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Gamma ray bursts and their afterglows

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Abstract

Gamma-Ray Bursts (GRBs) were among the greatest mysteries in modern astrophysics. They were first observed 50 years ago but it took three decades before optical counterparts could be found and the underlying physical phenomena studied in detail. GRB research represents currently one of the most rapidly growing areas in extragalactic astronomy. This is due in large part to the numerous connections that GRBs have with other disciplines like cosmology, supernovae, stellar evolution, nuclear physics, astroparticle and gravitational wave astronomy. Therefore, their study is of great importance to understand various astrophysical phenomena such as the formation of the first stars, the chemical evolution and the expansion of the Universe. Since gamma radiation can travel along cosmological distances without being affected by any possible intervening absorption, GRBs can be detected from the most distant universe, reaching redshifts up to $z = 10$ or more.

1 Introduction

GRBs are unpredictable transient events in the gamma-ray sky that consist of powerful flashes of gamma radiation (0.1–1 MeV), lasting from few milliseconds to thousands of seconds. They occur randomly and isotropically across the sky at a rate of about 1 per day. During the explosion a GRB releases in few seconds up to 10^{51-54} erg. The gamma radiation is highly variable and, therefore, the temporal profile of the bursts identifies them like a distinctive fingerprint. They shows a wide diversity of temporal profile patterns ranging from multiple peaks, single-spike bursts, a fast rise and exponential decay behavior, precursor events occurring hundreds of seconds before the main flash, or smooth emission lasting tens of seconds after the main event.

The initial burst of gamma radiation is the *prompt phase* which is followed by a much less energetic and long-lasting *afterglow*. The afterglow phase can be observed from the X-ray band ([15]), via the optical ([67]) up to the radio regime ([24]). The afterglow usually starts minutes after the prompt phase and can be detectable up to several days (in few cases even months [X-rays] or years [radio]). GRBs are the most energetic electromagnetic events known in the universe.

2 History

2.1 The 1960s: a fortuitous discovery

In the 1950s, in the middle of the Cold War, there was a continuous increase in the number of nuclear tests on Earth. As the consequences of such tests could be irremediable for life, in 1963 the *Limited Nuclear Test Ban Treaty* was signed by the Soviet Union, the United States and Great Britain in order to ban any test with atomic weapons in the atmosphere, on the ground, under water and in the outer space.

In order to verify if the Soviet Union followed the Test Ban Treaty, the US launched the spying Vela satellite program. It consisted in satellites equipped with gamma-ray detectors that were flying in pairs around the Earth. The main goal was to detect gamma-ray showers caused by atomic weapon tests. The first cosmic GRB was detected by two Vela satellites on July 2, 1967 and it was a fortuitous astronomical discovery. The discovery was finally reported in a seminal paper in 1973 in which 16 events were listed. These events were detected between 1967 and 1972 ([47]).

From 1973 to 1990 other satellites detected serendipitously many of these events but due to the lack of a rapid and accurate localisation (on the order of tens of degrees based on the Vela satellites), neither optical nor radio follow-up observations could be performed with the purpose of catching a transient event or finding an optical counterpart that could explain the aforementioned phenomenon. As a consequence, no potential host population could be identified. Therefore, the typical distance scale together with the energy budget remained unknown. In the early years, there were more theories to explain these events than GRBs ([58]).

2.2 The following years: 1970 – 1990

In the 1970s, the Interplanetary Network (IPN) had its golden age. Several satellites were launched to explore the outer and the inner planets, Venus, Jupiter, or Saturn. Since a gamma-ray detector only had the size of a box of cigarettes and a weight of a few 100 grams, they were routinely piggybacked on these space missions. Due to the Cold War, the communication between satellites belonging to the US with those from the Soviet Union was toilsome, and in all cases it took many weeks, or even years, before a GRB error circle was finally determined and publicly announced.

In the 1970s and 1980s most scientists believed that GRBs were produced by sources in our Galaxy, and neutron stars were the best candidates. More than 30 years later we know that there is indeed a population of neutron stars in our Galaxy that occasionally emits (soft) GRBs. These are the *Soft Gamma-Ray Repeater*. These neutron stars have very strong magnetic fields and can emit soft gamma-ray flashes in irregular time spans. So far, about 10 of these neutron stars are known ([64]). The most famous representative of this class was already localized in the 1970s in the Small Magellanic Cloud, when it emitted the most energetic SGR burst ever recorded ([53]). If all GRBs would have a Galactic origin like this source, as it was the general believe in the 1970s and 1980s, then they would liberate $\sim 10^{38}$ erg. However, a very small number of scientists were arguing that GRBs could be of cosmological origin. The most prominent member of this group was the polish astrophysicist Bohdan Paczyński (1940 – 2007). Already in 1986, when no big observational progress had been made, in a very challenging paper ([65]) he proposed that GRBs are at cosmological distances similar to quasars. Assuming a typical redshift of 1, the energy that had to be released within some seconds would be about 10^{51} erg. During the Hunstville GRB symposium in 1993 there was a big debate about the origin of GRBs similar to the "Nebulae debate" in 1920. In that conference, only 10% of the attendees voted for a Galactic origin while other 10% voted for a cosmological origin. The rest favored no option. Up to the 1990s, deep observational studies of the smallest IPN error boxes from the 1970s could not figure out what was special there, there was no excess of quasars, special stars or special galaxies (e.g., [83, 48, 78]). An optical counterpart that could explain the explosion of the source was missing, leaving open the characteristic distance scale.

2.3 The BATSE mission (1991 – 2000): the cosmological distance scale

It was not until 1991 that a dedicate satellite was launched to monitor and study GRB events in a systematic way, the Compton Gamma Ray Observatory (CGRO). Part of CGRO's payload was the *Burst and Transient Source Experiment* (BATSE; [20]). During its 9-year lifetime, on average one GRB per day was detected. The *BATSE* sample with 2704 events is still the largest GRB catalogue. It provided two important breakthroughs.

(1) GRBs are isotropically distributed over the sky. Already after the first year, with the first 300 detected bursts, the distribution tended to be isotropic, neither clustering around the Galactic center or the Galactic plane was seen, nor did it follow any known pattern like the distribution of galaxies in the Local Group, favoring then an extragalactic origin for these events ([55]).

(2) GRBs show a bimodal duration distribution. Evidence for a bimodality in the GRB duration distribution was already evident in Russian satellite data ([54, 63]). BATSE, however, showed it with high statistical significance: there are two different populations of bursts, long/soft and short/hard. This bimodal distribution, with a peak around 0.1 s and 20 s, consists of two curves with a Gaussian shape that overlap at $\sim$2 s ([50]). In the BATSE catalogue most bursts belong to the long-burst population (long:short $\sim$ 3:1). Until today, the concept to devide between long and short bursts is used and the borderline is set at 2 s, although in the last years additional physical parameters have been introduced in order to find a more physical classification scheme ([91, 43, 44]). When looking only to the duration of the GRBs, the long/short GRB samples are clearly contaminated by outsiders (e.g., [59]). However, it is still the duration that remains as a key parameter to characterize a GRB. The main drawback of *BATSE* was the positional accuracy of the burst localizations. Usually its error boxes had sizes of several square degrees, which was too big for performing deep rapid ground-based follow-up observations. Though attempts to handle this problem were performed world-wide.

2.4 *BeppoSAX* (1996 – 2002): the revolution in GRB research

BeppoSAX was an Italian-Dutch satellite that was launched on April 30, 1996 ([8]). Originally, GRB research was not its main task but *BeppoSAX* made a revolutionary step forward in this astronomical research field. The satellite carried an omnidirectional GRB Monitor (GRBM) composed of four identical detectors with an almost 4π sr field of view that worked in the energy range between 40 and 700 keV. It also contained two wide-field X-ray detectors (2–28 keV) with a localization accuracy of around 5 arcmin. When a source was detected and located with the wide-field X-ray detectors, follow-up observations could be performed thanks to a fast re-orientation of the entire satellite so that the target was in the FOV of one of the two narrow-field X-ray telescopes. The new pointing had a delay of typically 5 to 8 hours after a GRB trigger, an extraordinary fast response compared to all previous GRB follow-up observations in the X-ray band. *BeppoSAX* had no optical capabilities and all the instruments were mounted on the same platform. The main milestones achieved by *BeppoSAX* are:

1 Discovery of the first X-ray afterglows: *BeppoSAX* detected the first X-ray afterglow for GRB 960720. However the announcement came 2 months after the burst (error circle 10 arcmin; [70]) and no optical counterpart could be identified anymore. In the case of the 2nd detected and well-localized X-ray afterglow by *BeppoSAX* (GRB 970111) the response time was much faster, its discovery distributed on the day of the burst, but no optical afterglow was found either (e.g., [37, 26, 52, 30])

2 Discovery of the first optical afterglow: On the 28th February 1997, *BeppoSAX* discovered its third X-ray afterglow ([15]). The Wide Field X-ray camera localized the afterglow and the narrow-field instruments started observing 8 hours after the event. An uncatalogued, fading X-ray source was found. Follow-up optical observations were performed during the first night until one week later from La Palma with the WHT and INT. Finally inside the X-ray error circle, the first optical transient of a GRB was found ([67]). It was located next to a galaxy the redshift of which could be determined some months later to be z=0.695 ([19]).

3 Discovery of afterglow jet breaks: The light curve of the optical and X-ray afterglow of GRB 970228 showed a decline with time that was following a simple power law (flux density $F_\nu \sim t^{-1}$). This behaviour described all optical afterglows discovered in 1997 (four afterglows) and 1998 (five afterglows). In a preprint first circulated in 1998 James Rhoads then predicted ([72]) that if GRBs and their afterglows are due to collimated, non-isotropic explosions, this should manifest as a break in the afterglow light curve, a steepening of the light curve decay after some time. Indeed, two years after the first optical afterglow such a break was found first in the afterglow of GRB 990123 ([13]; redshift z=1.609). This was first evidence for a collimated explosion. Later on, most afterglow light curves showed such a break, typically about one day after the corresponding burst when the power-law decay steepens to about $F(t) \sim t^{-2}$. Jet half-opening angles can be derived based on the observed break times ([77]) and typical values found are some degrees (e.g., [89]).

4 Discovery of the GRB-SN connection: In April 1998 a supernova was found inside the 8 arcmin X-ray error circle of GRB 980425 ([27]). This SN, which explosion was contemporary with the GRB (within ±2 days, [41]) was located in a nearby spiral galaxy at a distance of ∼40 Mpc (z=0.0085; [85]). The supernova had no hydrogen and no helium lines and showed broad-band features corresponding to a Type Ic SN. Measured expansion speeds were in the order of $0.1\,c$ ([51]). This strongly suggested that some core-collapse SNe can produce GRBs. The GRB-SN connection was fundamental in building a theoretical model that could explain which astronomical objects do produce GRBs.

5 Discovery of a dark burst: After the discovery of the first optical afterglow most observers believed that all these events could be detectable in the magnitude range between R=19 and 21 mag within the first day after a burst. The third X-ray afterglow detected by *BeppoSAX* in 1998 however changed this picture. It was localized with 30" accuracy but observations with the WHT on La Palma starting 4 hours after the burst did not detect an optical transient down to a limiting magnitude of $R \geq 24$ ([36]). By comparing the ratio of the optical peak flux to the X-ray flux it was found that the optical counterpart of GRB 970828 was at least 1000 fainter than the one of GRB 970508 ([36]). The terminus technicus *dark GRB* was suggested to describe such optically dim events. In the *BeppoSAX* era (1996 – 2002) nearly every second afterglow was dark ([49]). The lack of an optical counterpart could be explained if the GRB had exploded in a star-forming region with a very dusty environment. This pointed directly to very massive stars as the possible progenitors of some GRBs ([66]).

6 Proof of the cosmological distance scale: Even though the first optical afterglow was discovered for GRB 970228, the first redshift measurement of a GRB afterglow was successfully performed for GRB 970508 ([57]). It was a blue star-forming galaxy at a redshift of z=0.835, confirming that GRBs are cosmologically in origin.

During its life-time *BeppoSAX* localised about 10 GRBs per year but this was enough to revolutionize the field. It resulted in the discovery of the X-ray afterglows of many GRBs and the follow-up observations of the corresponding afterglows from the optical to the radio band. For the first time it was possible to determine the redshift of an event and to identify the host galaxy. Finally, it became clear why the past observing strategies had failed to image an optical afterglow: observations were simply performed too many days/months/years after the corresponding burst. The experience gained with *BeppoSAX* paved the way to future GRB missions, *HETE*, *Swift* and *Fermi*.

2.5 HETE II (2000 – 2006): new insight on the GRB-SN connection

In the fall of 2000, the special GRB satellite *HETE II* was launched ([73]) after the failure of *HETE I* in 1996. *HETE-II* was able to localize an X-ray afterglow within a minute after the onset of a burst with a location accuracy of about 1 arcmin. However, its field of view in the gamma-ray band was only 0.9 sr and, therefore, in the first two years only two afterglows could be detected within minutes after the corresponding burst (GRBs 021004 and 021211).

The main contribution of *HETE II* for GRB research was the localization of the very bright GRB 030329 in March 2003, still the burst with the brightest GRB afterglow ever observed ([43]). When the optical afterglow was announced it had a magnitude of R=12.5 ([71]). A redshift of z=0.1685 was soon measured ([34]), explaining the extreme brightness of the gamma-ray burst as well as its optical afterglow. Simultaneous BVR-band observations over a period of 6 hours showed the jet-like behavior of this afterglow ([32]). The GRB was so intense that it led to a measured disturbance of the ionization degree of the Earth's upper atmosphere ([79]), although this burst came from a galaxy billions of light years away.

GRB 030329 led to a major discovery: it provided the final proof that long GRBs are due to supernova explosions. The burst was followed by a bright SN (light curve predicted by [87]) that could be confirmed spectroscopically (designated SN 2003dh; [38]). Its spectrum was very similar to that of SN 1998bw, confirming that SN 1998bw can be considered as the prototype of GRB-SNe, even though it had a much lower redshift. Both events were of type Ic, showing very broad spectral features, indicating a high expansion speed of the supernova envelope. GRB 030329 made clear that long bursts are associated with the explosions of massive stars, Wolf-Rayet stars with masses $\geq$20 $M_\odot$.

Within the collapsar scenario, a highly magnetized, temporary accretion disk is formed around the freshly-formed black hole in the center of a collapsing star ([84]). This accretion disk is rotating at very high speed and feeds the black hole for seconds, minutes or even hours, providing the energy for the formation of an ultra-relativistic jet (plus a counter jet) along its symmetry axis ([85]). The jets are then propagating outwards through the star. If its outer shells were very large/massive, the jets would be completely absorbed (die out) already within the collapsing star. Stars with completely removed outer H and He envelops are thus prime candidates to produce long GRBs, and such stars are those of type Wolf Rayet. Current models suggest that a GRB is released within these relativistic jets, while the afterglow is produced once the jet collides with the interstellar medium surrounding the exploding star and decelerates ([56, 69, 90]).

3 The current observational situation

The present days are characterized by routine GRB discoveries by NASA's *Swift* satellite, occasional GRB discoveries by the European satellite *Integral* and the 3rd Interplanetary Network (consisting of satellites in orbit around Earth, Mars, and Sun) as well as detailed GRB observations by the *Fermi* gamma-ray observatory which can detect GRBs even in the GeV regime. From the point of view of localization accuracy and optical counterpart detection, since more than 10 years the most productive GRB data delivery machine among these satellites is *Swift*.

Swift is a dedicated GRB satellite operated by a collaboration of various research facilities in Italy, UK, and the United States under the leadership of NASA and was launched on November 20, 2004 ([28]). Since then, it has been the work-horse to achieve many scientific breakthroughs. *Swift* is the first satellite GRB mission design with the main goal of observing GRBs during the prompt and afterglow phase just minutes after the GRB trigger. It has panchromatic observing capabilities from gamma to X-rays down to the UV/optical bands. The satellite carries three different telescopes: The Burst Alert Telescope (BAT; [3]) which is a wide-field telescope operating in the gamma-ray band. It works as an imager between 15–150 keV and as a photon-counting instrument up to 500 keV. The X-ray Telescope (XRT; [9]) is operating in the soft X-ray regime between 0.2 and 10 keV. Similar to BAT has the same two operational modes. Finally, the Ultraviolet/Optical Telescope (UVOT; [74]) observes in the ultra-violet and visible domains (150–650 nm).

Swift detects about 100 GRBs per year with BAT, localizes them with typically 3 arcmin accuracy (90% confidence level, error radius) and detects the X-ray afterglow within seconds or minutes after the onset of a burst (typically 3 to 5 arcsec radius error radius), followed by optical observations with UVOT. All this information is immediately send to the ground station[1] This procedure opened the door to routine detections of short-GRB afterglows, allowed for the first time a detailed study of the early X-ray afterglows just minutes after the GRB trigger, and provided a huge data set suitable for statistical studies, including the GRB host galaxies. A particular milestone achieved with *Swift* concerns the short bursts.

Swift/BAT detected its first short burst in May 2005 (GRB 050509B), shortly after entering its full science operation mode. XRT could detect a fading X-ray afterglow and localize it to 6 arcsec accuracy (error radius, 90% c.l.; [45]). This tiny error circle touches a giant elliptical galaxy at a redshift of z=0.225, strongly suggesting that this is the GRB host galaxy ([29]). Unfortunately, no optical afterglow could be detected ([39]). Not only was it for the first time ever that an elliptical galaxy turned out to be the most-likely host-galaxy candidate, the nature of this galaxy itself perfectly agreed with theoretical expectations according to which short bursts are due to merging compact stellar objects, i.e., stars that can be member of an old stellar population. The short burst with the first optical and radio afterglow was the final highlight discovery of the HETE II satellite (GRB 050709; [40]), while *Swift* saw its next well-localized short GRB in July 2005 (GRB 050724).

So far *Swift* has discovered on average 5 short bursts per year with a well-detected X-ray afterglow. Because of their smaller fluence and short duration, short bursts have a substantially smaller detection rate compared to long bursts (in the *Swift* catalog about 10% of the bursts are short events). Their optical afterglows are on average notably fainter than their long-burst cousins. They are rarely brighter than R = 20 mag even minutes after a trigger (e.g., [44, 60]). This general faintness makes their discovery and detailed follow-up very challenging. It is therefore not surprising that the number of well-localized short-burst afterglows is still small, in the order of just 40 cases (for a review, [7]).

The most popular model about the origin of short GRBs is the neutron star (NS) merger model which was first developed in the 1980s (e.g., [65]). In its present context the model relies on the idea that a NS binary (or a NS-black hole system) merges due to orbital decay caused by the emission of gravitational radiation. This picture is supported by the fact that short GRBs occur in all morphological types of galaxies, ranging from elliptical (about 1/3) to star-forming irregular galaxies (about 2/3; e.g., [22]), or even star-bursting galaxies

[1]for a detailed summary burst by burst see `http://gcn.gsfc.nasa.gov/ gcn3_archive.html` and `http://www.mpe.mpg.de/~jcg/ grbgen.html`.

([61]). Recently, the search for a specific electromagnetic signal in support of the merger hypothesis gained a considerable boost with the claim that an optical transient following a short GRB should be detected, the so-called kilonova light. While in recent years remarkable progress has been made in the theoretical understanding/modeling of kilonova light, and first claims about their detection have been published for GRB 130603B ([82, 6]) at at z=0.36. More recently, [86] claim to see a kilonova signal in the case of the short GRB 0606014. More observations are needed here, though they are a challenge even for 8-m class optical telescopes. Probably, it will take some more years before successful routine observations of kilonova light will be performed.

By November 2016, *Swift* has localized about 1500 GRBs (long + short), on average 100 per year. Most of these bursts belong to the long-burst population ($\sim$ 90%). For more than 1000 events an X-ray afterglow could be found, allowing for an arcsec accurate localization (typically 3 arcsec radius), in more than 600 cases an optical afterglow was discovered. Based on afterglow or host galaxy spectroscopy, more than 450 precise redshifts are meanwhile known (see `http:// www.mpe.mpg.de/ ~jcg/ grbgen.html`, `http:// gcn.gsfc.nasa.gov/ gcn3_archive.html`). The GRB redshift distribution peaks around z=1 with a long tail towards higher redshifts with the current record holder GRB 090423 at a spectroscopic redshift of z=8.2 ([75]) and GRB 090429B with a photometric redshift of z = 9.4 ([16]). Long GRBs are expected to trace the global star-formation rate along the history of the Universe ([46]). In principle, *Swift* should be able to detect bursts up to redshifts of about 20. Unfortunately, catching objects with redshifts >7 is very complex. Due to their optical faintness a spectroscopic confirmation even with 8 m-class optical telescopes can be very tricky.

On the cosmologically near site, the SNe physically related to long GRBs are of particular interest since they tell us directly about the nature of the GRB progenitors. Observations have shown that only a certain subclass of type Ic SNe is linked to long GRBs (e.g., [38]). A systematic analysis of supernova light in GRB afterglows found that for $\sim$2 dozen cases a chromatic bump has been seen in the late-time evolution of their afterglows ([88]). However, the data set of spectroscopically confirmed GRB-SNe is still very small ($\sim$20 cases by end of 2016; [10]). On average it increases by just one spectroscopically confirmed GRB-SN each year. The reason is that not all GRB-SNe are as luminous as SN 1998bw and extinction by dust in their hosts cannot be neglected. On the other hand, most GRBs are seen at high z so that the corresponding SN remains too faint even for 8-m class optical telescopes. In order to nail down the connection between the SN properties (progenitor mass, ejection velocity, luminosity) to the GRB properties (luminosity, duration, redshift), additional data must sum up. In particular, a still puzzled situation corresponds to those long GRBs at small redshift where, despite the observational effort performed, no underlying SN has been found (GRBs 060505 and 060614; [25]).

Worldwide a substantial observational effort is devoted to follow-up observations of GRBs, their low-energy afterglows (e.g., [76]) as well as their host galaxies (e.g., [80, 61, 62]). For the former, an increasing amount of robotic telescopes of the 0.5-m class come into play (e.g., the BOOTES telescopes, recently supplemented by the Javier Gorosabel telescope in Mexico; [12, 42], `http://bootes.iaa.es/`) as well as mid-size telescopes (e.g, the 1.23

CAHA telescope; ([31]). Nowadays, the world-largest optical telescopes like the Spanish 10m GTC telescope are intensively used, in photometric as well as in spectroscopic mode to follow all kind of GRB-afterglow observations (e.g., [17]) as well as GRB-host galaxy studies (e.g.,[33]). Finally, more dedicated multi-imager instruments like GROND ([35]) mounted at the MPG/2.2 m telescope on La Silla, Chile, or the future OCTOCAM ([18]) that will be mounted on the Gemini-South telescope in Chile, complete the diverse variety of instruments that are used to follow GRBs.

In the last years the electronic BACODINE/GCN circular system has developed into a very powerful tool for any kind of GRB follow-up observations, rapid data delivery, and coordinated observing campaigns (more than 20,000 GCN circulars by mid November 2016 ([4, 5]). Besides, in order to understand better the nature of GRB progenitors and to learn more about the physical conditions to produce them, studies of the host galaxies of GRBs become more and more important too.

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