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The Energetic Universe: An All-purpose Investigation of Gamma-Ray Bursts as Universe Probes

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Abstract

GRBs are the brightest electromagnetic phenomena that have ever been witnessed in the universe as a result of the bursting of gigantic energy within several seconds to several minutes. This review presents existing knowledge of GRB phenomenology, physics, and their application to the high-redshift universe. We describe the following bimodular classification between long and short bursts, which we associate with collapsars and compact binary mergers respectively. The paper discusses the conventional fireball model, relativistic jet contribution and multi wavelength afterglow phenomenon. More importantly, we evaluate the usefulness of GRBs in the study of cosmic star formation rates, the interstellar and intergalactic medium, and as a cosmological distance scale. The new data gathered with the help of such observatories as Fermi-GBM, Swift, and complex gravitational-wave detectors are combined to create a current and harmonious image. The conclusions also indicate the questions and the future on the next-generation observatories.

Keywords: Gravitational Waves; High-Energy Astrophysics; Multi-Messenger Astronomy; Star Formation; Gamma-Ray Bursts

1. Introduction

GRBs are short sharp bursts of Gamma-rays that were accidentally discovered by the Vela satellites in the late 1960s [1]. Their isotropic sky distribution meant at once that they had a cosmological origin, which was followed up by the observation of afterglows and redshift measurements in the 1990s. GRBs are astronomical phenomena, the isotropic equivalent energies of which go as high as 10^{54} erg, which is visible even in the observed universe [2]. They are also observed to be of two types: long GRBs (LGRBs, >2 s), and short GRBs (SGRBs, <2 s) with different progenitor systems [3]. LGRBs are related to the collapse of massive and spin-spinning stars (collapsars), and SGRBs are related to the collision of binary neutron stars or a neutron star and a black hole. The observation of GRB 170817A in 2017, as it coincided with the GW170817A gravitational-wave signal of a binary neutron star merger, gave irrefutable evidence of the parent of at least one type of SGRBs [4]. The purpose of this review is to summarize the conventional theoretical paradigms, provide essential observational data of the last 10 years, and comment upon the new application of GRBs as multi-messengers and cosmological instruments.

2. Methodology/Theoretical Framework

The present research paper has its foundation in the review of recent (2020–present) peer-reviewed publications, mission data archives (e.g., Swift BAT/XRT/UVOT, Fermi-GBM/LAT), and theoretical models. The case study is on the Standard Fireball and Afterglow Model.

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2.1. The Fireball Model

The black hole (accreting or magnetar) core emits an ultra-relativistic jet (Lorentz factor $\Gamma \sim 100 - 1000$). The instantaneous gamma-ray emission is due to internal shocks in the jet due to the differences in velocity [5].

2.2. Afterglow Physics

The jet in turn converts to a circumburst medium and causes a forward shock which radiates days-years later across the electromagnetic continuum (X-ray to radio) known as the afterglow. A back shock can result in the early optical flashes [6].

2.3. Progenitor Channels

- LGRBs: Busiest star cores-collapse in toto (low-metallicity) Star cores-collapse (solar metallicity progenitors).
- SGRBs: Major mergers of compact binaries (BNS or NS-BH), which have been observed by multi-messenger.

Cosmological Utility Cosmological Utility GRB afterglows can be used as backlights to investigate the population of host galaxies and the intergalactic medium (IGM) in terms of metallicity and dust content using absorption spectroscopy. Empirical relations (e.g. Amati, Yonetoku relations) between spectral properties and energy are studied with the possible use as standardizable candles [7].

3. Results and Observational Data

3.1. Statistical Properties

Fermi and Swift catalogs have been analyzed revealing the bimodal distribution during the period of duration (Fig. 1). Swift has identified more than 1500 GRBs and has measured redshifts of a good fraction of them, extending the limit to $z > 9$ [8].

3.2. Multi-Wavelength Afterglows

Swift XRT data transformed afterglow science. A canonical X-ray light curve typically exhibits a rapid decay (tail of prompt emission), a plateau (which could be because of continuing energy injection), and a final plateau power-law decay (forward shock) as shown in (Fig. 2) [9].

3.3. Host Galaxy Studies

LGRBs are available in the faint, irregular, and low-metallicity dwarf galaxies having a high rate of star-formation. SGRB hosts are less homogenous in the sense that they include early and late-type galaxies, which is to be expected given a late merger timescale [10].

3.4. Multi-Messenger Detection

Direct evidence of an SGRB progenitor, kilonova ejecta and verification of the relationship with r-process nucleosynthesis was discovered with the landmark event GW170817/GRB 170817A [4].

4. Discussion

4.1. Unifying the Picture

The collapsar and merger models are able to explain the gross differences in the observations between long and short GRBs (Table 1). Nevertheless, there are still problems that, among them, is the origin of ultra-long GRBs ($>10,000$ s) and the exact nature of the central engine (magnetically dominated vs. neutrino-driven).

4.2. GRBs as Cosmic Tools

- Star Formation Tracers LGRBs are connected to very large stars, which may be useful in tracing the cosmic star-formation rate, particularly in high- z where other techniques are ineffective. Their preference towards the low-metallicity environments, however, needs to be corrected carefully [11].
- Probing the IGM: GRB afterglow spectra at high- z will be pure sightlines to learn about the ionization history and metal-enrichment of the IGM.

- Cosmology: GRBs have the potential to constrain the high-z ($z \gtrsim 5$) expansion history of the universe in addition to Type Ia supernovae and the CMB [12].

4.3. Open Questions and Future Directions:

The questions to be answered here are the specifics of the process of accelerating the particle and radiation in the shocks (the GRB problem), the source of very-high-energy (TeV) photons detected by MAGIC and H.E.S.S., and the search of a neutrino analog. These will be dealt with by future facilities such as the SVOM satellite, the Einstein Telescope and the Lynx X-ray observatory [13].

4.4. Tables and Figures

Table 1 The main Observational Properties of Long and Short GRBs

Property	Long GRBs (LGRBs)	Short GRBs (SGRBs)
Duration (T_{90})	> 2 seconds	< 2 seconds
Progenitor	Collapsar (Massive Star Core-Collapse)	Compact Binary Merger (NS-NS, NS-BH)
Host Galaxy	Irregular, star-forming, low-metallicity dwarfs	Elliptical & Spiral, broader distribution
Energetics	Generally more energetic ($E_{iso} \sim 10^{53}-10^{54}$ erg)	Generally less energetic ($E_{iso} \sim 10^{49}-10^{52}$ erg)
Associated Emission	Type Ic-BL Supernovae (e.g., SN 1998bw)	Kilonova/Macronova (e.g., AT 2017gfo)
Redshift Distribution	High (median $z \sim 2-3$), up to $z > 9$	Lower (median $z \sim 0.5-1$)

Table 2 Significant Updating GRB Detection Missions

Mission/Instrument	Primary Band	Key Role	Launch
Swift (BAT/XRT/UVOT)	γ -ray, X-ray, Opt/UV	Rapid localization & multi-wavelength afterglow data	2004
Fermi (GBM/LAT)	γ -ray, GeV-TeV	Broad spectral coverage, high-energy emission	2008
INTEGRAL	γ -ray	Fine spectroscopy & localization	2002
LIGO/Virgo/KAGRA	Gravitational Waves	Multi-messenger detection of SGRB progenitors	2015+

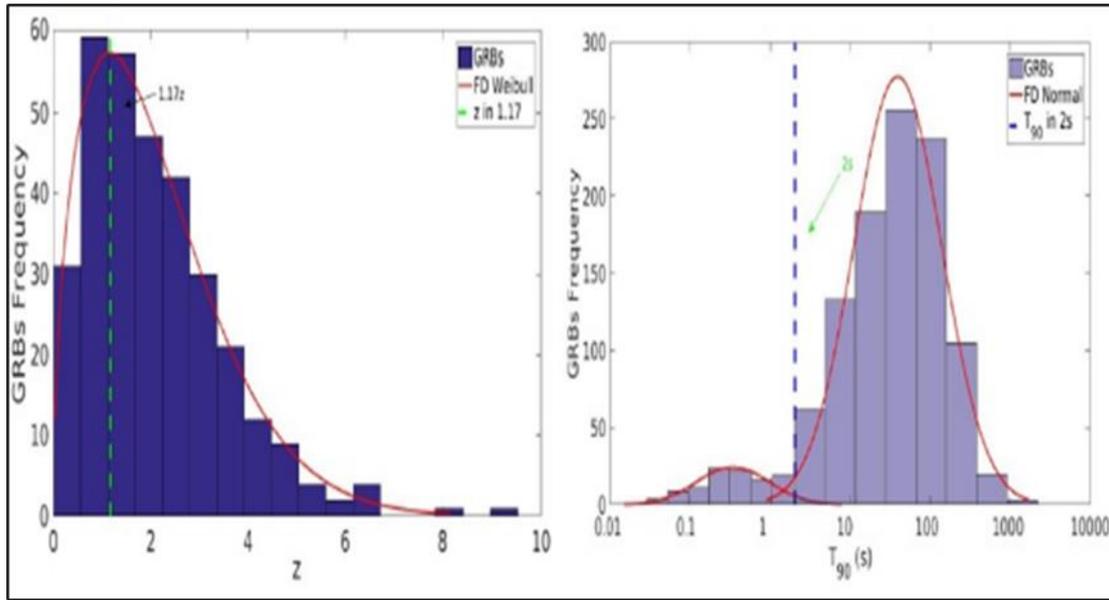


Figure 1 Schematic Bimodal Distribution of GRB Durations (T_{90})

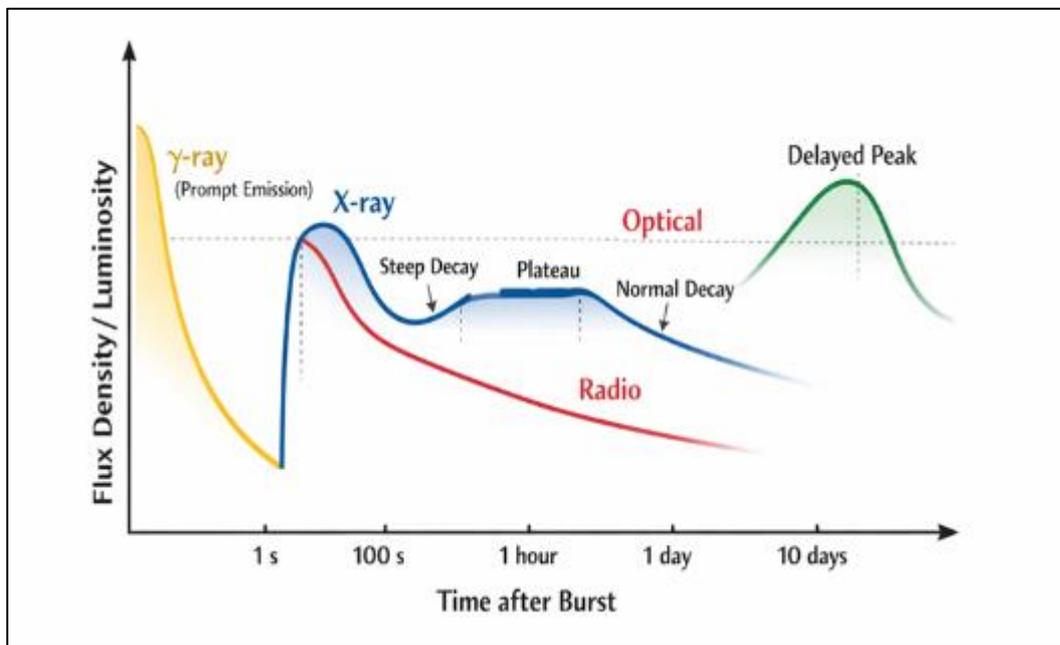


Figure 2 Multi-Wavelength Afterglow of a GRB (Light curves)

(A log-log plot would display overlays of light curves of γ -ray, X-ray, optical, and radio, in rapid decay, plateau and late-time power-law decay phases)

5. Conclusion

The Gamma-Ray Bursts have now become more than a mystery flash to become a potent cosmic flare. The combination of space-based and ground-based gravitational-wave detectors has opened the multi-messenger astronomy era which has cemented our knowledge on the progenitors of these phenomena. Though the standard fireball model is a very strong framework, new findings in very-high-energy emission and population features are still challenging and raising finer details in the theory. None of them can have a greater utility than as the probes of the far away universe, the demise of the giant stars and the nucleosynthesis of the heavy elements. The forthcoming missions and a synchronized

observation throughout the electromagnetic spectrum and beyond are likely to solve the remaining puzzles regarding the central engine, the composition of jets, and their eventual contribution to unfolding the history of the expansion and chemical development of the universe.

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