

Analysis of the Main Principles and Methods of Gamma-Ray Burst Observation

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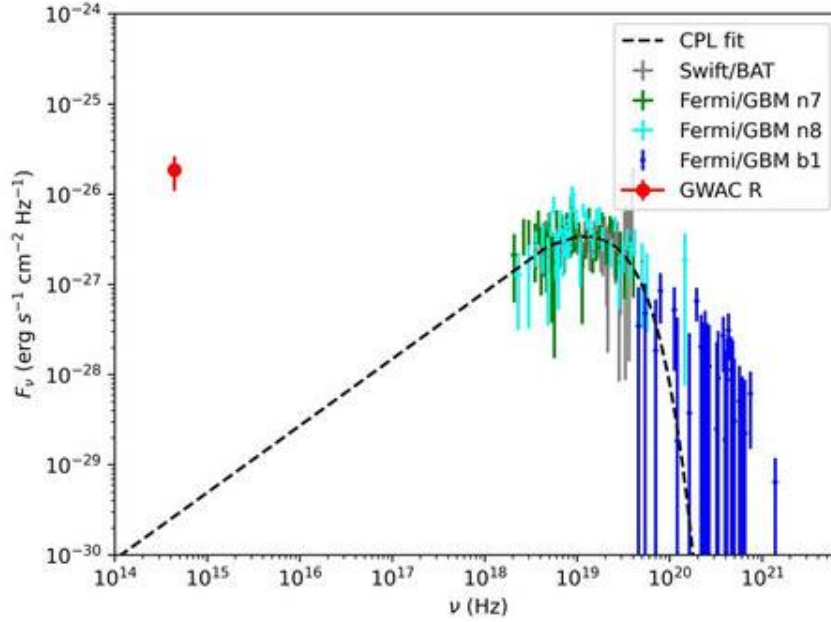
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Abstract: Gamma-ray bursts (GRBs) are extreme high-energy phenomena in the Universe, characterized by the sudden enhancement of gamma-ray originating from deep space within a very short period. The study of GRBs is important for understanding the extreme physical laws of the Universe, the formation and evolution of dense objects, and the limitation of cosmological parameters. Observations cover both instantaneous and afterglow radiation, with the former focusing on high energy, short time scales, and irregular light variations, which require high sensitivity and fast response of the equipment, and the latter focusing on long-term monitoring of multi-band radiation, which provides key information for understanding the physical mechanisms. Multi-messenger observational techniques such as LIGO, Virgo Gravitational Wave Detector and IceCube Neutrino Detector have enriched GRB studies by directly detecting spacetime perturbations and neutrino signals. In the future, with the development of new observational devices such as ET, CE, JWST, and eXTP, GRB research will play a more critical role in astronomy and cosmology to explore extreme physical processes, study the early structure and evolution of the universe, and test the fundamental physical principles.

1. Introduction

Gamma-ray bursts (GRBs) are extremely high energy phenomena in the Universe, which are characterized by a sudden enhancement of gamma-ray originating from deep space in a very short time (see Figure 1), involving complex processes such as relativistic jets, particle acceleration under extreme physical conditions, and the release of huge amounts of energy [1]. The study of GRBs is important for understanding the extreme physical laws of the universe, the formation and evolution of dense objects, and the limitation of cosmological parameters [2]. With the advancement of observation technology, from the precise positioning and multi-band afterglow observation by Swift satellite to the high-energy radiation detection by Fermi satellite to the joint LIGO/Virgo observation of binary neutron star merger events and their electromagnetic counterparts, all of them have pushed forward the deeper study of GRBs. As one of the few detectable multi-messenger objects, GRB observation data are essential for realizing joint observation and cross-validation in multi-messenger astronomy. As one of the few detectable multi-messenger objects, its observation data play an irreplaceable role in realizing joint observation and cross-validation in multi-messenger astronomy. They are of great significance in promoting the further development of astronomy and cosmology.



(Image source: https://nao.cas.cn/news/ky/202304/t20230427_6746887.html)

Figure 1. Transient gamma radiation from GRB 201223A

2. Origin and classification of gamma-ray bursts

2.1 Theories of the origin of gamma-ray bursts (GRBs)

Theories of the origin of gamma-ray bursts (GRBs) mainly include the collapse theory of massive stars and the merger theory of double-dense stars (neutron stars and black holes).

This theory is directly supported by the observations of the association of GRB 980425 with the supernova SN 1998bw. The theory of binary dense star mergers explains the origin of short bursts when two neutron stars or neutron stars merge with a black hole, they release huge gravitational wave energy and accompanying gamma-ray radiation, GW170817 and its electromagnetic counterpart GRB170817A provide conclusive evidence for this theory, and for the first time, the phenomenon of a kilonova after the merger has been directly observed. There are also other origin theories, such as primordial black hole evaporation and cosmic string breakage, which have not yet become mainstream, but provide new perspectives for understanding the diversity of gamma-ray bursts. With the continuous progress of observation technology, it is expected that more mysteries of the origin of gamma-ray bursts will be revealed, and the existing theoretical system will be improved.

2.2 Classification of gamma-ray bursts

Gamma-ray bursts (GRBs) are categorized into Long GRBs (> 2 s) and Short GRBs (< 2 s) depending on the value of their duration (see Table 1). Long storms are usually associated with collapse events of massive stars, as shown by the observation of GRB 980425 in association with the supernova SN 1998bw, which collapsed to form black holes or neutron stars after the failure of fusion in the core iron nuclei, accompanied by relativistic jets and intense gamma-ray emission. Short bursts, on the other hand, originate mainly from binary dense star (neutron star-neutron star or neutron star-black hole) mergers, as evidenced by the gravitational wave event GW170817 and its electromagnetic counterpart GRB 170817A, a process that releases large amounts of gravitational

wave energy and gamma-ray radiation, and which has led to the first direct observation of kilonova phenomena. Gamma-ray bursts are also categorized based on spectral properties, such as the superposition of thermal and non-thermal components and the emergence of additional power-law spectral components, and these categorizations, combined with specific observational examples, provide a rich perspective for a deeper understanding of the physical mechanism and origin of GRBs [3].

Table 1. Main types of GRBs and their characteristics

GRB type	Duration	Main causes	Concomitant phenomenon
Longmire	$T_{90} > 2$ seconds	Massive star core collapse	X-ray and optical afterglow
Short burst	$T_{90} < 2$ seconds	Dense object mergers (neutron stars or black holes)	Possibly accompanied by gravitational wave signals

3. Main principles of gamma-ray burst observations

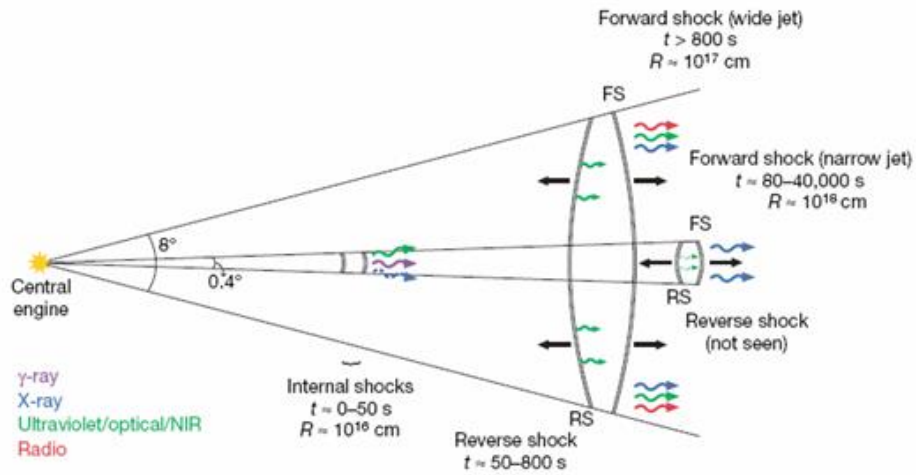
3.1 Principles of transient radiation in gamma-ray bursts

The transient radiation mechanism of gamma-ray bursts (GRBs) is a cutting-edge research area in astrophysics that centers on relativistic jets and energy dissipation. Relativistic jets are ejected from a central engine (e.g., a nascent black hole or neutron star) at speeds close to the speed of light, with Lorentz factors of hundreds or more. During the expansion of the jet, internal matter interactions lead to energy dissipation, producing intense gamma-ray radiation. The energy dissipation mechanisms include internal excitations, which involve collisions between shells of material with different velocities in the jet, and magnetic reconnection, which emphasizes the role of strong magnetic fields. The spectral properties of the transient radiation are complex, usually exhibiting a segmented power-law spectrum (Band spectrum) and the presence of thermal and additional power-law spectral components [4]. For example, a significant superposition of thermal and extra power-law spectral components is observed in the transient radiation of GRB 090902B, which provides a new perspective to understanding the radiation mechanism of GRBs. By combining multi-band observational data and theoretical models, scientists are gradually revealing the mysteries of the transient radiation of GRBs.

3.2 Key elements of system construction

Afterglow radiation from gamma-ray bursts (GRBs), observed in the X-ray, optical, and radio bands from hours to years after the bursts, is critical to the understanding of GRB physical processes. The afterglow radiation is based on the external excitation model, in which relativistic jets interact with the external medium to form excitations that accelerate electrons and produce synchrotron radiation. The X-ray afterglow light curve exhibits multiple phases, such as rapid decay, plateau radiation, and stochastic flares, which may be related to the activity of the central engine. The optical afterglow provides information on the redshift of the GRB, jet parameters, and environmental information, such as the kilonova component observed in GRB 130603B, offering clues to binary neutron star merger events. The long duration of the radio afterglow is important for studying the long-term interaction of the jet with the external medium, while the GRB 080319B radio afterglow reveals the lateral expansion and deceleration of the jet (see Figure 2). The spectral properties of the afterglow radiation are power-law spectra with slopes that evolve with time, reflecting surge-accelerated electron cooling and environmental changes. Multi-band observations and spectral analysis enable scientists to infer the physical parameters of the jet and the nature of

the surrounding environment, providing new perspectives for exploring extreme physical phenomena in the universe.



(Image source: <https://pmo.cas.cn/kycg2019/sdtwkjjz2019/202006>)

Figure 2. Schematic of the "two-component jet" model of the gamma storm GRB 080319B.

3.3 Multi-messenger observation principle of Gamma-Ray Bursts (GRBs)

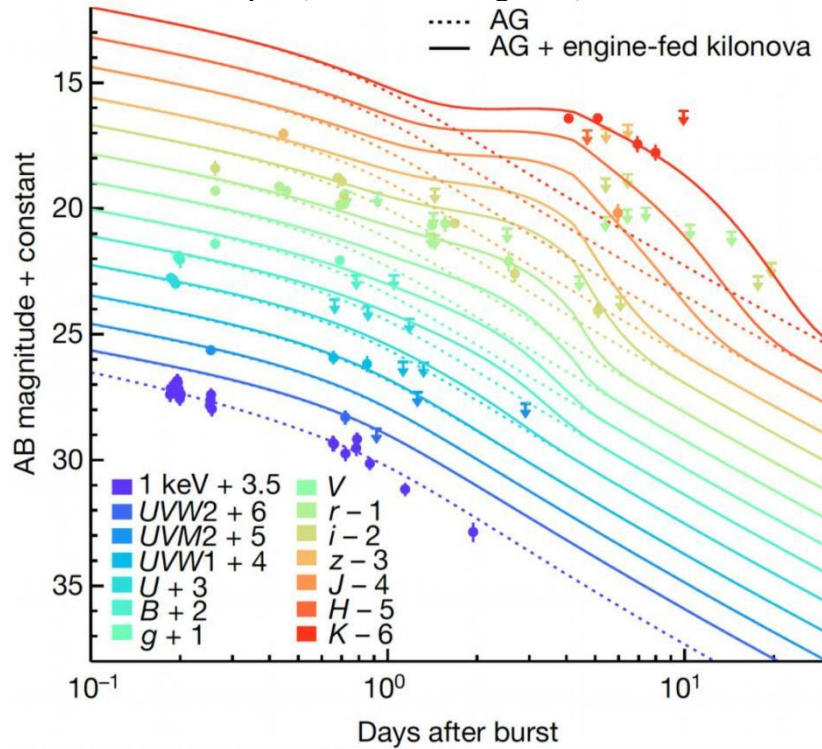
The Multi-messenger observation principle of GRBs, which integrates observations of gravitational waves, electromagnetic waves, neutrinos, and high-energy cosmic rays, provides an all-encompassing perspective for a deeper understanding of the physical mechanism of GRBs. Joint observations of gravitational and electromagnetic waves, such as GW170817 and its electromagnetic counterpart GRB 170817A, have directly verified GRB as the electromagnetic counterpart of the gravitational wave source and revealed the interactions between the physical processes of GRB and its surrounding environment. Although neutrinos are difficult to detect, their production and propagation in the GRB carries key information about the internal physics of the GRB, and the attempts of the IceCube Neutrino Observatory have opened up new avenues for understanding the high-energy physical processes of the GRB. Observations of high-energy cosmic rays, especially those exceeding 10^{18} eV, which are associated with relativistic jet-accelerated particles in GRBs, can help to shed light on the particle acceleration mechanism of GRBs. Combining the multi-messenger observations, scientists can have a more comprehensive understanding of the physical mechanisms of GRBs, jet properties, and their interactions with the surrounding environment, providing new perspectives and opportunities for exploration of GRB and extreme physical phenomena in the universe.

4. Main methods of gamma-ray burst observation

4.1 Satellite observation methods

Satellite observation is the core means of gamma-ray burst (GRB) research, and the application of high-energy gamma-ray satellites (e.g., Fermi satellites) and multi-band observation satellites (e.g., Swift satellites) is especially critical [5]. Fermi satellites, with their Large Area Telescope (LAT) and Gamma-Ray Burst Monitor (GBM), can precisely measure the high-energy radiation of GRBs, including transient radiation and long time afterglow, which can provide important data for revealing the physical mechanism of GRBs, while Swift satellites are equipped with X-ray Telescopes (XRTs), Ultraviolet/Optical Telescopes (UVOTs), and Gamma-Ray Burst Alert

Systems (BATs), which can precisely measure GRBs from the gamma-ray bursts. The Swift satellites are equipped with an X-ray telescope (XRT), a UVOT (UVOT), and a gamma-ray burst alert system (BAT), which provide comprehensive coverage of the GRB from the gamma-ray to the optical bands, and a rapid response capability that enables them to capture the early evolution of the GRB and provide clues to understanding the radiative properties of the GRB and its surrounding environment. Although satellite observations can provide long-time, continuous, and highly sensitive monitoring, they are limited by orbit, observation angle, and energy range, and the satellite design needs to be optimized in the future to improve the observation efficiency and sensitivity, to explore the mysteries of GRBs in depth.(As shown in figure 3)



(Image source: https://www.thepaper.cn/newsDetail_forward_21081257)

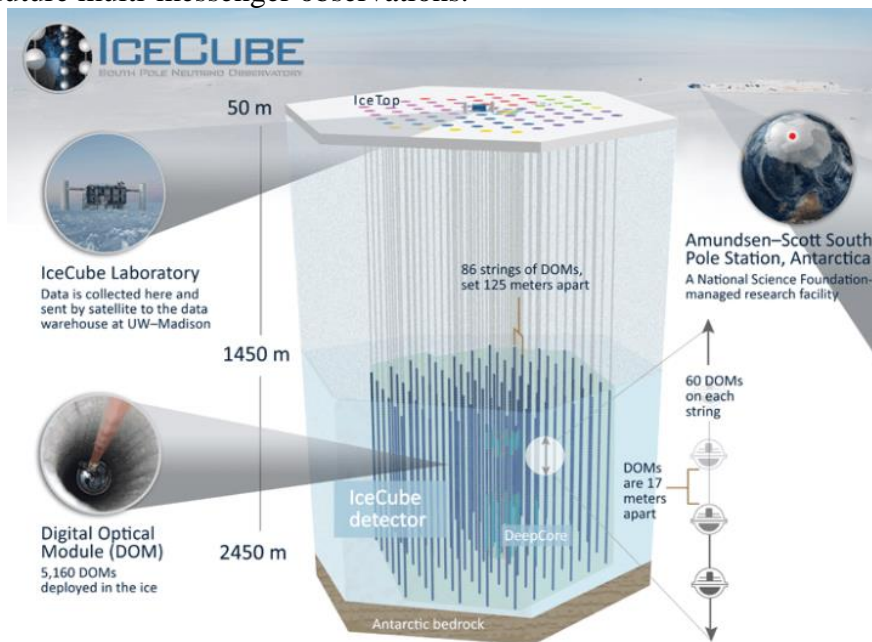
Figure 3. Multi-band observations of GRB 211211A and its model fit

4.2 Ground-based telescope observation methods

Ground-based telescopes, especially optical and radio telescopes, occupy an important position in gamma-ray burst (GRB) observations. Optical telescopes capture the light curves of GRB afterglows with high precision to reveal the outburst mechanism, jet structure, and surrounding environment, e.g., the Keck telescope and the Very Large Telescope (VLT) have successfully observed several GRB optical afterglows [6]. Radio telescopes, on the other hand, track long-term GRB afterglows, lasting from days to months, to reveal the evolution of the afterglow on larger spatial scales and the interaction of the jet stream with the environment, with the Very Large Array (VLA) and the Australian Telescope Tight Array (ATCA) providing key data for this purpose. Ground-based telescopes have the advantage of high sensitivity and resolution but are limited by atmospheric conditions, observation time, and geographical location. In the future, it is necessary to optimize the design of telescopes, improve the efficiency of observation, and strengthen the synergy with other means of observation to fully reveal the mysteries of GRB.

4.3 Multi-messenger observation techniques

Gravitational wave detectors, such as LIGO and Virgo, utilize high-precision laser interferometry to directly detect spatial and temporal perturbations generated by extreme astrophysical events in the Universe, and measure the tiny length change of a laser beam in a vacuum arm by the principle of Michelson interferometry, thus revealing the existence of gravitational waves [7]. For example, the LIGO/Virgo collaboration successfully detected gravitational wave signals from the GW170817 binary neutron star merger event, opening a new era of multi-messenger astronomy. Detectors are being continuously upgraded to improve detection sensitivity and frequency range, aiming to detect more types of gravitational wave sources. On the other hand, neutrino detectors, such as IceCube, achieve indirect detection of neutrinos by detecting high-energy neutrinos produced by cosmic rays interacting with the Earth's atmosphere and potential astrophysical sources of neutrinos, utilizing Antarctic ice as a detection medium, and deploying thousands of photomultiplier tubes for detecting Cherenkov radiation (see Figure 4). In the gamma-ray burst observation, IceCube adopts a real-time trigger mode to focus on searching for neutrino signals in the direction of the GRB, and although it has not yet directly detected a neutrino event in concert with the GRB, its observation results have already imposed stringent constraints on the process of the GRB hadronic radiation and the neutrino production mechanism, which lays the foundation for future multi-messenger observations.



(Image source: <https://icecube.wisc.edu/news/research/2016/12/>)

Figure 4. IceCube detector

5. Conclusions and outlook

Observations of gamma-ray bursts cover the detection of transient and afterglow radiation and the integrated application of multi-messenger observing techniques. Transient radiation observations focus on high energy, short time scales, and irregular light variations, which require high sensitivity and fast response of the equipment; while afterglow radiation observations focus on the long-term monitoring of multiwavelength radiation, which provides key information for understanding the physical mechanisms. Multi-messenger observation technologies, such as LIGO, Virgo gravitational wave detector, and IceCube neutrino detector, have enriched the understanding

of gamma-ray bursts and their physical origins. In the future, gamma ray burst observations will see the rapid development of new equipment and technologies, such as the Einstein Telescope (ET) and the Cosmic Explorer (CE), which will increase the sensitivity and frequency range of gravitational wave detections, and the James Webb Space Telescope (JWST) and the Explorer of Energetic Transients (eXTP), which will provide unprecedented observational capabilities and resolution. The study of gamma-ray bursts not only explores extreme physical processes, but also serves as an important probe to study the early structure and evolution of the Universe, is of great significance in testing fundamental physical principles, and will play an even more critical role in the fields of astronomy and cosmology with technological advances and theoretical developments.

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