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# Gamma Ray Bursts: Fundamentals, Challenges and Insights from Recent Observations

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## Abstract

In astronomy, gamma-ray bursts (GRBs) are some of the most intriguing and enigmatic phenomena. GRBs are the most luminous events in the cosmos and they are bursts of strong but brief gamma-ray (GR) flashes. GRBs have a highly interesting nature and can last anywhere from a few hundred seconds to a tiny fraction of a second. A GRB produces an afterglow that last longer and gradually fades. The discovery of afterglow has brought about a revolution in the area of GRB. We have discussed GRBs and their classifications in this paper. Moreover, we summarized the mechanisms behind the bursts, the features seen, the afterglow, and the fireball model of GRBs. Apart from the fireball model of GRBs, alternative models are also discussed, for example, the accretion model for the long GRBs and the pulsar model used to explain the short GRBs.

**Keywords**: Gamma-rays, afterglow, prompt emission, X-ray flashes (XRF), gamma-ray burst models.

## 1. Introduction

At cosmological distances, the most distinct astronomical event ever observed in the universe, i.e., GRBs are transient, intense radiation flashes that peak in the gamma waveband and often happen once a day throughout the whole sky [1]. The bursts might last anything between a few and several hundred seconds. With a GR energy

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spectrum between −100 keV and 1 MeV, GRBs have a typically isotropic energy range of $10^{48-52}$ erg following Le & Mehta [2], but the true energy range is of $10^{50-54}$ erg [3,4,5], and produce low luminosity GRBs range from $10^{46\text{-}48}$ erg $s^{-1}$ and high Luminosity GRBs have $L \geq 10^{50}$ erg $s^{-1}$ [6], which are $10^6$ times higher w.r.t the utmost electromagnetic brightness of an exploding star supernova [7]. The discovery of the first GRB events was done in 1967 by the US Vela satellites, which were launched into a high orbit in accordance with the Nuclear Test Ban Treaty [8]. It took around six years before the Vela satellite results were made public, but they were shortly corroborated by the data released from the Soviet Konus satellites [9]. Figure 1 shows an artist's impression of two galaxies in the early universe. The exquisite explosion on the left is a GRB. On its journey to Earth, the burst's light passes across both galaxies (outside the right frame). The Very Large Telescope (VLT) at European Space Organization (ESO) was used to analyse the light from this GRB, and the results revealed that these two galaxies are enormously rich in heavy chemical components.

Figure 1: This artist's impression shows two galaxies in the early universe. (Credit: ESO/L. Calçada)

The Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO), along with data from the Oriented Scintillation Spectrometer Experiment (OSSE), the Compton Telescope (Comptel), and the Energetic Gamma Ray Experiment Telescope (EGRET), made the most important discovery in the field of GRBs in the 1990s [8]. According to Meegan et al. [10], it was discovered to be scattered equally over the sky, suggesting either an extragalactic or galactic-halo origin [7]. This issue was eventually overcome right after the Italian/Dutch BeppoSAX satellite discovered afterglow occurrences in 1997 [11]. The long-lasting, fading X-ray radiation that follows a GRB is known as the afterglow. It was possible to identify host galaxies and determine the associated redshifts, which range from 0.16 (or likely as low as 0.0085) to 4.5 in practically all cases where precise afterglow positions were discovered [12]. Recent studies show that GRB redshift ranges from 0.0085 [13] to the highest redshifts observed at 9.4 [14,15]. The redshift value establishes the cosmological distance at which the GRBs are located. The study of GRBs has benefited dramatically since the afterglow, providing a wide opening. According to Kolb [16], the light curves of GRBs exhibit a range of time dependences, including smooth rises, fast decays, single or multiple spikes, and rapid variability in most bursts. As we now know, about $10^{51}-10^{53}$ ergs of energy is emitted during GRBs in a few seconds, which makes them comparable to supernovae in terms of the release of energy in total [12]. The division of GRBs is done in two groups: short (SGRBs) and long (LGRBs), separated by a fine duration of 2 seconds.

## 1.1 Classification of GRBs

Kouveliotou et al. [17] have examined the initial BATSE catalogue's GRB duration distribution. They discovered a bimodality in the distribution that divides GRBs into two classes: GRBs with burst duration of less than two seconds and burst duration of more than two seconds. Their findings offer the first classification method for GRBs that combines their temporal and spectral characteristics. The duration of GRBs, as detected by the BATSE instrument, is used to categorize them using $T_{90}$ i.e. the time needed for the counts in aggregate to increase from 5% to 95% over the background(in the 50-300 keV band) and comprise 90% of all GRB counts [18]. According to D'Avanzo [1], two modes GRBs fall into one of two categories: LGRBs ($T_{90}$ > 2 sec) or SGRBs ($T_{90} < 2$ *sec*). However, researchers also asserted the existence of a third class which is intermediate to LGRBs and SGRB, ranging from $2.5 < T_{90} < 7$ sec [19,20]. However, the statistical significance of this kind of three-class GRB division is unclear [21]. The spectra hardness ratio of SGRBs and LGRBs is anticorrelated with their duration, as SGRBs are generally harder, and LGRBs tend to be softer [18]. The bimodal distribution came into picture as per this Monte Carlo simulations demonstrate distinct bimodal distributions in the GRBs' power law and Gaussian angular distribution, with lognormal-like forms for both SGRBs and LGRBs. The GRB jet's discrete emission regions- such as subjets or patchy shells- are the bimodality sources [22]. By the study of Toma et al. [22], $T_{90}$ depends on multiplicity ($n_s$) and their study showed that for $n_s = 1$, $T_{90} < 1s$ events and for $n_s \geq 2$, $T_{90}$ increases far more than $n_s = 1$. $n_s \geq 1$ results long GRBs and $n_s = 1$ gives short GRBs.

The progenitors of SGRBs are considered relativistic jets that result from the merging of compact objects, e.g., a black hole (BH) and a neutron star (NS) or two NSs. In the instance of the short GRB130603B, Berger et al. [23] & Tanvir et al. [25] announced the discovery of a kilonova (associated with r-process nucleosynthesis), providing concrete proof of the merger and SGRBs. Compared to LGRBs, the afterglow in SGRBs is often fainter. In the case of LGRBs, the progenitor is believed to be the core collapse of stars or a hypernova (core collapse of massive stars). Some of the supporting evidence is as follows:

**a. Host Galaxy Properties:** Unlike LGRBs, which seem to favor regions that form stars in young galaxies, SGRBs typically occur in older galaxies with less star formation, validating the idea that persistent stellar evolution eventually leads to a compact binary system, giving birth to SGRBs.

**b. Offsets:** SGRBs are often farther away from their host galaxy's center than LGRBs, making sense because massive stars reside closer to the galactic core, where star formation is concentrated, while binary NSs can wander further after formation.

**c. Kilonovae and Supernovae Associations:** SGRBs are frequently accompanied by a special type of emission called a "kilonova," which is believed to be the afterglow of a merger of two NSs. However, LGRBs often have a connection with supernovae, which are violent deaths of massive stars.

Apart from GRB 130603B, other intriguing cases, like the GRB 170817A event, provided the first conclusive multi-messenger detection of a kilonova that came after an SGRB. Additionally, it provided independent confirmation via gravitational waves, solidifying the notion of compact binary mergers for SGRBs [26]. GRB060218A, GRB071112C,GRB100316D,GRB111209A,GRB111228A,GRB120714B, GRB120729A, GRB130215A, GRB130831A, GRB161219B and GRB171010A of Swift catalogue have been detected to be associated with supernovae as well as well-characterized with the help of spectroscopy [27,28,29,30,31]. The afterglow in the optical and/or radio regimes of the spectrum in LGRBs suggests that it is related to the core-collapsed deaths of young stars or massive stars [32]. A high proportion of young, massive stars in very blue galaxies host LGRBs. These stars' short lifespan and high burning intensity greatly contribute to the galaxy's total blue light emission. For astronomers looking for possible sites of GRBs, the correlation between blue galaxies and LGRBs is a vital clue. In addition to their duration, SGRBs and LGRBs can be distinguished by their prompt emissions observed, insignificant spectral lag, fainter afterglow, and spectral hardening [34,35]. For 1-2 seconds, LGRBs' prompt emission shares some initial characteristics with SGRBs, and both classes' spectral evolutions are comparable [1].

## 1.2 Drawbacks and New Classification Schemes of GRBs

Traditionally, GRBs are classified as either short (duration less than 2 seconds) or long (duration exceeding 2 seconds). Recent data have challenged this binary classification, indicating a more continuous spectrum of GRB features rather than a discrete short-long divide. The traditional scheme overlooks the diverse range of properties observed in GRBs. These include variations in light curves, spectral behaviour, and energetics. However, some recent observations highlight drawbacks in the traditional classification scheme. For example, LGRBs are linked with a very massive star's death, whereas SGRBs are linked to the merger of compact objects.

**GRB200826A:** GRB200826A is an SGRB, with a rest-frame duration of 0.5s. But, in another way, this energetic and soft event corresponds to LGRBs. According to Rossi et al. [36], GRB 200826A is a typical collapsar event in the lower tail of the LGRB duration distribution. These assumptions support the hypothesis that collapsars can create events as brief as 0.5 seconds in the host frame. We must rely on more than the time factor to differentiate the GRB classification.

**GRB211211A:** Similarly, Yang et al. [37] reported a peculiar long-duration burst, GRB 211211A. Its prompt emission properties significantly differ from all known type SGRBs. However, the multi-band observations of this GRB result in a non-massive star origin.

**GRB230307A:** According to Levan et al. [38], GRB 230307A is a long-duration GRB associated with compact object mergers, with a kilonova but no star formation at its location.

**GRB060505 and GRB 060614:** According to the 'collapsar' model, each LGRB is accompanied by a broad-lined and bright type Ic core-collapse supernova. Observations of multiple nearby GRBs have validated this relationship. Fynbo et al. [39] reported that GRB 060505 and GRB 060614 do not produce supernovae. In their observations of GRB 060505 and GRB 060614, they discovered that any supernova associated with these two LGRBs must have been not only fainter than any previous supernova associated with a GRB but also significantly fainter than any non-GRB-related type Ic supernova observed till date. The scientific community is continuously working to develop a global classification scheme that researchers could use to classify GRBs adequately. Some new classification schemes are:

**Lü et al.** [40] introduced a new parameter, $\varepsilon$, to classify GRBs. They divided GRBs with known redshifts into two categories with a separation of $\varepsilon = 0.03$. This classification approach is more similar to Type II and Type I classifications. The high $\varepsilon$ corresponds to Type II GRBs, while the low $\varepsilon$, represents Type I GRBs.

**Minaev & Pozanenko** [41] suggest the new classification method, based on the $E_{p,i}$ -$E_{iso}$ correlation and introduce two parameters, $EH = E_{p,i,2}\, E^{-0.4}_{iso,51}$ and $EHD = E_{p,i,2}\, E^{-0.4}_{iso,51}\, T^{-0.5}_{90,i}$ , where $E_{p,i,2}$ is the value of $E_{p,i}$ parameter in units of 100 keV, $E_{iso,51}$ is the value of $E_{iso}$ parameter in units of $10^{51}$ erg, and $T_{90,i}$ is the rest-frame duration in units of seconds. EHD is found to be the most reliable parameter for the blind type I/ type II classification to classify GRBs with no redshift.

**Dimple et al.** [42] analyzed GRBs associated with kilonovae, which are bright emissions believed to be produced by mergers of binaries involving NSs. They use data from the Swift/Burst Alert Telescope (BAT) 2022 catalogue and machine learning algorithms to analyse light curve properties. Their analysis reveals five distinct clusters of GRBs, not just the long-short binary classification. Interestingly, the kilonova-associated GRBs fall into two clusters within this new grouping.

**Jespersen et al.** [31]**'s** classification is based on prompt emission light curves. Every burst with an associated supernova falls into the longer group, while bursts with kilonovae fall into a shorter group. This classification points us to the bimodal nature of GRBs based on time distributions. They found two bursts without a supernova, belonging to the longer group, which were the product of directly collapsed BHs that occurred after the deaths of more massive stars.

## 2. Observed Properties

### 2.1 Prompt Emission

Prompt emission from the GRBs comprises low-energy emission at hundreds of keV and GRs. It often has a variable light curve, no repetition, and lasts for a few seconds or less. Furthermore, here is no consistent pattern in the spectra that could be easily associated with any simple emission model; instead, they differ from burst to burst. The actual emission mechanisms, or the prompt emission of the GRB, is still an open question because of the various reasons stated before. There are several empirical models, such as the Band function [46,47] and some deviation incorporated in Band function like an extra thermal component, breaks, or multiple spectral components [52,48] to elucidate the emission of GRs by using spectral information. Similarly, there exist multiple physical models to explain the GR emissions. These consist of synchrotron emission from optically thin regions, photospheric emission (thermal emission from the photosphere), and the contribution of energetic protons either through direct synchrotron emission or photopion production ([52] and the references therein). Moreover, the "fireball" model explains the relativistic outflows contributing to the emission. The internal shock model is the most widely accepted emission mechanism for the prompt GR emission [49]. As per this, shocks are produced due to collisions between the shells of plasma or fireball, and some portion of kinetic energy is transformed into random particle energy radiating via a synchrotron mechanism, leading to the observation of non-thermal GRs. Internal and external shock mechanisms for the emission of GRs are also discussed in the "fireball" section 3. In such cases, photospheric emission helps in understanding the emission mechanisms. According to photospheric emission, there will be a dissipation of kinetic energy near the photosphere by shock or other mechanisms like neutron-neutron decoupling and interaction [46,50,51].

#### 2.1.1 Light Curve

A noticeable characteristic of GRBs that has yet to be observed in other astronomical phenomena is their short duration, ranging from milliseconds to tens of minutes. The form of the light curve is a vital feature of GRBs. The light curve of GRBs is one of the most challenging areas to study since it is irregular, with single or several peaks, diverse, unpredictable, and complicated. Considering the aforementioned characteristics, it's clear that no two GRB light curves are the same [52]. According to observations, the variability in GRB light curves on a time scale ranges from smooth with fast rise and exponential decay (FRED) in some LGRBs to milliseconds in others [10,53]. During bursts, there is a shorter rise and fall time (sharp spikes). The leading edge of bursts often has a shorter length than the tailing edge [54]. Since GRB variability and brightness are correlated, it is possible to estimate the luminosity of bursts with unknown redshifts [55]. The field of GRBs expanded in the 2000s thanks to satellites like Swift [56], INTEGRAL [57], and GLAST (Fermi) [58]. Over time, new information on GRBs also emerged.

##### 2.1.1.1 The Advancement of the GRB Field with Swift and Fermi

Prior to Swift's [48] and Fermi's [59], launches in 2004 and 2008, there were numerous unanswered concerns about the progenitors of SGRBs, high energy radiation and counterparts from GRBs, the distribution of redshifts in bursts and their application for the understating early universe, and jet outflows. Both the Swift and Fermi are NASA missions launched primarily to study high-energy astrophysical phenomena, particularly GRBs. The launch of these two satellites established the beginning of a new era. Swift has an exceptionally rapid and efficient burst detection algorithm that automatically repoints the observatory in the direction of bursts and suggests burst coordinates [60]. Fermi detects GRBs at a rate of ~300 per year, with quality spectroscopy and coordinate with 10-degree accuracy [61]. To fill the temporal gap between the observation of prompt emission and the afterglow, Swift was designed. The Burst Alert Telescope (BAT, [62]) and the X-Ray Telescope (XRT, [48]) of Swift helped in revealing non-thermal prompt X-ray emissions from LGRBs transitioning to decaying afterglow. BAT has an energy coverage of 15 keV to 150 keV. Swift has detected GRBs at accurate locations with afterglow observation and successfully determined the redshifts. Swift's ability to precisely locate SGRBs and its observation of the afterglow have revolutionized the physics of short bursts [63,61]. The Gamma-ray Burst Monitor (GBM, [59]) and the Large Area Telescope (LAT, [64]) of Fermi play a crucial role in the detection of bursts and the measurement of GRB spectra. GBM has an energy coverage range of 8 keV to 40 MeV, whereas LAT has 20 MeV to 300 GeV. With the help of GBM and LAT observation, hundreds of >100 MeV photons and broad-band spectra can be studied. The broad energy coverage of combined Swift (BAT:15-150 keV) and Fermi (GBM (8 keV-40 MeV) and LAT (20 MeV-300 GeV)) provides a wonderful platform to perform temporal studies to get insights into the physics of GRB emission mechanisms and the evolution of these energetic events. LAT has detected both LGRBs and SGRBs as well as the most energetic GRBs, like GRB 080916C (at $z = 4.35$) [65]. Both missions have advanced the understanding of the GRB field, like SGRB progenitor studies, the nature of bursts and their counterparts, the precise location of the burst, measurements of spectra, temporal studies, and the mechanisms of the outflows leading to the emission of GRs emission.

### 2.1.2 Spectrum

The preponderance of GRB emission is composed of high-energy particles with energies greater than 50 keV. The nature of the GRB spectrum is non-thermal. No two bursts have the same spectrum as each other. The spectrum consists of a broad frequency range of EM radiation. The spectra and two power laws connected by exponential spectra demonstrated a remarkable phenomenological fit [58]. Identifying the GRB prompt emission process directly would provide more limitations on the energy dissipation mechanism and, ultimately, the composition of the GRB jets. The "Band function," also known as the smoothly broken power law function, has traditionally been used to characterize GRB spectra [47]. With success, this function captures the primary characteristics of the GRB spectra. This function has four free parameters: low-energy spectral slope, high-energy spectral slope, break energy, and an overall normalization. The empirical formula for band function can fit a large number of spectral data [68]. From burst to burst, the energy at which peak power is released varies and may be seen to alter swiftly with bursts despite certain similarities in the spectral patterns of several bursts [54]. A series of pulses can be seen in bursts. The bursts have a spectrum-softening trend as the peak energy of individual pulses declines over time [16]. At this point, the pulse lasts longer. The apparent time scale variability for different GRBs ranges from micro to millisecond time scales (i.e., about 256 $\mu$s to 33 ms) [69]. In general, a spectral analysis is a time-integrated examination of flux during the entire prompt emission period. Photons should be collected sufficiently for a better analysis outcome, and the analysis procedure should apply forward folding techniques [52]. The forward folding technique is a spectral analysis technique in which we first choose the model spectrum, and second, the chosen model is convolved with the detector response and compared to the detected count spectrum. Third, the model parameters are varied in search of the minimal difference between the model and the data. The outcome is the best-fitting parameter within the framework of the chosen model. This analysis method is the only one that can be used because of the non-linearity of the detector's response matrix [22]. There is much use of Fermi time-resolved spectral analysis for GRBs. Therefore, many novel features in the field of GRBs can be known and verified by observation with the development of technology and new satellites.

The synchrotron mechanism is one of the proposed mechanisms for GRB emission. It helps in explaining the rapid variabilities observed in GRB emissions. The spectral parameter is determined by the energy distribution of the radiating electrons in synchrotron emission, which consists of a low-energy spectral slope following a power law [70].

Synchrotron emissions can explain spectral parameters such as the spectral index (power-law index), break frequencies, and the rapid cooling of electrons due to a strong magnetic field leading to the shaping of the spectral properties of synchrotron emission [52]. Synchrotron emission gives a good fit to spectra in some GRBs, but in most GRBs, it fails to fit [65]; this inability is termed as the "synchrotron line of death" [71]. The interpretation of data in the context of theoretical models, underlying physics of proper emission mechanisms, observed spectra, and variability are still in debate, which are some challenges in the GRB community [60].

## 2.2 Afterglow

BeppoSAX (Italian-Dutch satellite) discovered the first X-ray afterglow from GRB970228 in February 1997 [11]. There was no proof of GRB counterparts at other wavelengths prior to that. At the same location, an optical afterglow was also noticed [72]. The precise position of the bursts' surroundings may be measured, thanks to optical afterglow, which also plays a key role in estimating the redshifts of GRBs [73]. When a burst is described as "dark", there are no optical afterglows [74]. This suggests that some GRBs are in regions that are optically dense for optical radiation and rich in gas and dust. The precise positions provided by afterglows allowed us to identify the galaxies that host numerous bursts. Frail et al. [75] reported an afterglow in the radio waveband in GRB970508. As confirmed by afterglow, GRBs exist at cosmological distances of billions of light-years. The afterglow spectrum does not follow a decay like a supernova but rather follows a smooth or broken power-law decay, which is consistent with the synchrotron emission mechanism [76]. Afterglow light curves typically exhibit an achromatic break followed by a rapid decline. In most cases, the afterglow fades quickly and cannot be seen for more than a few weeks. The afterglow is significantly dimmer than its host galaxy at this stage, and correspondingly, the light curve shows a plateau behaviour [12]. The afterglow's light curve provides a fascinating chance to measure the jet opening angle that is located beneath the GRB [73]. These three bands—X-ray, optical, and radio—display characteristics of power-law decay. Not every burst has all three afterglow types visible [77]. The discovery of their afterglows has significantly increased the prospects for comprehending the physics of GRBs.

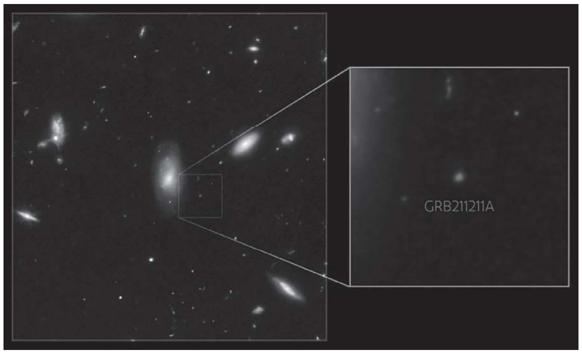

Figure 2: An image of near IR afterglow of a kilonova created by an LGRB (GRB 211211A). (Credit: International Gemini Observatory/NOIRLab/ NSF/AURA/M. Zamani; NASA/ESA)

Figure 2 shows a view from Gemini North placed on a Hubble Space Telescope image, revealing the distinctive near IR afterglow of a kilonova created by an LGRB (GRB 211211A). This finding contradicts the widely held belief that LGRBs originate only from supernovae, which are enormous stars' last explosions. In GRBs, the prompt/afterglow emission is identified as radiation produced by the launch of an ultra-relativistic jet from a freshly formed compact object. The ejecta is initially dissipated internally. In the later stage, the ejecta undergoes external dissipation caused by interactions with the surrounding medium. The two different dissipation processes occur at different typical distances from the central engine (R $\sim 10^{13-14}$ cm and R $\sim 10^{15-20}$ cm) and identified as the prompt and afterglow emission, respectively [79]. The visibility of these radiations can be seen several days after the actual GRB. Hydrodynamics of the associated shock are often impacted by this radiation process, which may be radiative in the early stages while wasting a substantial amount of kinetic energy [80]. The radiation process becomes less efficient with time, and an adiabatic phase begins. In this phase, the losses due to radiation become less, and the hydrodynamics of the system do not even get affected. In some long-range bursts, the afterglow begins to form while internal shocks are occurring inside, and the initial part of the afterglow gets merged with the remaining parts. There is a transition within the GRB from a harder, inner core to a softer, smoother signal. These transitions in GRB afterglow have been noticed in several recent observations.

During a long-lived afterglow phase, strong emission can be seen at longer wavelengths, e.g., X-ray, optical, and radio. These emissions can be described with the help of synchrotron emission, which is produced by accelerated electrons when a magnetic field is present. This afterglow phase carries lots of essential facts and figures to describe the different energetics, structure, and density profiles of GRB. Based on the different types of radiation generated in the afterglow, these radiations produce various types of afterglows, as described in the following section.

**X-Ray afterglow**: This one is the first and shortest afterglow. Sometimes, it starts appearing while the GRB is taking place. Only a small percentage of the GRB's total energy is emitted during an X-ray afterglow. The narrow field instrument on board BeppoSAX started recording GRB 970228's position within light hours of its detection [11]. After the GRB, they observed a translation X-ray source that faded with a power-law slope over time.

**Optical afterglow:** The optical afterglow fades faster and can be observed right after a GRB. The light curves of optical afterglow exhibit either peaks or plateau behaviour. Immediately following the GRB, an optical afterglow is visible. When optical afterglow becomes fainter, its host galaxy and light curves show plateau behaviour depending upon the emission coming from the host galaxy. The earliest detected afterglow from GRB 970228 lasted about half a year and was seen by its optical light curve [81].

**Radio afterglow:** The observation on GRB970508 detected first radio afterglow [75]. The studies related to GRB afterglows in radio range have been an excellent course of action for understanding the afterglows significantly. Due to the radio afterglow emission's delayed growth, some of their curves have peaks that appear far later. This emission lasts longer, for months or even years. Optical afterglow emission spectrum initially rises with respect to frequency, then flattens, and then shows a power law shape declining with time. More or less, 80% of the radio afterglow bursts carry optical afterglow and vice-versa. Radio afterglow can be detected from almost 50% of well-localized bursts.

The GRBs with X-ray afterglow but without optical afterglows are termed ‘‘dark GRB (DGRB)” [82]. The definition of DGRB has been reviewed by adding a time and luminosity limit. They can be observed with the help of the Čerenkov Telescope Array for Galactic supernovae [83]. The nature of DGRBs is still a mystery and a research topic. There are three proposed explanations for DGRBs. First, they are farther away than other GRBs with optical transients. Second, they are nearly identical to other luminous GRBs, except the fact that significant absorption occurs as a result of passing through massive, dusty molecular clouds in their lines of sight. Lastly, the optical afterglow of DGRBs is intrinsically two to three magnitudes fainter than the other GRBs [84].

## 3. Fireball Model

Observation of the non-thermal spectrum suggests it must have emanated from an optically thin region. However, a straightforward estimate based on the number of photons above 500 keV and the source’s size suggests that the source has a substantial optical depth (is optically thick) and should not emit non-thermal radiation. This issue is known as the compactness problem [85]. This problem motivates the development of the relativistic fireball model. Goodman [86] and Paczyanski [87] suggested this model of a relativistic fireball. They have shown that when a significant number of GR photons are abruptly released into a small space, the formation of electron-positron pairs can result in an opaque photon-lepton “fireball”, and in this context, an opaque radiation plasma with an initial energy significantly higher than its rest mass is referred to as a “fireball” [88]. The fireball hypothesis for GRBs is consistent with the afterglow observations in high energy wave bands and with all the prompt emissions. The fireball model is crucial for correctly understanding GRBs and is the most appropriate interpretation. It describes how GRBs and their counterpart’s work. GR’s rapid temporal variability confirms a limited emission region of less than ~100 kilometers [54]. GRBs are so far from being understood that they are associated with some catastrophic star explosive event that leaves behind what is known as a central engine [16]. The central engine consists of a tiny volume of space containing massive energy. A high luminosity indicates a high photon density. The central engine is loaded with photons, electron-positron pairs, and relativistic expanding baryons, causing its central engine to be optically thick. This model illustrates the GRB process at ultra-relativistic energy with baryons and materials having low optical depth. Fundamentally, the inner power source ceases to be transmittable during a GRB event due to the optical thickness and the denseness of the source. The mechanism behind the inner engine is crucial, as it is highly compact, which leads to the prediction of the inner engine as either a BH or a NS. We can differentiate a SGRB from a LGRB based on how the mechanism of the source is operating. This cosmological entity showed that they occur with a long-lasting afterglow related to energetic events that take place at the end stage of the evolution of giant objects with masses about ten times the solar mass, because of which the internal-external shock model comes into play. Inner shocks are the process by which GRs are produced, which have high intensity. Shocks from the inside begin to radiate shortly after the first emission at high relativistic speeds (v/c ~0.99994) [89]. Due to the dynamic nature of fireballs, compact sources emit different shock waves at different speeds, and interaction between them results in highly energetic GRs. Internal shocks, which move at relativistic speed, convert kinetic energy into GR photons. Synchrotron emission and inverse Compton effect generation may be seen [90]. Early models claimed that interior shocks and fireballs were only radiative but could not be able to explain clearly the whole emission mechanism [88]. A small amount of baryonic mass was introduced to tackle the problem. The increase in the extra mass makes shocks coming from inside much more powerful, and some radiation energy converts into kinetic energy, which aids in giving the relativistic kinetic energy of the shock waves more push, ultimately leading to an increase in overall energy [91]. As the shell becomes optically thin after expansion and cooling of an optically thick fireball shell, it allows GR photons to escape through the inverse Compton effect, slowing the shock front and increasing the number of shock interactions with each other. External shock waves were utilized instead of internal shock waves to explain the wavelengths observed in the initial BeppoSAX afterglow observation in 1997 [92]. The range of wavelength lies from X-ray (soft) to radio. Shock waves interact with the interstellar Medium (ISM), especially molecular clouds (dust or gas), after emitting from the source, which results in the afterglow. The external shocks are mainly thermal emissions. The energy from shocks travels to the ISM, where materials are trapped before radiative emission occurs. Because of this capture, the results of the long afterglow can show us all parts of the energy spectrum. Even if we consider all GRBs to have external shocks, almost 50% of the afterglow is not detectable due to scattering, absorption, and reddening in the environment of optically thick molecular clouds. Many results regarding model predictions demonstrate that the model naturally supports X-ray and optical observations of GRBs in sources like GRB970228 and GRB 970402 [93].

## 4. Accretion Model

The generation of GRBs involves several models; the accretion model is one of them. In the accretion model, a massive object, such as a BH or a NS, is surrounded by a disk (~ 0.1 $M_0$) of gas and dust (called an accretion disk) [94]. This could include mergers of NS-NS binaries, NS-BH binaries, White Dwarf (WD)-BH binaries, BH-He-star binaries, and models based on "failed supernovae" or "Collapsars" [94]. As the gas and dust in the disk spiral inward towards the central object, they gain gravitational potential energy. This energy is then released as kinetic energy and radiation, some of which are GRs. About a fraction of a solar mass per second is the mass accretion rate for a common GRB model [95].

Two main types of accretion disks are thought to be involved in GRBs:

**Neutrino-dominated accretion flows (NDAFs):** A neutrino-dominated accretion flow (NDAF) will form for a smaller and denser accretion disk, in which most of the mass will reach the core by neutrino cooling. This category includes models that can produce powerful GRBs like mergers of BH-NS binaries and double NS binaries [96].

**Convection-dominated accretion flows (CDAFs):** Compared to NDAFs, here, the disks are denser and hotter, and convection is the primary energy loss mechanism. LGRBs are hypothesized to be connected to CDAFs. In the case where the accretion disk is larger than a few tens or hundreds of Schwarzschild radius, the accretion will occur through CDAF [95]. In CDAFs, instead of going into the central BH, a large portion of the mass escapes the system [97,96,98,99].

Models involving the mergers of BH-WD binaries and BH-He-star binaries belong to this category. Since very little mass reaches the BH, GRBs are unlikely to be produced in this type of accretion [95].

The specific details of how the accretion disk interacts with the central engine and produces the GRB still need to be better understood. However, it is thought that the release of energy from the disk can make powerful jets of matter and radiation that are collimated by the surrounding material. These jets are then thought to be responsible for the observed GR emission. The relativistic (but not as relativistic as in GRBs) jets in AGNs, propelled by accretion onto BHs, are consistent with this model [94].

## 5. Pulsar Model

Scientists detected several binary systems and pulsars in the X-ray and radio regions from which extremely high-energy GRB occurs in pulsed form [100]. Based on this, they have proposed a new Pulsar model. Earlier, several models had been developed to explain the less energetic X-ray emission from pulsars, where GRB occurred far away from NSs [101,102], but they failed to explain the high energy range when emission from Cyg X-3 was surveyed for curvature radiation from accelerated electrons, which comprises open magnetic field lines.

When acceleration mechanisms are observed in this model, charged particles acquire high energy, even if a fraction of the potential is applied. Since it is investigated near the pole, the trajectory of charged particles follows the magnetic field lines very closely at a highly relativistic speed. We get pulsed emission because the magnetic moment is not aligned with the rotation axis. In this model, for the acceleration mechanism to occur, charged particles are provided by the neutron star's surface. Conduction electrons with zero work function can be seen at the surface [103,104,105,106,107]. For an intense surface magnetic field, the work function value of the conduction electron increases.

In the case of young radio pulsars, accretion occurs from nebulae present in their surroundings and for X-ray binaries from the companion object. Still, accretion does not occur for isolated old radio pulsars, because of which the precession of NSs ceases. That's why candidates that are not similar need to be detected through this model, which has extremely high energetic photons.

Pair production also occurs where attenuation of extremely high-energy photons can be seen, and Erber [108] found out the coefficient of attenuation at a magnetic field by assuming that the electric field (E) = 0, but later, inconsistency with this assumption was raised for most of the pulsar magnetosphere as maximum photon energy had been tried to estimate. So, the consistency of this model must be checked since attenuation of GR photons through pair production occurs. The cyclotronic effect comes into play if the energy of photons is much more than the threshold energy. As a result, curvature GR emission is not much attenuated in this pulsar model when comparisons of observational data have been made for Vela X-1, LMCX-4, 4U 0115 + 63, Hercules X-1, Vela Pulsar, etc [100].

## 6. Recent Discoveries

Starting with BeppoSAX, some active missions and observations left their footprints on the science community. The research findings related to GRBs and their relating discoveries with the help of dedicated GR missions are mentioned below. After collecting data on SGRB in 2005 at Brera Astronomical Observatory, National Institute of Astrophysics (INAF) analyzed and published about the coalescence of NS and a BH, which results in an explosive GRB event termed as a kilonova or macronova because of which the decay of heavy elements in a radioactive manner starts and we get high-intensity GRs [109]. Swift and NASA's Fermi Gamma-ray Space Telescope began searching for GRBs together in 2008; today, roughly 3,500 have been seen. Its GBM and LAT allow the detection and tracking of bursts ranging from X-rays to the highest-energy GRs ever recorded in space. Consequently, it has been observed that GR afterglows possess billions of times the energy of visible light[1]. From 2008 to 2018, Fermi-GBM was turned on for transient events around twice a day; 2356 of these events have been identified as cosmic GRBs [110]. The long GRB 211211A resulting from a binary merger, the optical flare from

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[1] https://www.nasa.gov/universe/nasa-looks-back-at-50-years-of-gamma-ray-burst-science/

GRB 210204A, the extremely weak optical afterglow of GRB 200412B, the counterpart of the very-high-energy (VHE) burst GRB 201015A in optical range, and the near-IR counterpart were all detected using the Devasthal Optical Telescope in India [111]. In September 2021, Neil Gehrels Swift Observatory of NASA spotted a GRB event of about 12.8 billion years in the early universe of object GRB210905A, which appeared as an orange dot, as confirmed by the X-shooter spectrograph of ESO's VLT in Chile [112]. Astronomers ruled out the likelihood that the signal originated from a magnetar, a giant star's extremely compact dead core with enormous magnetic energy, based on this occurrence since the object's energy was too much for a typical magnetar. Announcement of the finding of the incredibly fantastic long-duration GRB, GRB 221009A, detected by the Neutron Star Interior Composition Explorer (NICER) mission, Monitor of All-sky X-ray Image (MAXI), and Neil Gehrels Swift Observatory (Swift). Although the location of the intense GRB was very nearby with a redshift of 0.151, it was possible to see the afterglow for an extended period. This object is a potent probe of Milky Way dust due to its high X-ray brightness and low Galactic latitude [113].

The advancement in the facilities of detectors working in a broad range of electromagnetic radiation and non-electromagnetic detectors has led to an era of multi-messenger astronomy. The application of multi-messenger astronomy has helped in answering fundamental questions of astrophysics. One such event is the detection of GRB 170817A [114] coupled with gravitational wave source GW170817 [115], which was the first such event in which gravitational and electromagnetic waves from a single source were observed [116]. The gravitational wave was associated with the merger of binary NSs [115,26,114]. The observation of the GR was a prompt SGRB [116,26,115]. Hence, the long-standing hypothesis of SGRB progenitor was answered by the merger of binary neutron stars [115,117,118]. The presence of heavy elements like gold, platinum, and uranium provided evidence of the origin of heavy elements [120]. The delay between X-rays and their radio counterpart provided information about the binary environment. These are some questions answered by this astonishing event. With the answers, many new questions were also raised, such as the question of the diversity of progenitors in SGRBs like the merger of NS and BH, and the counterparts produced after this event posed challenges to existing models of GRB emission, which is an open area of research. This event provided the importance of multi-messenger activity in order to understand and study binary mergers and gain insight into GRB physics. The field of gravitational waves provides a better opportunity to elucidate GRBs like its detection can give evidence of a merger, which helps in probing the progenitors of GRBs in understanding the environment and conditions related to GRBs, thus helping to formulate theoretical models to test and understand GRB physics. It also provides insight into the dynamics of relativistic jets, such as the interaction between the ejected materials and their vicinity. In the future, such multi-messenger events will give more insight into GRB physics with better detectors with good temporal and spectral properties.

## 7. Conclusion

An astonishing amount of energy is emitted as GRs during a GRB event. Even after decades of research, many features of GRBs are still mysterious, including their exact origin and the mechanics driving their enormous energy release. GRBs help study the early universe as they have high energy and immense brightness, which provides a window to observe galaxies and extreme environments. The latest findings of the present telescopes operating in the very high energy range have unveiled a novel avenue for seeing GRBs inside the EM spectrum. A high-energy component, like an afterglow component in TeV energy range, has been definitively established, and investigations on the presently accessible data sets have showcased the capacity of these detections to explore many unresolved inquiries within the discipline of GRBs. The study of afterglow has provided important information about the environment and the properties of the progenitors. When we consider utilizing high-redshift cosmic universe exploration tools, it is crucial to underscore the necessity of conducting meticulous and precise spectroscopic afterglow observations with sensitivity and mid- or high-level resolution capabilities. These data are useful for measuring the attenuation due to intervening material and for validating the redshift. Such observations are necessary for the full potential of these tools as cosmic probes to be explored. High-quality afterglow spectra of GRBs in the southern hemisphere have been extensively obtained in recent years using the VLT’s mid-resolution long region X-shooter spectrograph [121]. On the other hand, mid-to high-resolution optical spectrum coverage for GRBs in the northern hemisphere has been less accessible in the last several years [122]. The recently launched James Webb Space Telescope (JWST), the European Southern Observatory's planned Extremely Large Telescope, and other large-scale telescopes will provide a rare chance to investigate many afterglows in the high redshift universe using the fireball model prediction for GRBs [123]. Using a gamma-ray spectrometer, the forthcoming ISRO's 'Daksha' mission will look for and analyse GRBs in the hard X-ray and GR wavelength ranges. With polarization investigations, timely soft spectroscopy, and precise time-resolved spectrum studies, Daksha can make significant progress in GRB research [124]. The Space-based Multi-Band Astronomical Variable Object Monitor (SVOM) is another upcoming Chinese-French satellite project. GRB detection and research in the far ultraviolet and soft X-ray wavelength ranges are the main objectives of SVOM. The prompt energy coverage is extended to 5 MeV by the onboard Gamma-Ray Monitor (GRM). Following the slew, two more onboard instruments, the VT (visible telescope) and the MXT (multi-pore optics X-ray Telescope), examine the GRB afterglow and improve the GRB location. SVOM is the focus of two different kinds of ground-based telescopes. The Ground Follow-up Telescopes, or GFTs, are equipped with photometric redshift, autonomous repointing to GRB alarms, and improved localization capabilities [125]. SVOM and Daksha should substantially improve our knowledge of GRBs and their effects on the cosmos. The research of GRBs has come a long way, yet there are still challenges to overcome and issues to be explained, such as the exact mechanisms relating to the enormous release of energy, the central engine's nature, and the heterogeneity in GRB populations. These are some areas of ongoing research. GRBs will continue to be a highly significant domain of research in astronomy as they inspire us to increase our understanding of the universe's most energetic and mysterious phenomena, their significance in advancing our understanding of fundamental physics, and their potential as probes of distant cosmic history.

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Devi handled the extensive literatre study and the gathering and arrangement of the information; Biplob Sarkar chose the subject and oversaw the project. The manuscript was reviewed by all authors.

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