GAMMA RAY BURSTS AND THEIR OPTICAL COUNTERPARTS*

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(Received December 1, 2005)

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Gamma Ray Bursts (GRB) have been discovered 38 years ago and still remain one of the most intriguing puzzles of astrophysics. In this paper we remind briefly the history of GRB studies and review the current experimental evidence with the emphasis on GRB optical counterparts. At the end we introduce "π of the Sky" project designed to catch prompt optical emission from GRB sources.

PACS numbers: 98.70.Rz, 95.75.Rs, 95.55.Aq

1. Introduction

Gamma Ray Bursts (GRB) stands for one of the greatest puzzles of contemporary astrophysics. The term is used today to name the phenomenon involving a powerful explosion followed by emission of all sort of radiation from radio waves to TeV photons. The name refers to the most characteristic signature of the phenomena, namely short and strong gamma ray pulses. The pulses last 0.01–100 s and they are often brighter than all other gamma sources in the sky taken together. Observing all sky one could detect as much as 2–3 bursts per day. The sources are randomly distributed over the whole sky.

The GRB phenomenon was discovered 38 years ago. Over 3000 GRB's have been observed so far and almost 100 of them have been seen in visible light. The number of papers per year devoted to GRB's is approaching 300 and still growing. In spite of that, the origin of the explosions is still uncertain and it is very likely, that there are different mechanisms responsible for different classes of GRB's.

* Presented at the XXIX Mazurian Lakes Conference on Physics August 30–September 6, 2005, Piaski, Poland.

In the next section we briefly review the history of GRB studies. This will be followed by an outlook of the current observational evidence. Finally, we will present "π of the Sky" experiment, which is a new attempt to gain knowledge about prompt optical emission from GRB's.

2. History of GRB study

2.1. The discovery

The first GRB have been observed by military satellites VELA 4a and 4b [1]. They were designed to monitor the international treaty banning nuclear test in space. They were placed on high orbits to be able to detect γ-rays from explosions even at the other side of the Moon. The first burst have been observed June 2, 1967. The pulse shape was different from that expected for a nuclear explosion. The direction and the distance were unknown.

In 1969 new generation satellites VELA 5 and 6 have been launched. They were equipped with detectors having time resolution of $1/64\,$s. Measuring the time difference between pulses seen by the two satellites one could estimate the direction with $\sim 5^\circ$ precision. Till 1973 sixteen bursts have been observed. The distance turned out to be larger than one million kilometres. Directions excluded the Sun and the Solar System planets. The spatial distribution was quite uniform, as far as one can tell having 16 sources.

The results have been presented in June 1973 at the 140th meeting of the American Astronomical Society in Columbus, Ohio. Journalists begin to speculate about nuclear war between extraterrestrial civilisations. Scientist also got excited, because it was evident that something really new has been discovered.

2.2. The first theories

Already in 1975 Ruderman reported dozens of possible explanations [2]. He noted, that the number of theories trying to explain the GRB origin is greater than the total number of bursts known at the time. Attempts were made to answer the three basic questions:

- **Where** the explosions occur?
- **What** are the GRB sources?
- **How** the enormous energy is produced and released as γ-rays?

Answering the first question, the widest possible range of distances was considered, from the Solar System, through the Galaxy and its halo, to the farthest regions of the Universe. All known and hypothetical objects were discussed as the source of GRB's: main sequence stars, white dwarfs, black holes, neutron stars, planets, comets, dust grains, white holes, cosmic strings, wormholes, *etc.* All possible energy forms were explored to answer the question "how?": gravitational, thermonuclear, magnetic and kinetic (rotational). The Cartesian product of these three sets of answers gives the full set of theories discussed. It became evident, that more data are needed to solve the puzzle.

2.3. Inter-Planetary Network (IPN)

In the late seventies, several spacecrafts equipped with gamma detectors happened to be far from the Earth for different reasons. Among them were:

- Prognoz 7 (USSR) — satellite of the Earth
- Helios 2 (Germany) — satellite of the Sun
- Pioneer Venus Orbiter (USA)
- Wenera 11 i 12 (USSR) — mission to Venus
- Kosmos (USSR) — satellite of the Earth
- Vela 5 i 6 (USA) — distant orbits around the Earth

In 1978 Kevin Hurley from Berkeley proposed to use combined data from these satellites to find directions to GRB's and estimate the distance. He created what he called Inter-Planetary Network (IPN) [3]. The IPN made many interesting observations and it is still operational today, with different spacecrafts involved over the years.

One of the greatest discoveries of the IPN was the burst of March 5, 1979. It was identified to come from the direction of a supernova remnant in Large Magellanic Cloud (LMC). At that time it was a strong argument in favour of the galactic origin of GRB's. Today we know, that it belongs to a different class of phenomena called Soft Gamma Repeaters (SGR).

2.4. The second Great Debate about distances in the Universe

At the beginning of nineties most of the astronomers were convinced that the GRB sources are not too far from the Sun, inside our Galaxy. There were several arguments to support this hypothesis, in addition to the LMC burst mentioned above. Few experiments observed some peaks and "hollows" in gamma spectra, which have been interpreted as spectral lines. The peaks were attributed to e^+e^- annihilation close to a neutron star, whereas the "hollows" were explained as absorption lines at cyclotron frequencies of electrons in magnetic field of a neutron star.

Three GRB's have been found to be preceeded by optical flashes recorded on photographic plates about 50 years before. This would mean, that the energy released in the burst cannot be to large in order not to destroy the source. Very large energy flux observed lead to the conclusion that the sources cannot be distant. After several years it turned out, that all these conclusions were wrong, because of some misinterpretations of the data.

Very few astronomers in 1990 were advocating the extragalactic origin of GRB's. At that time there were only two arguments in favour of this hypothesis. One was the uniform distribution of sources in the sky. The second was the deficit of weak GRB's which could be understood as the lack of GRB sources in the distant (and thus — early) Universe.

The situation was similar to that of half a century before, when astronomers discussed whether the nebulae are objects within our Galaxy or they are other galaxies, similar to our Milky Way. On 26 April, 1920 the famous Great Debate about distances in the Universe happened between Harlow Shapley and Heber Curtis. Almost exactly 50 year later, on April 22, 1995, another Great Debate about distances was organised. It was lead by Don Lamb, Martin Rees was defending the galactic origin hypotheses, whereas Bohdan Paczynski advocated cosmological distances. The debate was not conclusive. Again, it became evident, that more data are needed to find the answer.

2.5. BATSE

A real breakthrough in GRB studies was made by the Burst And Transient Source Experiment (BATSE). It was a set of 8 γ-ray detectors placed at corners of the cosmic Compton Gamma Ray Observatory. The satellite was launched in 1991 and it was collecting interesting data till the year 2000, when the mission was terminated in spite of good conditions of the instruments. BATSE recorded on average one GRB per day. In total it collected almost 3000 bursts [4].

BATSE precisely measured the pulse shapes. It turn out, that they are very different: from single and double peaks, through multipeak structures, to packets of random oscillations. Pulse duration distribution exhibit two Gaussian-like shapes (in a log scale) with maxima at 0.3 and 50 s (Fig. 1). The bursts shorter than 2 s turned out to be somewhat harder in energy. This opened speculations, that the two classes of GRB's might be caused by different mechanisms.

The key feature of the BATSE detector was the possibility to measure the GRB position with precision of 4° to 10°. The sky map of GRB sources demonstrated random isotropic distribution with great precision. Position information sent quickly to the ground enabled follow up observations by Earth based optical and radio telescopes.

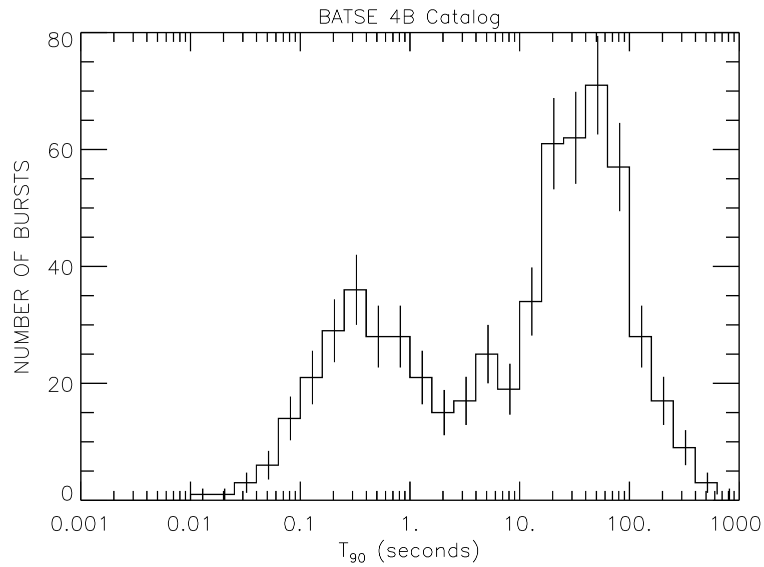

Fig. 1. Distribution of GRB duration time. (Figure taken from Ref. [4])

2.6. The first afterglows

Another breakthrough in the domain of Gamma Ray Bursts was made with the help of an Italian–Dutch satellite called BeppoSAX. It has been launched in 1996. It was equipped with 3 instruments: wide field (40°) X-ray camera, precise (resolution of 3 arcmin) X-ray camera and a γ-ray monitor. This combination was very fortunate. It turned out that the gamma bursts are accompanied by X-ray emission which lasts for several hours. It enabled precise determination of the source position and made possible pointing large telescopes to the target.

The information was transmitted through the BAtse COordinate NEtwork (BACODINE) invented by Scott Barthelemy from NASA [5]. Later, BACODINE was renamed to Grb Coordinate Network (GCN) and it operates successfully till today.

The first optical afterglow has been observed 21 hours after GRB 970228[1]. The observation was done with the 4.2 m William Herschel Telescope on La Palma (Canari Islands) [6].

Very important discovery have been made after GRB 980425 has been detected by BeppoSAX. Optical afterglow was fading for several days and then it rebrighted again exhibiting behaviour typical for a supernova. Spectral analysis confirmed the supernova hypothesis.

[1] GRB's are named with the date they happen in the format `yymmdd`.

2.7. New satellites

After the great success of BATSE and BeppSAX, another satellite was designed for GRB studies. High Energy Transient Explorer (HETE) was launched by NASA for the first time in 1996, however it was destroyed, trapped within the rocket shielding which did not open in time. A copy called HETE-2 was finally launched in the year 2000.

Important observations have been made also by Integral satellite launched by ESA in 2002. The scientific program of Integral is wider, but its detectors are also useful for GRB detection.

Significant step forward in gamma bursts studies has been made in November 2004. NASA launched the Swift satellite, dedicated for this purpose. It is equipped with 3 instruments:

- BAT — γ-ray detector covering 2 steradians
- XRT — X-ray detector with resolution of 4 arcmin
- UVOT — optical and ultraviolet telescope

Burst position determined with BAT and XRT is available in seconds. Then, the satellite slews in order to point UVOT towards the target. In 40–100 s UVOT is able to take pictures and send them to the Earth. Its limiting magnitude is 17 and it can observe prompt optical emission from brighter GRB's.

During the first year of operation almost 100 bursts have been discovered by Swift. Roughly 40 of them have been observed in visible light and about 20 redshifts have been measured. BAT and XRT detectors were proven to be excellent trigger devices. UVOT was not as successful as expected, because of the finite slewing time. Most of the optical GRB counterparts have been caught by ground based robotic telescopes which are either faster or more sensitive than the UVOT. It does not change the fact, however, that those observations were made after BAT/XRT triggers and count for the success of the Swift mission.

3. Current status of GRB optical observations

3.1. Optical afterglows and distance determination

Optical observations are especially important for two reasons. Firstly, optical telescopes give the best spacial precision which enables to identify GRB sources. Secondly, optical spectrum can bring a lot of information about the physical processes in GRB sources. Redshift measurement is the only method to evaluate the distance to the source.

Till the end of October 2005, in total 63 redshifts have been measured. The values are plotted in Fig. 2 *versus* discovery date. The impact of the Swift mission is clearly seen in 2005. Redshift distribution is shown in Fig. 3. The closest GRB happened at $z = 0.0085$ (GRB 980425) and the farthest one at $z = 6.29$ (GRB 050904).

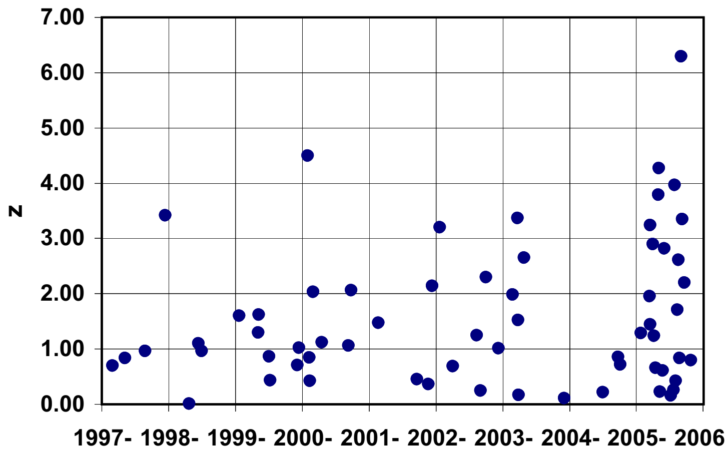

Fig. 2. GRB redshift z as a function of discovery date.

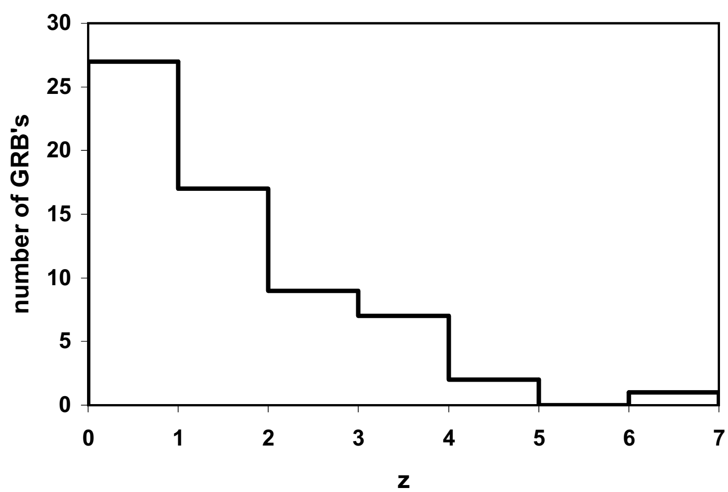

Fig. 3. GRB redshift z distribution.

3.2. Supernova connection

After the first discovery of supernova SN 1998bw associated with GRB 980425, several supernovae connected to GRB have been observed. The most spectacular was GRB 030329 = SN 2003dh. It happened at $z = 0.168$ and it was very bright. Detailed observations seem to confirm the hypothesis that long GRB's are due to a collapse of a massive star after it spent all its fuel. Depending on the details of the model such a star is called hypernova or collapsar [7]. Regular supernova ends up with a neutron star. Hypernova or collapsar goes through the neutron star stage and continue to fall until a black hole is created.

Some of the gamma bursts exhibit a small peak before the main emission, called precursor. Representative examples are GRB 041219 and GRB 050124. Paczynski and Haensel speculate that the precursor can be a sign of neutron star stage, whereas the main burst is due to a hypothetical quark star [8].

3.3. Prompt optical emission

Most of the optical afterglows have been observed only many hours or even days after the GRB. The delay was caused by big inertia and small field of view of large telescopes. With the advent of small and fast robotic telescopes [9] it became possible to catch also the prompt optical emission. The first discovery of this kind has been made by ROTSE detector [10] equipped with four 10 cm telephoto lenses by CANON. After the GRB 99123 trigger by BATSE the ROTSE cameras were quickly turned to the target and the first picture was taken 20 s after the beginning of the gamma burst. The optical emission begun already during the gamma burst and it was exceptionally bright. It reached 8.6 magnitude in the peak!

Even more rapid observation was made by 40 cm RAPTOR S telescope for GRB 050124. It registered optical emission just before the gamma burst. It was possible, because the burst was preceeded by a precursor, which was strong enough to release the Integral trigger. Third prompt observation was performed after GRB 050820. In this case, however, the optical emission peak occurred only 7 minutes after the gamma burst.

Prompt optical emission is crucial to understand the GRB central engine. An important question is whether it begins before, during or after GRB [11]? So far we have three mentioned above observations and three different answers. Once more in this paper we have to repeat: more observations are very much needed!

4. Project "π of the Sky"

4.1. The concept

Catching the prompt optical emission from GRB is a challenge. Trigger decision and signal propagation from a satellite to a ground based telescope takes usually 15-30 seconds. Moreover, even the fastest robotic telescopes have finite slewing time. Therefore, this method is not suitable to detect the optical emission before or during the gamma burst.

Different approach has been proposed by "π of the Sky" collaboration. It profits from some ideas developed in particle physics experiments. The observation is performed continuously and the trigger is used to select among already taken data. Because no one knows where the next burst will occur, one has to observe large part of the sky simultaneously. It results with a huge data stream, which needs to be reduced.

In many cases, it is impossible to design single algorithm which is fast enough to select efficiently interesting events (*e.g.* optical flashes) in a huge data stream. Instead, one can design a multilevel trigger. The first levels are simple and fast, as their only role is to reduce the data stream by one or two orders of magnitude simply skipping noninteresting data. Suspected events are passed to higher trigger levels which could be more sophisticated as they have less data to analyse. Algorithms designed for "π of the Sky" are discussed in detail elsewhere [12].

4.2. The prototype

A prototype consisting of two cameras has been build and installed at Las Campanas Observatory (LCO) in Chile. Each camera has a CCD of 2000×2000 pixels of $15 \times 15\,\mu\mathrm{m}^2$. Cameras are equipped with Carl Zeiss Planar T* photo lenses of $f = 50\,\mathrm{mm}$, $f/d = 1.4$, giving $33^\circ \times 33^\circ$ field of view (FoV) and the scale of 1 arcmin/pixel. The limiting magnitude for 10 s exposures is 10^m–11^m and for 20 exposures added together it is 12^m–13^m depending on the sky background varying with the Moon phase, atmospheric conditions *etc.*

The cameras are installed on a robotic mount controlled by a computer. The apparatus is controlled by a PC located inside the dome. Second PC, located in a nearby Control Room is used for off-line data analysis. The system is fully autonomous, but also fully controllable via Internet. During the normal operation the system runs autonomously according to the preprogrammed schedule. Dedicated script language has been developed to make the schedule programming easy and flexible.

For most of the time the cameras follow the field of view of the HETE satellite. Its position is read out from the Internet in regular intervals and the mount position is automatically corrected accordingly. If the HETE FoV is not visible, another location in the sky is programmed. The system is also listening to GCN alerts. Should an alert located outside the current FoV arrive, the mount automatically moves towards the target and exposures are being taken. Twice a night an all sky scanning is performed, which lasts 2×20 min.

The 10 s exposures are being taken continuously. The images are immediately analysed while in the computer RAM in search for flashes with a rise time of the order of seconds. Then, they are temporarily stored on a disc and can be reexamined in case of late arrival of an external alert. If a flash candidate is found the 100×100 pixel samples of ± 7 frames are stored permanently for the record. In the meantime, the images are copied to the second PC, which superposes the images and searches for optical transients with a rise time of minutes.

During the day, two analyses are performed in parallel on the temporarily stored data. The first PC runs fast photometry on individual frames, which can be used later to study rapidly varying objects. The second PC performs precise photometry on images superposed by 20. This could be used to study variable stars *etc.* The results are stored permanently on a hard disk. Out of almost 30 GB of data taken every night, about 2 GB of results is stored permanently. After 2–3 months a 200 GB removable disk with the results is replaced and taken to Warsaw for further analysis.

4.3. The first results

During almost one year of running the system detected about 100 optical flashes of unknown origin, which were seen by two cameras, but only on single frame. Seven flashes visible in at least two consecutive frames have been observed. It is rather improbable that these are caused by flashing satellites, which is the background most difficult to eliminate. One case was unambiguously identified with an outburst of the CN Leo flare star. This observation confirms that the system is capable of automatic discovery of true optical flashes.

From 1.07.2004 to 7.08.2005 satellites observed 89 gamma ray bursts with known positions. Most of them happened during the day or below the horizon at LCO. Only 2 occurred within "π of the Sky" FoV: GRB 040825A and 050412. In several other cases the system has slewn to the target shortly after the alert. No new optical sources have been found. Limits have been given and published for the cases, when "π of the Sky" was faster than others: GRB 040916B, 041217, 050123, 050326, and 050607. Most interesting limits for optical counterparts of GRB set by "π of the Sky" are:

GRB	limit before	during	after the GRB
040825A	$> 10.0^m$ for $t < t_0 - 11\,\mathrm{s}$	$> 12^m$	$> 9.5^m$ for $t > t_0 + 7\,\mathrm{s}$
050412	$> 11.5^m$ for $t < t_0 - 11\,\mathrm{s}$	$> 11^m$	$> 11.5^m$ for $t > t_0 + 7\,\mathrm{s}$
050607			$> 12.5^m$ for $t > t_0 + 60\,\mathrm{s}$

4.4. Full π design

The designed apparatus consists of two sets of 16 CCD cameras, with each camera covering $20^\circ \times 20^\circ$ FoV. The total FoV of the system is thus 2×2 steradians. The two sets observe the same part of the sky from distant ($\sim$100km) locations to enable rejection of near-Earth objects by parallax. Each camera has a CCD of 2000×2000 pixels of $15 \times 15\,\mu\mathrm{m}^2$ Cameras are equipped with CANON EF $f = 85\,\mathrm{mm}$, $f/d = 1.2$ photo lenses. This gives the pixel scale of 0.6 arcmin/pixel. The expected limiting magnitude for 10 s exposures is 12^m and for 20 exposures added together it is 14^m. The apparatus is currently under construction.

Such limiting magnitude does not guarantee that all GRB's optical counterparts will be observed. Several GRB's detected by Swift BAT gamma detector have not been observed by its UVOT telescope having limiting magnitude of 17. On the other hand a few afterglows have been found quite bright. Recently observed are:

- GRB 041219: 14.9^m (infrared) after 0.8 h by the Palomar 200-inch Hale Telescope
- GRB 050502: 14.3^m after 23 s by ROTSE
- GRB 050525: 14.7^m after 6 min by ROTSE

Extrapolation to the first minute suggests that at least two of them would be visible by "π of the Sky". In the past, the two brightest bursts were

- GRB 990123: 8.6^m after 20 s by ROTSE
- GRB 030329: 13^m after 1 h by telescopes at Riken (25 cm) and Kyoto (30 cm)

These would be certainly visible, even by the current "π of the Sky" prototype.

This work is supported by the Polish Ministry of Education and Science under grants 1 P03B 064 29 and 1 P03B 103 29. We are very much obliged to B. Paczynski for encouraging and support. We are also very grateful to G. Pojmanski for sharing with us his experience. We would like to thank the staff of the Las Campanas Observatory for their help during the installation of the apparatus.

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