GAMMA RAY BURSTS*

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I present the observational properties of gamma-ray burst and outline the current theoretical models of these phenomena. I review the main problems in the gamma-ray burst science and sketch the prospects for the future.

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1. Introduction

Gamma ray bursts (GRB) discovery was announced more than three decades ago [1]. Gamma ray bursts were then described as: short burst of intense gamma radiation with durations between 0.1 and 30 seconds with most intensity between 0.1 an 1 MeV. The first measurements using triangulation excluded Earth and Sun as sources of GRBs. Over the past three decades GRBs have been a subject of intense studies by many satellite observatories. A crucial role in revealing the nature of these sources was played by BATSE, an experiment on board of Compton Gamma-ray Observatory, and then by a small Italian–Dutch satellite Beppo SAX. The observations of BATSE provided a huge database of almost 3000 GRBs with locations, lightcurves and spectra. The Beppo SAX observations led to discovery of afterglows, identification of host galaxies and establishing the distance scale to GRBs.

Quite a few extensive reviews of GRBs exist already in literature. Therefore the aim of this paper is to provide a summary of the properties of GRBs, give a brief overview of the theoretical models, and refer the reader to other sources of more detailed information on the subject.

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2. Observational properties

I begin with an overview of the observational properties of gamma-ray bursts. The basic observational facts are summarized below.

- The distribution of GRBs on the sky is isotropic. Moreover, up to recently no class of GRBs has exhibited any degree of anisotropy [2]. There is one exception — the class of the so called long lag burst [3] which shows some clustering in the super galactic plane.

- The distribution of brightness of GRBs is usually described by the number of bursts with the flux greater than a given value. Such distribution has a slope of $-3/2$ for bright bursts, consistent with a homogeneous distribution in Euclidean space. For weak bursts this slope flattens and its value reaches almost ≈ -0.5, indicating a paucity of weaker sources.

- The durations of GRBs span an interval from 0.01 s to 1000 s. The distribution of durations is bimodal. There are two classes — the short bursts with durations below ≈ 2 s and the long bursts with longer durations [4].

- The lightcurves of GRBs vary from one burst to another and there seem to be no identical two bursts. Some GRBs are smooth, while some are very variable. The long bursts are smoother on the average than the short ones.

- The variability of GRBs can be very fast. An individual pulse may rise on a timescale as short as a millisecond.

- The spectra of GRBs peak in the region between 100 keV and a MeV [5]. There is now a large interest in the so called X-ray rich bursts, or X-ray flashes which look like GRBs with the peak energies in the X-ray range. The spectra are non thermal and can be modelled by a broken power law, with the low energy photon index between 0 and unity, and a high energy index above 2. One has to note, however, that there are some bursts for which the high energy spectra appear to be rising with energy. There was a detection of GeV photons following a GRB (1.5 hours later), and recently a detection of TeV photons coincident with a burst.

- Within a burst the spectrum evolves from hard to soft. Also a similar evolution is seen in the spectra of individual pulses.

- Some GRBs are accompanied by optical flashes during the bursts [6,7]. In one case the flash was bright nearly enough to be observable with the aid of binoculars!

2.1. Afterglows

Gamma-ray burst afterglows are the phenomena following the GRB phase. As already mentioned above, the afterglows were discovered using the Beppo SAX satellite. After observing a GRB on February 27, 1997 the SAX team decided to observe the same field with an X-ray camera. Such observation was repeated three days later and the comparison of two images lead to identification of a fading X-ray source [8]. The X-ray source had a much more precise localization than the GRB itself. Further optical observations led to identification of a fading optical source [9], and identification of the host galaxy. Further optical observations provided an estimate of the redshift $z = 0.695$ and the distance to the source. Currently we know forty GRBs with measured redshifts.

The properties of the afterglows can be summarized as follows:

- GRB afterglows fade as a power law with time $F \propto t^{-\alpha}$ with $\alpha \approx -1$ in the early phase of the optical afterglow.

- A characteristic feature of the afterglows are achromatic breaks in the lightcurves [10, 11]. Such breaks take place typically a few days after the burst.

- The spectral of the afterglows are very broad and stretch from radio to the X-rays. They can be modelled by synchrotron emission from a non thermal plasma.

- There is some evidence for X-ray lines in some phases of the afterglows. Such lines are interpreted as atomic iron lines.

- The radio afterglows exhibit a very strong variability in the early phase of the afterglow and then a transition to a smooth behavior. The variability is consistent with being caused by galactic scintillation, and later ceases when the angular size of the source increases.

The discovery of afterglows led to identification of GRB host galaxies. GRBs take place inside the host galaxies, which are typical for their redshift. The GRB host galaxies are usually undergoing strong star formation episodes, what indicates a connection between GRBs and massive stars. Furthermore a GRB supernova connection seems to be now established quite clearly. A first indication of such correlation has been found in GRB980425 which appeared to take place simultaneously with supernova 1998bw, in a nearby galaxy at $z = 0.0085$ [12, 13]. Later the lightcurves of several afterglows showed bumps which could be interpreted as flaring of a supernova buried under the afterglow lightcurve and taking place at the same time. Recently a spectral analysis of some afterglows confirmed the association [14,15] in the optical observation of GRB030329.

The distribution of redshifts of the observed afterglows clusters between $z = 1$ and $z = 2$, and the largest measured redshift is $z = 4.5$ in the case of GRB000131.

2.2. *Summary and requirements for models*

The distance scale to GRBs and their measured fluxes immediately imply that the sources involve huge energies. The estimated isotropic luminosities are typically in the range between 10^{51}–10^{53} erg. Together with the spectral information (non thermal spectra), and the estimate of the size of the source from the very short variability it implies that the sources must involve extreme relativistic motion. For static sources the pair production optical depth would have been far too large to allow any non thermal spectrum to emerge [16]. The Lorentz factors of the relativistic bulk motion are typically above a few hundreds.

The observation of the host galaxies with intense star formation implies that the sources are connected with young massive stars or their remnants. This is also confirmed by the observed connection with supernovae. The energy requirements are consistent with such scenario, the energetically requirements are similar to the binding energy released in collapse of star, or to the energy available in the merger of a stellar mass black hole with a neutron star, or in a merger of two neutron stars.

3. Theoretical modelling

3.1. *Model of emission*

A standard model GRB phenomenon appeared over the past few years. Within the model it is assumed that there is a central engine which at some point produces the required energy of 10^{53} ergs and injects it in a small region of the size 10–100 km. I will discuss the possible candidates for the engine in the next subsection. The energy injection leads to formation of a fireball and to a relativistic outflow. The central engine must persist for the duration of the burst and produce a number of waves in the outflow. These waves will collide and form shocks, called internal shocks. In such shocks the electrons are rapidly accelerated and begin to radiate their energy out due to synchrotron as well as inverse Compton processes. This phase is responsible for the prompt gamma-ray emission. In each collision a forward and a reverse shock is formed. It has been found that the radiation emitted in the reverse (backward) shock will lead to optical or ultraviolet flash during the burst.

As the different waves collide and propagate outward they finally start to plough into the interstellar medium. This leads to further accelerating of the electrons at the cost of shock deceleration. Radiation in this phase forms the afterglow. It is much smoother than the prompt GRB emission. Since the motion is still relativistic the radiation is beamed in a narrow cone of the angular size with the size of inverse bulk Lorentz factor $\approx \Gamma^{-1}$. As the shock slows down the emission cone becomes larger and finally it becomes comparable to the angular size of the outflow. This takes place approximately at the same time as the light manages to cross the shock. At this time the radiation from the shock begins to fade away faster since the observable region is larger than the size of the shock. Moreover, the shock begins to expand sideways and slows down even faster. This process is responsible for the achromatic breaks in the lightcurves of gamma-ray bursts. The observations of the breaks in the lightcurves have been used to estimate the opening angles of the jets in some bursts, and to a precise estimate of the energies involved in these GRBs. It is surprising that the result showed that the typical energy in a burst is constrained to a narrow interval around 10^{51} erg [17].

3.2. Models of sources

The next question that needs to be answered is the nature of the enigmatic central engine. There are basically two major classes of models floating around the literature. The first one involves formation of a rotating black hole with the mass $\approx 10\ \mathrm{M}_\odot$ surrounded by an accretion torus of a similar perhaps somewhat smaller mass. The basic idea is that there will be strong magnetic fields in the system, and that these magnetic fields will aid in extraction of the rotational energy from the black holes through some variation of the Blandford–Znajek mechanism. An additional reservoir of energy in such system is gravitational energy that may be released through accretion from the torus onto the black hole. Such a configuration can be obtained in various astrophysical situations.

A natural way to form a black hole surrounded by dense matter torus is as a result of a merger of two neutron stars or a black hole and a neutron star. There is ample angular momentum in the system so that formation of a quickly rotating black hole is unavoidable. The neutron star is shredded by tidal forces and is likely to form an accretion torus, at the same time neutron star carry strong magnetic fields which can be amplified due to differential rotation. Thus, a coalescence naturally includes the necessary ingredients: a rotating black hole, an accretion torus and magnetic field. A similar configuration may also be attained in a merger of a neutron star or black hole with a helium star or a white dwarf.

The problem in these class of models is that the binary mergers may not necessarily take place inside galaxies. This is due to the fact that newly formed neutron stars receive large kicks, up to a few hundred $\mathrm{km\,s^{-1}}$ in the supernova explosions. A careful study of the distribution of merger sites of compact object binaries led to conclusion that black hole neutron star binaries may be excluded as GRB progenitors as they merge outside the host galaxies [18].

An alternative way to form a black hole with accretion torus is in the model of hypernova or a collapsar. This includes a rotating massive star which at some point undergoes a supernova-like collapse. A black hole is formed in the center of such star. Due to rotation of the star an accretion torus may be left around the newly formed black hole. In this case the required configuration is formed yet is embedded in the stellar matter. There remains a question if a jet or a relativistic outflow can plough through the star and blast off a gamma ray burst. Recent numerical simulation suggest that this may be possible. Such a scenario naturally predicts a correlation of the GRB site with a star forming region in host galaxy.

A different scenario involves a formation of a highly magnetized rotating neutron star in a supernova explosion [19]. The surrounding matter shell is ejected. The rotating neutron star will rotate differentially which shall amplify the magnetic field. The onset of the differential rotation may be triggered by instabilities on the surface of the neutron star. One such mechanism involves emission of gravitational waves through r-mode instabilities. This will slow down the crust and some differential rotation will inevitably take place. Once the magnetic field reaches about 10^{17} G it will start to dominate the dynamics of the star and may lead to ejection of a Poynting flux jet. Such jet will then be responsible for the gamma ray burst. Within these scenario gamma-ray burst will take place inside galaxies, and will be associated with supernovae. However there may be a delay between the supernova and the GRB.

4. Current issues and perspectives

The entire discussion regarding the nature of GRB sources is valid only for the bursts belonging to the long class. No afterglow was detected for any of the short bursts. Detection of such afterglows is simply a much more difficult task. The Beppo SAX satellite was sensitive to the long bursts only and could not trigger on the short ones. This may change in the near future with the launch of the SWIFT satellite, currently scheduled for September 2004. The nature and properties of the short bursts are still unknown.

Another interesting point in the GRB research is the discovery of correlations between the luminosity and other properties of the bursts. It appears that the variability of a burst is proportional to its luminosity [20, 21]. Similar relations have been found between the luminosity and the so called channel to channel lags [22], and the energy of peak emission with luminosity [23, 24]. A channel to channel lag is the amount of time between a peak at one and at another energy channel in the detector. This quantity is related to the total luminosity of a burst. The above relations have been found using the sample of currently forty GRBs with precise distance determinations through measurement of redshifts. What is the nature of this relations is still not clear.

Such relations can be used to determine the distance to GRBs in a similar way as Cepheid variability was used to measure distances to galaxies. Such an exercise was applied to a sample of GRBs observed by BATSE with the result that the redshifts of some GRBs was as high as $z = 30$. If true it implies that GRBs may be used as probes of the properties of the very early Universe and conditions at the epoch when first star were formed. Moreover the light from such distant GRBs could be used to probe the evolution and formation of the large scale structure in the Universe.

Another very interesting issue came from the observation of GRB021206 by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite. It found that the gamma ray emission is nearly totally polarized with the measured polarization degree of $80 \pm 20\%$ [25]. This observation seems to confirm the synchrotron model, yet it raises additional questions: Are all GRBs polarized? Are the magnetic fields in the jet ordered?

Observations have always been the driving force of the GRB research. There is a number of satellites involved in the observations of GRBs at this moment. One should mention here the HETE-2 mission, which lead to establishing a firm supernova GRB connection recently, and the INTEGRAL observatory where some components of the Burst Alert System have been done at the Space Research Center in Warsaw. The future also looks promising. I have already mentioned the SWIFT satellite to be launched later this year. The GLAST satellite to be launched in 2007 will allow investigation of GRB properties in the GeV range. These instruments are supported by a number of ground based observatories, including rapid response telescopes that are ready to observe a GRB field within seconds of a localization information from a satellite.

One has to note that the development of non electromagnetic instruments like the gravitational wave observatories: LIGO and VIRGO may aid understanding of GRBs. A detection of a gravitational wave accompanying a GRB would definitely shed light on inner working of the GRB central engine. All models of GRBs predict large emission of neutrinos. In some models these neutrinos should be detectable with the upcoming detectors like *e.g.* ICE cube.

There is quite a number of GRB reviews that are more detailed than this paper and can be recommended for more detailed study of these phenomena. The GRB observations have been described in [26–28]. Theories of GRBs have been described in [29,30]. There is also a number of general reviews of GRBs [31–40] and recently [41].

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