Gamma ray bursts: observations and theoretical conjectures*

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Abstract
Gamma Ray Bursts (GRBs) are short bursts of very high energy photons which were discovered in the late 1960s. Ever since their discovery, scientists have wondered about their origin. Nowadays it is known that they originate outside the Milky Way because of their high red shift first measured in the afterglows thanks to the Beppo-SAX satellite and ground-based observations. However, theoreticians still do not agree about the mechanism that generates the bursts, and different competing models are animatedly debated. Current GRB experiments include the Swift satellite and the Pierre Auger Observatory that could detect GRBs with an increase of the background. A forthcoming dedicated experiment is GLAST, a satellite observatory for detecting gamma rays with energies up to 300 GeV, whose launch is scheduled for early 2008.

1 Observational progress

Gamma Ray Bursts (GRBs) were discovered by the US military satellite Vela in 1967 while monitoring for clandestine tests of nuclear weapons. This information was not released to the scientific community until the following decade. GRBs are among the most energetic known objects ever measured and their origin and mechanism became a puzzle to the community [1, 2].

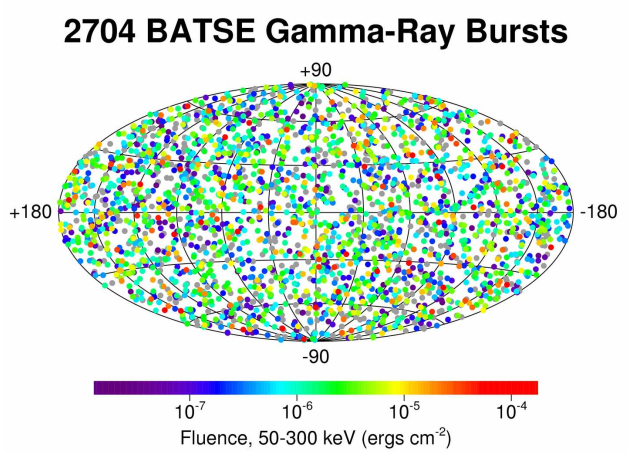

Fig. 1: GRBs measured by BATSE in Galactic coordinates [3]

In the early 1990s the Compton Gamma Ray Observatory (CGRO) was launched and started to unravel these questions. It included four different detectors to measure gamma rays, one of which was BATSE with a 4π sr field of view, 0.3–1.2 MeV energy range, and a precision of 2 degrees.

At that moment, not only was the origin of GRBs unknown, but also their location in space, and many scientists speculated that they were explosions occurring within our Galaxy. When the map showing an isotropical distribution of the GRBs as measured by BATSE was published (Fig. 1), it was clear

*Work performed as a student project under the supervision of E. Nardi.

that there were two possibilities: either they were originating very near to us, or they had a cosmological origin. With a lack of candidates within such short distances, the latter represented the most likely hypothesis, and the need to measure the red shift (z) of GRBs became evident to prove definitely their extra-Galactic nature.

An intriguing property of GRBs is the absence of any clear pattern associated with the gamma-ray emissions, that is all GRBs have different behaviour in time. This is apparent from Fig. 2 (left) where different examples of GRB brightness vs. time measured by BATSE are shown. The histogram in Fig. 2 (right) illustrates the different durations of GRBs. There are two distinctive types: short GRBs (lasting less than 2 seconds) and long GRBs (more than 2 seconds). The time duration represents the main classification property of GRBs, and is thought to be related to the mechanism for their generation.

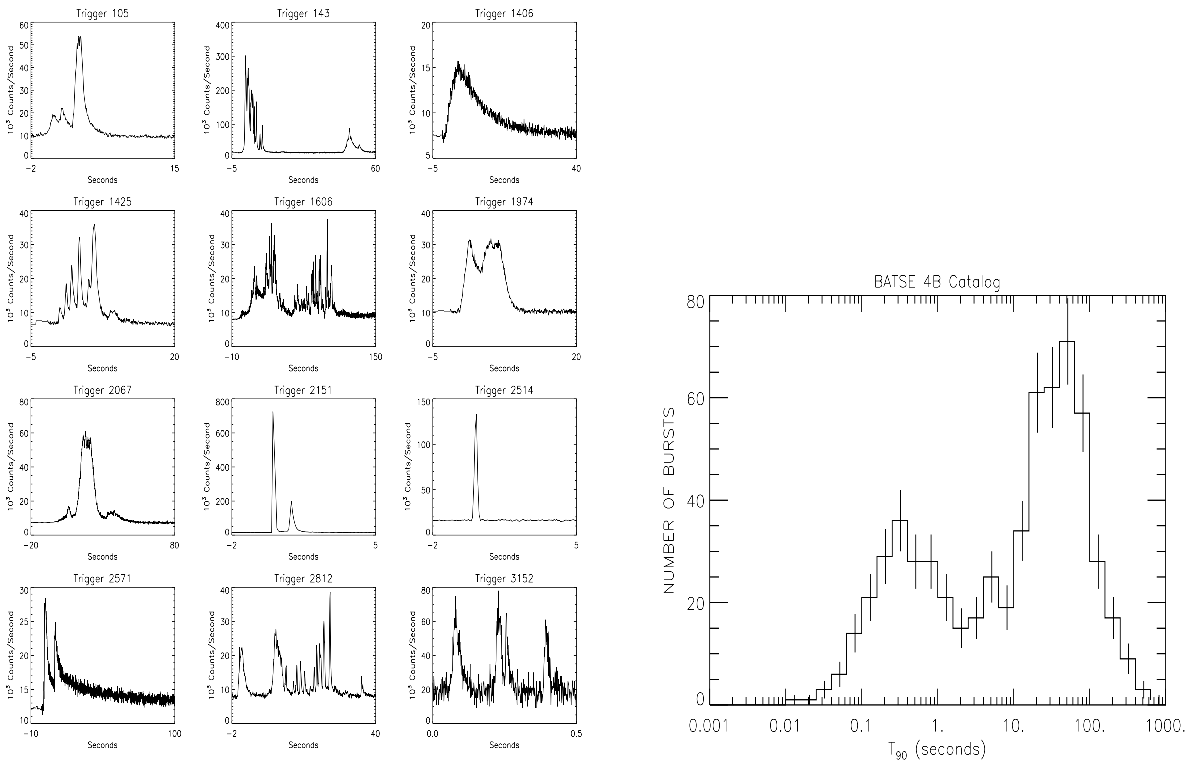

Fig. 2: (Left) different examples of brightness vs. time [3] and (right) histogram of duration of GRBs [4]

The first experiment that allowed the measurement of the red shift of a GRB was the Beppo-SAX satellite in 1997. Beppo-SAX carried out a GRB follow up in X-ray wavelengths, and its observations allowed ground based telescopes to carry out follow ups in the optical and in other wavelengths, a few hours after the burst (afterglow measurements). These combined observations were rendered possible since Beppo-SAX had arcminute precision in locating the position of the burst.

In Fig. 3 the first measurement of a GRB afterglow is shown. Two X-ray images are presented, corresponding to 8 hours and 3 days after the GRB. The red shift measured ($z = 0.865$) finally confirmed the cosmological origin of GRBs.

Since that first measurement, several GRBs with higher red shift have been detected. This is shown in Fig. 4 where we can see that GRBs with $z > 6$ have been spotted recently.

2 Overview of the theoretical status

At present, since some of the GRBs have had their red shift measured, it is possible to estimate the amount of energy released in these processes. Assuming an isotropic emission, the radiated energy lies between

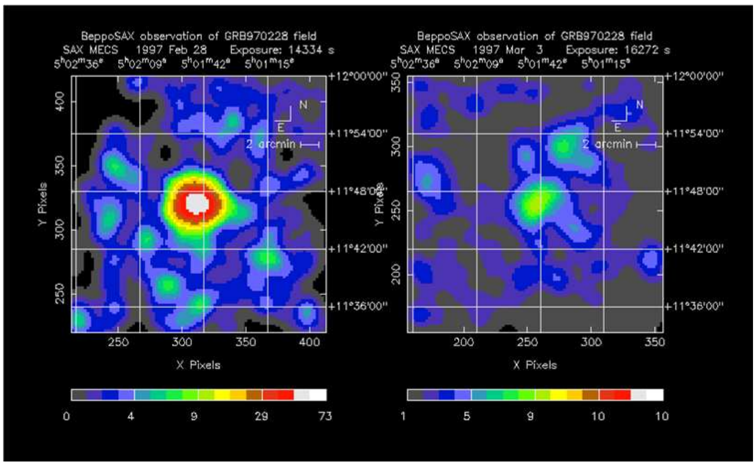

Fig. 3: First afterglow measured by Beppo-SAX in 1997 [3]

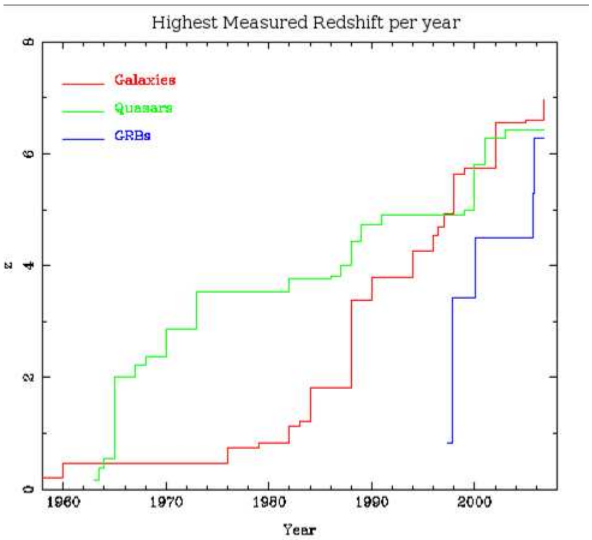

Fig. 4: Highest red shift z measured for GRBs, galaxies and quasars as a function of the year [5]

10^{51} and 10^{54} ergs. This is of the same order of magnitude as the solar rest mass ($m_\odot = 2 \times 10^{54}$ ergs) and therefore GRBs are commonly associated with catastrophic stellar events [2, 6, 7]. Models aimed at explaining the GRBs should address several questions, for instance they should predict the gamma-ray emission and the observed afterglow, they should state whether or not the emission is isotropic, they should explain the GRBs' short time variability, the spectrum of the prompt GRBs' emission and the observed afterglows.

Two main scenarios have been proposed to explain the progenitors of the bursts, namely the merging of the partners of a binary system and the collapse of massive stars. The former is now assumed to produce the short bursts and the latter the long ones [2]. In the following we briefly describe two models that have been put forward to explain the GRBs' emissions for the long bursts: the cannonball model and the fireball model.

The cannonball model, which was introduced by de Rújula and collaborators [7], assumes that, after the explosion of a massive star, a remanent rotating compact core accelerates matter from a surrounding accretion disk and ejects it as high velocity 'cannonballs' (Lorentz γ-factor $\sim$ 100–1000). As the expelled matter travels, its electrons scatter the ambient light up to gamma-ray energies through inverse Compton scattering [7]. The pulses observed in the GRB spectrum are due to the emission of several cannonballs.

In the fireball model, a fraction of the gravitational energy from the collapse, together with the energy from the matter accreted by the dense core (normally a black hole), is converted into the kinetic energy of a fireball. The fireball is a shell of matter consisting of $e^{\pm}$, γ and baryons. The prompt emission is due to collisions between different parts of the fireball, and the afterglow emission is due to the collisions between the fast moving fireball and the interstellar medium. Within this framework, synchrotron radiation is emitted, and therefore the GRB spectrum should exhibit a power-law behaviour [2,6].

3 Present and future GRB observations

GRB prompt emissions have been studied extensively from keV and MeV energy ranges up to 10 GeV, but energies above this range still remain mysterious. There is ongoing research to explore the unknown higher energy regions. In this section, a ground-based experiment at the Pierre Auger Observatory, and the Swift and GLAST satellite experiments are briefly described as examples of the current and future experiments to study GRBs.

The Pierre Auger Observatory, which studies ultra-high-energy cosmic rays (energies above about 10^{18} eV) could make a contribution in the detection of GRBs at ground level using a method known as the 'single particle technique' [8, 9]. GRB emissions produce cascades in the atmosphere but they are not directly detectable at ground level because of their low energies. However, these emissions increase the background rate of all the running detectors at the same time, and this could allow their indirect detection. The Pierre Auger Observatory is a 3000 km^2 array located in Argentina with 1600 water Cherenkov tanks which are sensitive to photons. There is an ongoing project known as LAGO whose objective is to place Cherenkov tanks at higher altitudes (over 3000 m above sea level) which would increase their sensitivity to these emissions.

The running experiment Swift [10, 11] is a robotic spacecraft which was launched in November 2004. The experiment was built and is operated by an international collaboration. Swift has already observed more than 270 GRBs. It has the particularity of being able to reorientate itself to point its instruments in the direction of a detected GRB.

Swift is composed of three detectors: the Burst Alert Telescope (BAT), the X-Ray Telescope (XRT) and the UV/Optical Telescope (UVOT). BAT is a gamma-ray telescope operating in the 15–150 keV energy range. Its goal is to detect GRBs and calculate their positions in the sky with a precision of 1 to 4 arc-minutes in order to point the two other detectors in the burst direction. XRT is an X-Ray (0.3–10 keV) telescope used to take images and study spectra of the GRB afterglow. XRT enhances the precision on the GRB position to about 3.5 arc-seconds and then performs a long term study of the afterglow. UVOT is an UV/Optical Telescope (170–650 nm) taking images and measuring spectra of GRB afterglows. These images can again enhance the GRB position (0.3–2.5 arc-seconds) and are used to measure red shifts.

Swift is therefore a full-featured GRB observatory: it can detect GRBs, study their afterglows, and measure precisely their positions and red shifts in order to help in understanding their origins.

The Gamma ray Large Area Space Telescope (GLAST) is scheduled for launch in early 2008. It will reside in a low Earth orbit of 550 km, with a minimum operational lifespan of 5 years (expected 10 years). General Dynamics will build the spacecraft, and install the scientific instruments provided by several international institutions.

The satellite will carry two instruments, the GLAST Burst Monitor (GBM), and the Large Area Telescope (LAT). The observable energy range for GBM will be between 8 keV and 25 MeV, while LAT will extend the sensitivity to much higher energies, covering a range between 20 MeV and 300 GeV [12].

In this respect LAT will provide an important extension in energy sensitivity with respect to

AGILE, the Italian Space Agency satellite that was launched just a few months ago (on 23 April 2007) and that is currently taking data in the energy band 30 MeV to 50 GeV [13].

Of the two GLAST instruments, LAT is intended as a multipurpose detector, while GBM is geared particularly towards GRB detection. The GBM will observe the whole sky not obscured by the Earth [14]. GLAST is expected to observe upwards of 200 GRBs a year [15].

For the first year of operation, GLAST will perform a full sky survey by rocking the focus direction as it orbits. During this operation there will also be the opportunity for pointed observations, should an object of high interest be seen. After the completion of the full sky survey, GLAST will operate in a mixture of the two modes [12]. When either of the two instruments detects a GRB, the observatory will direct itself towards the source automatically.

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