the duration of it.

The important aspect of the collimation is the jet break. This jet break is due to two reasons. Firstly it is due to the edge effect of the jet and secondly the sideways expansion of the outflow. In advance terms we can say that mainly the jet breaks occur due to relativistic and hydrodynamic effects.

The jet opening angle is given by the formula

$$\theta_j = 0.13\ (t_{j,d}/1 + z)^{3/8}\ \ (n_0/E_{52})^{1/8}$$

Where θ_j is the jet angle, $t_{j,d}$ is the time at which the jet break occurs, z is the redshift, n is the density, E is the energy.

There is also a beaming corrected factor association with the jet angle given by the formula

$$f_b \equiv [1-\cos(\theta_j)]$$

In long gamma-ray bursts, due to easily taken out light curves in x-ray, optical or radio region we can with certainty determine these jet angles. For a typical long gamma-ay bursts the jet angle varies from 3-10 degrees. Also the beamig corrected factor is $f_b = 6 \times 10^{-3}$.

In short gamma ray bursts there is bigger problem of data. The information regarding collimation of jets of short gamma-ray bursts is very limited. This is mainly due to comparatively fainter afterglows. Still have been a few detections like GRB051221A with $\theta_j \approx 6-8^\circ$ (Soderberg et al. 2006a), GRB 130603B with $\theta_j \approx 4-8^\circ$ (Fong et al.2013) , GRB090426 with $\theta_j \approx 4^\circ$(Nicuesa Guelbenzu et al. 2011).

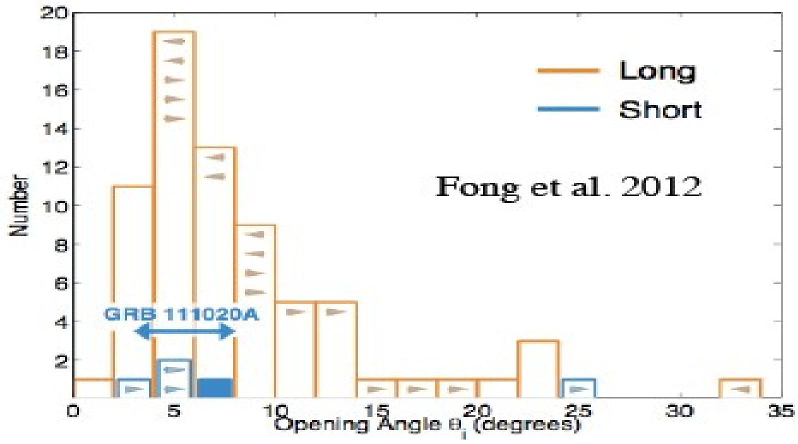


Figure opening angle LGRBs & SGRB showing the average angle for LGRBs to be 3-10 degrees. The data is less for SGRBs showing some possibility of opening angles at higher values too :source (Fong et al. 2012)

On the basis of the data collected of a few short gamma-ray bursts their energy scales were determined. These bursts showed an E_γ of the magnitude of 10^{49} ergs approximately which is less than the energy scale of long gamma-ray bursts by two orders of magnitude.

7. SHORT GRBs PROGENITOR MODELS

Short gamma-ray bursts as we know lasts in the scale of milliseconds to a few seconds. This was in contrary to the long gamma-ray bursts. Hence it was inferred that these two surely have different progenitors.(Eichler et al. 1989; Narayan, Paczynski & Piran 1992) . To fit this, compact binary merger model was proposed which is theoretically expected to be of the same time scale. This compact binary merger model consists of either two neutron stars spinning together in a binary system losing energy in terms of gravitational waves, slowly collapsing into each other with the formation of a black hole at the centre accreting the mass of the two neutron stars and finally erupting as a burst. The other part consists of a black hole asymmetrically accreting the mass of the neutron star revolving on its horizon.

Figure NS-NS merger artistic depiction showing how two neutron stars form a binary system and eventually lose energy and collapses; souce wikipedia

Several aspects of this model compact binary model-
First, the delay time between the binary formation and eventual merger is expected to span a wide range that depends on the initial separation and constituent masses, $\tau_{GW} \alpha\ a^4/(\mu M_2)$, where a is the initial binary separation, $M \equiv M1 + M2$ is the total binary mass and $\mu \equiv M1M2/M$ is the reduced mass. As a result of the wide delay time distribution, the resulting short bursts will occur in both early- and late-type galaxies.

Second is the natal kick which is the reason these binaries have a clear offset distribution in the host galaxies. The mechanism is referred to the supernova explosion in the environments of these binary systems away from the place of their births.

Thirdly these merges will not be accompanied by supernova explosion clearing its non-supernova associations at all.

Fourth is the emission of strong gravitational waves with are produced during this compact binary merger process of short gamma-ray bursts. Several detectors such as Advanced LIGO/Virgo detectors are trying to detect these gravitational waves by collecting data.

Figure Artistic depiction of a black hole accreting neutron star mass and eventually engulfing the celectial body to emit gamma radiations; source wikipedia

There are several differences too in the merger models itself. Such as the mass ratio of Neutron star- Neutron star binary and the Neutron star-Black hole binary. Due to the larger mass of Neutron star-Black hole binary it experiences less natal kicks and are expected to be found at comparatively less offset position from the host galaxy than the Neutron star- Neutron star binary.

8. SOME OTHER PROPERTIES OF SGRBs

8.1 DISTRIBUTION OF REDSHIFT

Various spectroscopic and photometric techniques are used to determine the redshift of the bursts and also their host galaxies. Some galaxies are so faint that the afterglow spectra is recorded to measure their redshifts. GRB 090426 at z = 2.609 (Antonelli et al. 2009, Levesque et al. 2010a) and GRB130603B at z =0.356 (Cucchiara et al.2013, de Ugarte Postigo et al. 2013) are the examples of such short gamma-ray bursts. With the calculations done by various researcher the data depicts the median of short gamma-ray burst redfhift to be <z>=0.5 (Edo Berger et al.) which does not include the bursts with faint host galaxies whose redshifts cannot be determined.

Whereas median of redshift of a long gamma-ray burst is observed to be <z>=2 (Edo Berger et al.). Hence we conclude that in general long gamma-ray bursts have higher redshift than short gamma-ray bursts. However there are some exceptions of short gamma-ray bursts with redshift more than 2. There is no clear trend between redshift and host galaxy type, with both early- and late-type hosts spanning the same redshift range with similar median values (Figure 4; Fong et al. 2013).

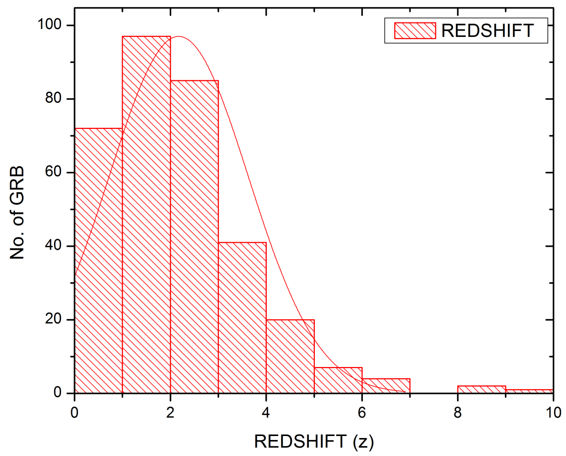


Figure LGRB redshift distribution of 348 detection plotted in this project; data source GRBOX. The plot shows the average redshift to be approximately 2.

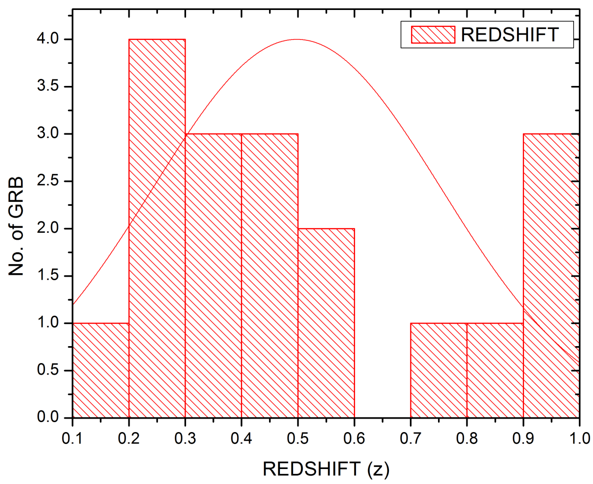


Figure SGRB redshift distribution of 23 sources plotted in this project; data source GRBOX. This plot shows the average redshift ti be approximately 0.5.

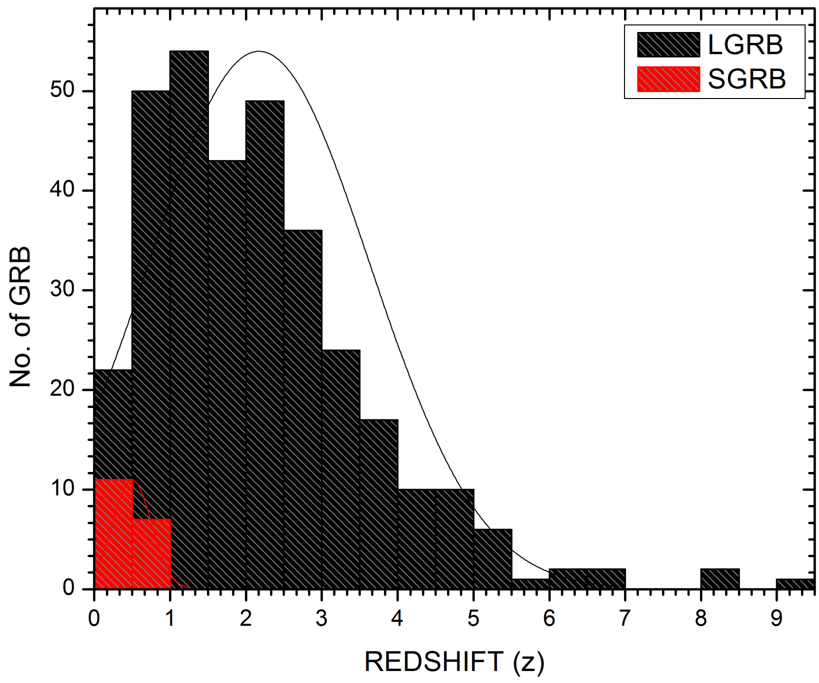


Figure ; 348 LGRB vs 23SGRB redshift distribution plotted in this project ; data source GRBOX. This plot shows that the average redshift of LGRBs is more than that of SGRBs.

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REDSHIFT DISTRIBUTION OF SGRBs

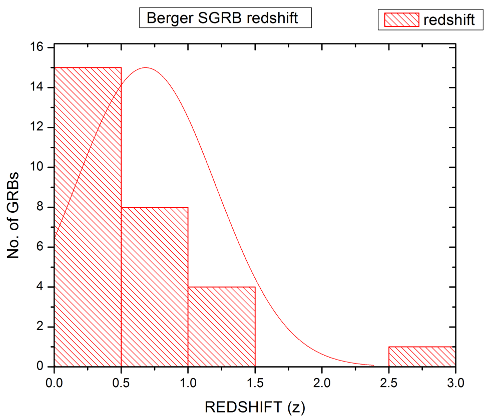

Figure SGRB 23 detections distribution of redshift plotted in this project; data source Berger et. al 2014. Average redshift is 0.75.

REDSHIFT DISTRIBUTION OF LGRBs

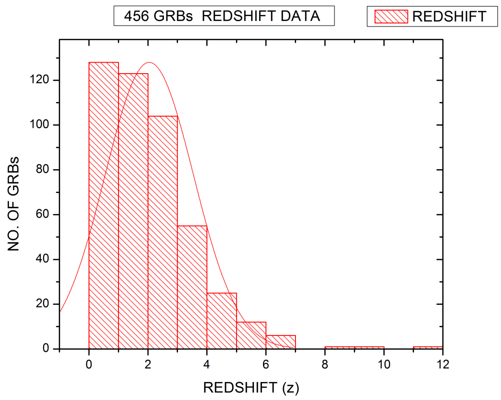

Figure 36 : LGRB 456 detections distribution of redshift plotted in this project; data source Berger et. al 2014. Average redshift is 2.

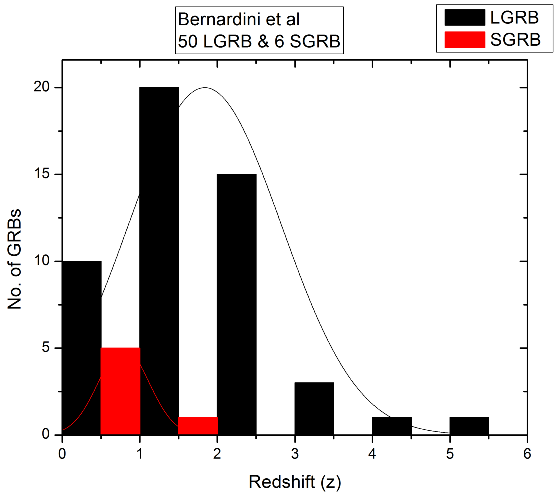

Figure SGRB vs LGRB distribution of redshift plotted in this project; data source Bernardini et. Al. The comparison shows that the redshift of the data on an average of LGRBs is greatet than SGRBs.

8.2 METALLICITY

The calibration of metallicity is done in terms of the formula 12 + log(O/H), which is different for both short and long gamma-ray bursts. According to study this value of metallicity in short gamma-ray bursts varies as $12 + \log(O/H) \approx 8.5 - 9.2$ and the corresponding median value is 8.8 approximately (Berger 2009, D'Avanzo et al. 2009). This is clearly higher than the median value of metallicity of long gamma-ray bursts which is 8.3 approximately (Stanek et al. 2006,Modjaz et al. 2008, Levesque et al. 2010b). There is clear positive relation between the metallicity and host galaxy luminosity (Tremonti et al. 2004).

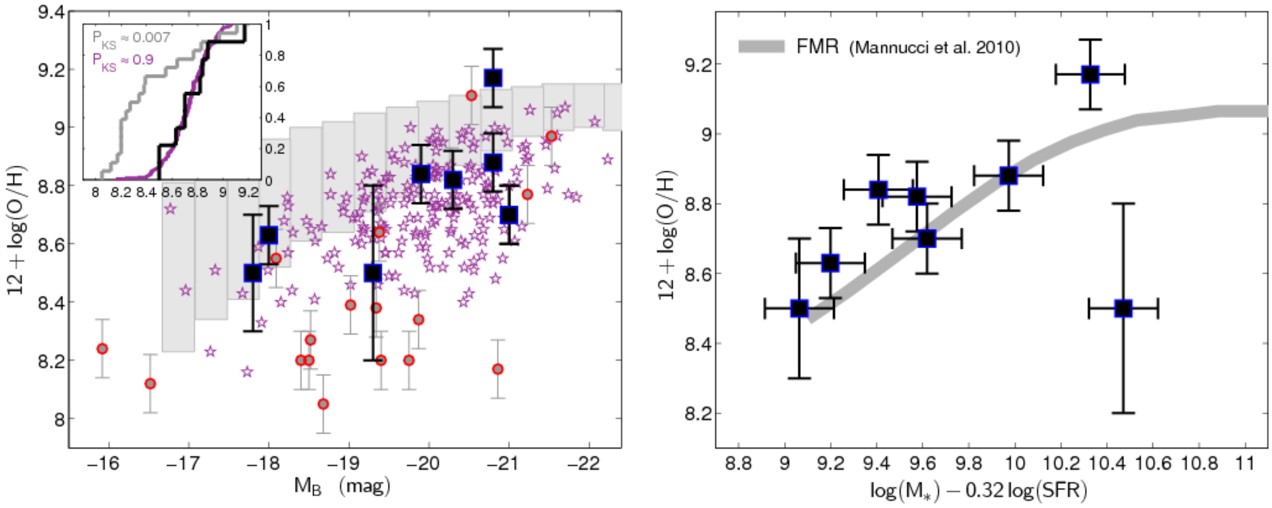

Figure SGRB host as a function of fundamental metallicity relation of star forming galaxies (right)
Figure Metallicity as a function of host galaxy rest-frame B-band luminosity(left) ; source (Berger 2009, D'Avanzo et al. 2009).

8.3 STAR FORMATION RATES

Ultra violet spectroscopy is the technique used to locate the star forming regions. Studies suggest that long gamma-ray bursts are mainly found in the star forming regions of the host galaxies. Whereas short gamma-ray bursts are found at large offsets away from the star forming regions of their host galaxies.

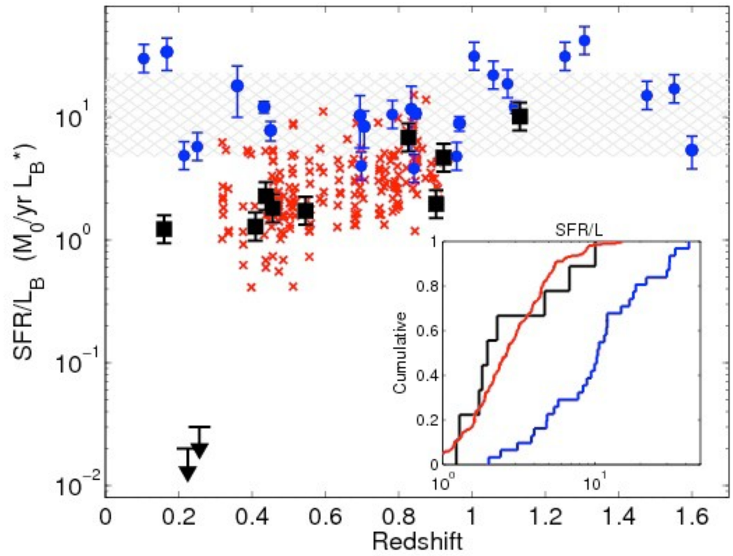

Figure star formation rates of SGRBs and LGRBs as a function of redshift ; source Berger et al. 2009

8.4 HOST GALAXIES

Short gamma-ray bursts are generally found at offset positions of elliptical galaxies. Though due to small data set we say they are found in a mix of spiral as well as elliptical galaxies. While according to the demographic distribution 20% of these bursts are found in the early type galaxies (Fong er al. 2013). These studies basically conclude that short duration gamma-ray burst are found in elliptical galaxies and shows that the progenitor belongs to an old stellar population.

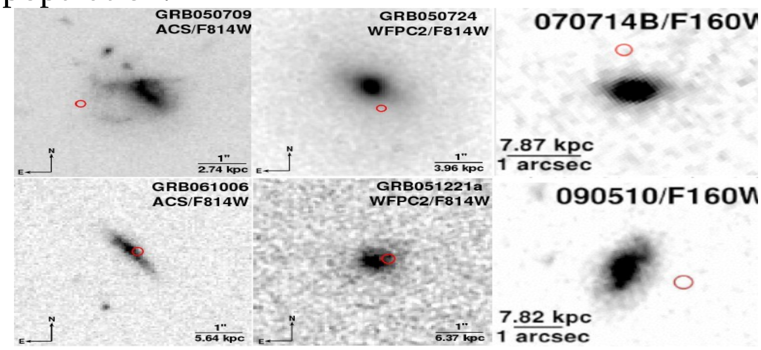

Figure Offset distribution of SGRBs from host galaxies. ;source Hubble Space Telescope

8.5 OFFSET DISTRIBUTION OF SHORT GRB

Short gamma-ray bursts have systematically larger radial offsets from their host galaxies than long gamma-ray bursts(Bloom, Kulkarni & Djorgovski 2002), but match the predicted offset distribution of compact object binaries from population synthesis models that include natal kicks. About 10% of short GRBs have offsets of ∼ > 20 kpc, extending beyond the typical visible extent of their host galaxies. These bursts appear host-less in deep optical/near-IR imaging from *HST*, but exhibit nearby galaxies with a low probability of chance coincidence.

The short GRB offsets normalized by host galaxy size are similarly larger than those of long GRBs, core collapse SNe, and Type Ia SNe, with only 20% located at $\sim < 1$ *re*, and about 20% located at $\sim > 5$ *re*. These results are indicative of natal kicks, or an origin in globular clusters, both of which point to compact object binary mergers. The inferred kick velocities are $\sim$ $20 - 140$ km $s{-1}$, in reasonable agreement with Galactic NS-NS binaries and population synthesis models

8.6 NO SUPERNOVA ASSOCIATION

The study of this nature is based on spectroscopic and photometric observations. On one side the close property overlap of long gamma-ray bursts with supernova type Ic core collapse and also its exclusive locations in star forming regions of the galaxy consolidates its association with supernova, the other side the same analogy put forward the answer of non supernova association of short gamma-ray bursts.

A study was conducted of both long and short gamma-ray bursts at lower redshift as a function of magnitudes less than SN1998bw (Berger et al. 2014) plot to find out interesting results. It showed large offset of some short gamma-ray bursts from the supernova magnitude whereas the long ones lied well within the supernova range. Some of these short bursts were found in star forming region but still had large offset from supernova magnitudes suggested that these do have a different progenitor and is not phenomenon of super massive star collapse.

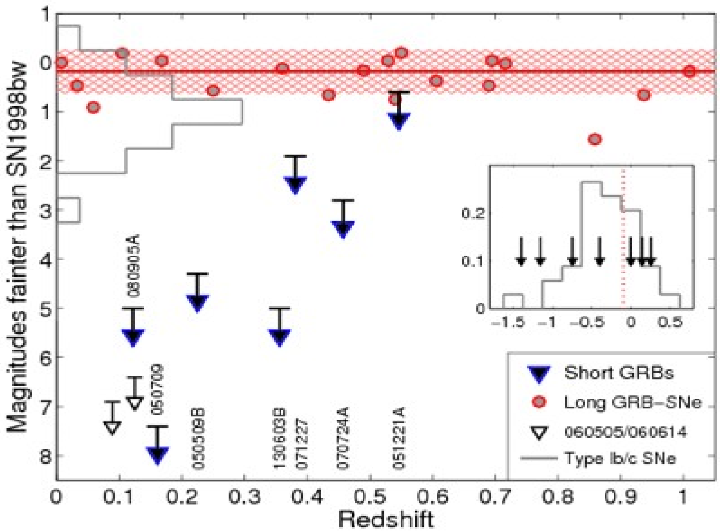

Figure Limits on supernovae associated with short GRBs (filled triangles) relative to the peak absolute magnitude ; source Berger 2014

8.7 KILONOVA EMISSION

The ejection of neutron rich matter during the compact binary merger event due to the decay of heavy r-process ions production is known as kilonova emission. Due to the low ejecta mass and rapid expansion velocity, the event is of a shorter timescale and low luminosity as compared to supernova emissions hence they are known as “mini-nova”, “kilonoava” or “macronova”.

According to a study (Rosswog et al. 1999, 2000; Ruffert& Janka 2001; Rosswog 2005; Etienne et al. 2008; Bauswein, Goriely& Janka 2013; Piran, Nakar& Rosswog 2013; Rosswog, Piran & Nakar 2013) several calculations were made which showed that the ejecta mass released during the process is of the range 10^{-3}−few×10^{-2} $M_{\odot}$. Also the velocity of the ejecta was calculated to be $v_{ej} \sim 0.1-0.3c$.

The theoretical prediction was that this ejecta mass increases with increased asymmetry of the merger so as to speak BH-NS merger has greater ejecta than NS-NS merger. One such breakthrough in kilonova was the GRB 130603B. The study on this short gamma-ray burst at redshift z=0.356 was conducted which produced near IR band afterglow of the event (Berger, Fong & Chornock 2013; Tanvir et al. 2013). However the flux measured was low with no corresponding counterpart in optical data. This study is one of the key evidence for compact object binary as the progenitors.

8.8 SHORT GRBs AS A SOURCE OF GRAVITATIONAL WAVES

Theories have suggested that these compact object binary mergers such as neutron star-neutron star, neutron star- black hole or black hole- black hole serves as a source of strong Gravitational Waves. The binary system loses energy in terms of gravitational waves and hence collapses into a black hole. Therefore with the technological advancements detectors like the Advanced LIGO and Virgo has been established to detect such traces of gravitational waves (Abadie et al.2010). These detectors detect the electromagnetic counterpart of the so called gravitational waves.

However there are a few obstacles in the way of such studies.
Detectability is the primary concern. The detector has to be sensitive enough to track the electromagnetic counterpart. Its threshold should not be above the burst range.
One more problem is the localisation of these bursts with arcsecond precision. Also these bursts occur at low redshift and the duration is small with respect to the detector accuracy. Such low luminosity is very difficult to analyse the x-ray, optical or radio follow up.
The end problem is distinguishing the required observation and eliminating the noise in the data.

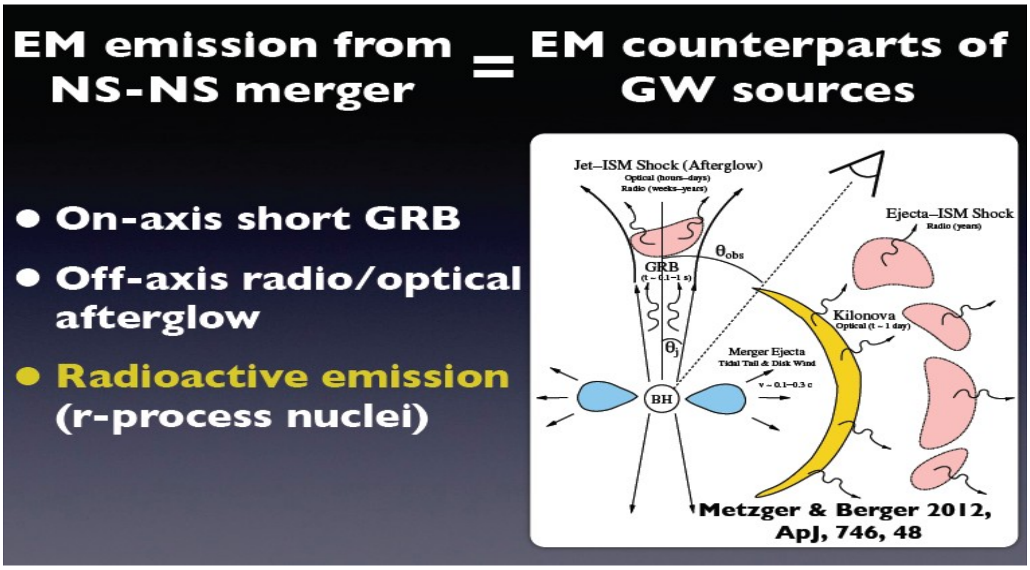

Figure electromagnetic counterparts of compact object binary mergers as a function of the observer viewing angle ; source Berger 2014

8.8.1 <u>ON-AXIS GRB COUNTERPART</u>

The compact binary mergers facing us are called on-axis gamma-ray bursts. Since the mergers are predicted to emit radiations during the event perpendicular to its place or in the direction of the axis of rotation, therefore we can observe these bursts very well. Due to this reason only instead of being at a lower redshift the afterglows will be exceedingly bright for the ground as well as space based telescopes.

One such approach in the context of joint γ-ray and GW detections is to carry out a systematic search for GW emission in temporal coincidence with short GRBs (Abadie et al. 2012a;Metzger & Berger 2012; Kelley, Mandel & Ramirez-Ruiz 2013).

8.8.2 OFF-AXIS OPTICAL AFTERGLOW COUNTERPART

The optical afterglow of an off-axis event can be easily obtained as there will be a time when the viewing jet will eventually decelerate and spread into observer's line of sight. Very large offsets are a problem as the viewing jet angle will take a larger time to come to observer's line of sight. Also the there will be reduced brightness peak and faint luminosity. Metzger & Berger (2012) utilized the off-axis afterglow models of van Eerten, Zhang & MacFadyen (2010) with the parameters appropriate for on-axis short GRB afterglows (§8) and found that for an off-axis angle that is twice the jet opening angle (θ_{obs} = $2\theta_j$) the peak brightness of the afterglows is calculated to be approximately equal to 23 − 25 mag with a peak time of approximately 1−10 d.

Optical Counterparts - Summary

Model Source	Type	Filter	M(Filter)	m@200Mpc	t_{peak} (days)
Metzger 2012	On-axis	r	-26.5 – -16.5	10 – 20	<0.1
	Off-axis	r	-17.5 – -7.5	19 – 29	1 – 10
	Kilonova	r	-17.5 – -13.5	19 – 23	0.5 – 4
Kasen & Barnes	Kilonova	R	-15.5 – -11.2	21 – 25.3	~0.5 – 10
2013		I	-16.7 – -12	19.8 – 24.5	"
		H	-18 – -14	18.5 – 22.5	"
Tanaka &	Kilonova	r	-14 – -10.5	22.5 – 26	~1
Hotokezaka 2013	1.3-1.4 $M_\odot$	z	-15.5 – -13	21 – 23.5	1 – 2
		J	-15.5 – -13.5	21 – 23	1 – 5
		H	-14.5 – -12.5	22 – 24	1 – 7
Grossman et al.	Kilonova	r	-14.5 – -11	22 – 25.5	0.5 – 1
2013	1.3-1.4 $M_\odot$	B	-13.5 – -10	23 – 26.5	0.3 – 0.5
		J	-14 – -12.5	22.5 – 24	0.5 – 2
		H	-14 – -13	22.5 – 23.5	1 – 4

Figure Optical counter part of SGRB emissions ; source wikipedia

8.8.3 OFF-AXIS RADIO AFTERGLOW COUNTERPART

The off-axis radio afterglow is faintly observed. This is because of the reason that by the timescale of radio emission the collimated jet starts to spread to quite wide angle and also the jet remains mildly relativistic to give low afterglow. Hence the synchrotron emission spectrum shifts to radio GHz band. (Nakar & Piran 2011) Now the only factor to boost up the detection is the kinetic energy of the blastwave and the density of the circumstellar medium.

While radio counterparts are in principle detectable from all viewing angles, existing facilities are not well-matched to the faintness of the anticipated signals. In addition, since the radio signal is delayed compared to counterparts at other wave-bands, a more profitable approach may be to use radio observations to follow up candidate counterparts from γ-ray, X-ray, or optical/near-IR searches, potentially as a way of distinguishing a true counterpart from unrelated sources (e.g., supernovae, AGN).

9. CONCLUSION

In this review we have made the following conclusions by understanding the ongoing studies by researchers around the globe-

1- We learnt about the basic classification of bursts on the basis of duration of the event. The bimodal distribution of the data collected by various satellites makes it evident. Events for less than 2 sec are generally short gamma-ray bursts and events more than 2 sec are long gamma-ray bursts.
2- The energy scales of these bursts are about 10^{48}-10^{52}. Also we learnt that short gamma-ray bursts are of some magnitude of energy lower than long gamma-ray bursts.
3- Redshift measurement shows yet another classification between the bursts. Short gamma-ray bursts have lower redshift of around 0.5 whereas long gamma-ray bursts have redshift of around 2.
4- Long gamma-ray bursts have high luminosity as compared to short gamma-ray bursts and are easily detectible. Often short gamma-ray bursts are located on their afterglow basis.
5- We learnt about the progenitor models of both the bursts type. On one hand long gamma ray bursts are associated with core collapse model and on the other hand short gamma-ray bursts are associated with compact binary mergers.
6- The afterglow properties of both types of bursts were discussed. The time scale of X-ray, optical and radio of long gamma-ray bursts is longer than short gamma-ray bursts.
7- Short GRBs occur in both early- and late-type galaxies, with the former accounting for about 20% of the sample. The sub-dominant fraction of early-type hosts indicates that the short GRB rate is influenced by both stellar mass and star formation activity.
8- The host galaxies of short gamma-ray bursts have larger stellar masses, older stellar population ages, higher metallicities, and lower star formation rates and specific star formation rates than the hosts of long gamma-ray bursts.

9- The kilonova emissions discussed in the review which provides strong evidence for compact binary mergers to be the progenitors of short gamma-ray bursts.

10- Also we concluded with an open and interesting area of detection of electromagnetic counterpart of gravitational waves from these compact binary mergers.

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