GAMMA-RAY BURSTS

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Abstract

Gamma-ray bursts (GRB) are sudden, intense flashes of gamma rays which, for a few seconds, light up in otherwise dark gamma-ray sky. They are detected at the rate of about once a day, and while they are on, they outshine every other gamma-ray source in the sky, including the sun. Major advances have been made in the last three or four years, including the discovery of slowly fading x-ray, optical and radio afterglows of GRBs. In this paper I’ll show some characteristics of GRBs and will apply some models to these observations.
1 Introduction

Gamma-Ray Bursts (GRBs) were first reported in 1973, based on 1969-71 observations by the VELA military satellites monitoring for nuclear explosions in verification of the Nuclear Test Ban Treaty. When these mysterious gamma-ray flashes were first detected, which did not come neither from Earth’s nor from Sun’s direction, the first suspicion was that they might be the product of an advanced extraterrestrial civilization. Soon, however, it was realized that this was a new and extremely puzzling cosmic phenomenon. A major advance occurred in 1991 with the launch of the Compton Gamma-Ray Observatory (CGRO), whose results have been summarized in [1]. The all sky survey from the Burst and Transient Experiment (BATSE) onboard CGRO, which measured about 3000 bursts, showed that they were isotropically distributed, suggesting a cosmological distribution.

Until a few years ago, GRBs were thought to be just that, bursts of gamma-rays which were largely devoid of any observable traces at any other wavelengths. A dramatic development in the last years has been the measurement and localization of fading x-ray signals in relation with GRBs by the Beppo-SAX satellite. These afterglows, lasting typically for weeks, made possible the optical and radio detection of afterglows, which mark the location of the fiery and brief GRB event. These afterglows in turn enabled the measurement of redshift distances, the identification of host galaxies, and the confirmation that GRBs were in fact at cosmological distances of the order of billions of light-years, similar to those of the most distant galaxies and quasars. Even at those distances they appear so bright that their energy output during its brief peak period has to be larger than that of any other type of source\(^1\). This

\(^1\)The energy is of the order of a solar rest-mass if isotropic, or some percent of that if collimated.
energy output rate is comparable to burning up the entire mass-energy of the sun in a few tens of seconds, or to emit over that same period of time as much energy as our entire Milky Way does in hundred years.

Much work has been concentrated on modelling the central engine responsible for such energy release. The main ideas invoke the formation of several solar mass black hole with a disrupted debris torus which is rapidly accreted. This can result from either the merger of a compact binary\(^2\) or from the tidal disruption of a solar-mass star by a supermassive black hole (SMBH).

## 2 Temporal characteristics of GRBs

One of the features of the time profiles of GRBs are their morphological diversity and the large range of their durations. Because of this diversity it is very difficult to classify the bursts into well defined types, based on their time profiles. Despite the huge differences in time profiles of GRBs, Fishman and Meegan [1] managed to classify gamma-ray bursts into four classes:

1. single pulse or spike events (Figure 1);
2. smooth, either single or multiple, well defined peaks (Figure 2);
3. distinct, well-separated episodes of emission (Figure 3);
4. very erratic, chaotic, and spiky bursts (Figure 4).

![Figure 1: Examples of single spike events.][12]

\(^2\)Such binary is for example a double neutron star, observed in gamma-rays but so far without identified long-wavelength afterglows.
Figure 2: Examples of strong bursts that show no structures on fine time scales.[12]

Figure 3: Bursts that have distinct, well-separated episodes of emission.[12]

Figure 4: Examples of GRBs with complex temporal structures.[12]

The single pulse events have little or no additional structure. The approximate range of the duration of these bursts is from \( \sim 30 \) ms to \( \sim 100 \) s. In many of the smooth, multiple-peak events of class 2, the rise-times and fall-times tend to be similar. The events of class 3 show relatively long periods of time between the peaks during which there is no detectable emission. The total time of these no-activity intervals can
be much longer than that of the detectable emission. Most of the class 4 bursts are highly structured, many of them having complex and overlapping peaks. The duration of peaks is < 0.1 s. In many of these bursts, there seems to be an underlying “envelope” of emission from which the peaks arise. Another property of all the GRB time profiles is that at higher energies the overall burst durations are shorter and the spikes within a burst are sharper.

The durations of GRBs range from about 30 ms to over 1000 s. However, the duration, like the burst morphology, is difficult to quantify because it depends on the intensity and background and the time resolution of the experiment. The BATSE group has settled on a T-90 measure which is the time over which 90% of the burst fluence is detected. The distribution of the durations is shown in Figure 5.

![Figure 5: The duration distribution of gamma-ray bursts from BATSE catalog.][14]

A bimodality is seen in the logarithmic distribution, with broad peaks around 0.3 s and 70 s and a minimum at around 2 s. The distribution drop-off at short durations is due to an instrumental bias - the minimum time scale over which the BATSE experiment can trigger on bursts is 64 ms. So if there exist gamma-ray bursts with shorter durations we have no means of detecting them for the time being.

3 Spectral characteristics of bursts

A unique feature of GRBs is their high-energy emission. Almost all of the energy is emitted above 50 keV. Most bursts have a simple non-thermal continuum spectrum.

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3Some care should be taken when classifying weak bursts as type 3, because there is less certainty in distinguishing periods of emission.

4Fluence is the energy flux of the burst integrated over the total time of the event.
Figure 6 shows a typical burst spectrum from 0.1 MeV to 10 MeV, with the peak energy at about 600 keV.

Figure 6: Left: The spectrum of GRB 910601 observed over a wide energy range. Right: The spectrum of GRB 910503.[1]

Although the spectral shapes of many bursts are similar, the energy at which peak power is emitted changes from burst to burst and changes rapidly within a burst. Some significant changes on time scales as short as milliseconds have been observed. Within most bursts, a hard-to-soft spectral evolution is observed which results in the lower energies peaking earlier. It has also been noted that shorter bursts tend to have harder spectra as measured by hardness ratio (Figure 7).  

Figure 7: The hardness vs duration of gamma-ray bursts.[1]

An interesting spectral comparison has been made between short single pulse bursts and short spikes of comparable duration that are found in within longer GRBs.

[1] Hardness ratio is the ratio between the number of photons in high energy band and the number of photons in low energy band.
The two have different spectral properties. There are indications that the spikes have a lower average photon energy than the single pulse bursts.

There were reports of spectral lines in GRBs which were interpreted as cyclotron lines produced in the intense magnetic fields of neutron stars. These lines were the main reason for associating GRBs with neutron stars. While it had been widely accepted that spectral lines are superposed on the continuum of many GRBs, now it is generally thought that that is not the case. A search for lines (either absorption or emission) with the BATSE detectors has so far been unable to confirm the earlier reports of spectral lines.  

4 Spatial distribution

The most direct evidence of the spatial distribution of the sources of GRBs comes from their observed angular and intensity distributions. The angular distribution provides two of the dimensions of the spatial distribution, while the intensity distribution is a convolution of the unknown luminosity function and the unknown radial distribution. Even though neither distribution function is known, the intensity distribution data can provide strong constraints on the allowable spatial distributions and luminosity functions of GRB sources.

Let us assume that the sources are standard candles distributed homogeneously in Euclidian space, i.e. the density and luminosity functions are independent of position throughout the observed volume of space. Let $E$ be the energy of the burst, $S = E/r^2$ the signal we receive (peak flux), and $n(S) = dN/dS$ the intensity distribution of bursts. The number of bursts $dN$ with the peak flux $S$ in the interval $[S, S + dS]$ is therefore

$$dN = n(S) dS = n_r 4\pi r^2 dr = -\frac{1}{2} n_r \frac{E^3}{\sqrt{4\pi}} S^{-\frac{3}{2}} dS,$$

(1)

where $n_r = dN/dV$ is the density of bursts. If bursts are distributed homogeneously in space, $n_r$ is constant. The number of all bursts with the peak flux greater than $S$ is

$$N(> S) = \int_{S}^{\infty} n(S) dS = -\frac{1}{2} n_r \frac{E^3}{\sqrt{4\pi}} \int_{S}^{\infty} S^{-\frac{3}{2}} dS = \frac{1}{3} n_r \left(\frac{E}{S}\right)^{\frac{3}{2}},$$

(2)

which is known as the $-3/2$ power law. The distribution shown in Figure 8 significantly deviates from the power law (dashed line).

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6Although some lines are occasionally seen by one of the BATSE detectors during a portion of a
To test the homogeneity assumption, one performs the $V/V_{\text{max}}$ test, which is as follows. With $S = E/r^2$ and the equation (2) one gets for $N$

$$N(> S) = \frac{1}{3} n_r 4\pi r^3 = n_r V . \tag{3}$$

This means that for each burst, there is a corresponding volume of space $V$ which is covered by the signal of the burst. Let $V_{\text{max}}$ be the maximum volume of space our detector covers. The ratio $V/V_{\text{max}}$ then becomes $V/V_{\text{max}} = (S_{\text{min}}/S)^{3/2}$, and if bursts are indeed homogeneously distributed in space, this ratio will be uniformly distributed between 0 and 1. The probability density $w$ to find a burst within a space of volume $V$ will therefore be constant $w = 1/V_{\text{max}}$. The average volume $< V >$ covered by all detected bursts is

$$< V > = \int_0^{V_{\text{max}}} w V dV = \frac{V_{\text{max}}}{2} . \tag{4}$$

So the average value of the $V/V_{\text{max}}$ test is $< V/V_{\text{max}} > = 1/2$ for homogeneously distributed bursts. The BATSE observations give $< V/V_{\text{max}} > = 0.32 \pm 0.01$ and the observations from other experiments are very similar.\(^7\) In summary, intensity distributions show conclusively that the distribution of sources is not homogeneously burst, none of them has been verified at a high enough confidence level by another detector.\(^8\)

\(^7\)Standard candles are light sources of known luminosity.

\(^8\)Observations from the Solar Max Mission give $< V/V_{\text{max}} > = 0.400 \pm 0.025$; Ginga $< V/V_{\text{max}} > = 0.35 \pm 0.035$; PHEBUS-GRANAT $< V/V_{\text{max}} > = 0.376 \pm 0.017$. 

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Figure 8: Left: The peak flux distribution of 796 gamma-ray bursts observed by BATSE. The flux is measured over the energy range 50-300 keV. The diamonds represent the number of bursts observed, and the crosses represent the number of bursts after correcting for trigger efficiency. Right: The log $N – \log P$ distribution from combined BATSE and PVO data. The PVO data, which has recorded more strong bursts than BATSE during its long lifetime, is seen to follow a $−3/2$ power law for strong bursts.[1]
distributed in space.

The distribution in galactic coordinates of 2704 bursts observed by BATSE is shown in Figure 9. The apparent isotropy, supported by statistical analysis, has severely challenged the hypothesis that bursts originate within the galaxy.

![2704 BATSE Gamma-Ray Bursts](image)

Figure 9: The locations of 2704 Gamma-Ray Bursts recorded with BATSE in galactic coordinates.[13]

However, a satisfactory geometrical model, by which burst sources originate in an extended Galactic halo, can also be constructed. Isotropy of observed bursts requires the size of the halo to be significantly greater than the distance between Earth and the Galactic center. The radial distribution and luminosity function can be adjusted to reproduce the observed intensity distribution. Hakkila et al (1994) compared BATSE observations to several galactic models. Their study determined that a simple extended halo model is acceptable if the halo extends beyond 125 kpc, but not beyond 400 kpc. It must be noted, however, that there is no direct physical or other observational evidence for such an extended Galactic halo. Its existence is postulated specifically to solve the gamma-ray burst problem.

On the other hand, the observed isotropy is a necessary requirement for cosmological models. The apparent inhomogeneity could result from redshift effects and possible source evolution. Cosmological distributions have been fit to the observed intensity distribution and satisfactory fits can be found using standard candle luminosities, standard cosmologies, and no source evolution.

A great breakthrough happened with the discovery of GRB afterglows and their host galaxies. On 28 Feb 1997 BeppoSAX detected the first clear evidence of X-ray emission - the X-ray afterglow - following GRB 920228. The X-ray source was seen to vary by a factor of 20 in 3 days. The X-ray fluence was \( \sim 40\% \) of the GRB
fluence, implying that the afterglow was not only the low-energy tail of the GRB, but also a significant channel of energy dissipation of the event on a completely different timescale. The precise X-ray position led to the discovery of the first optical afterglow. Finally, after two years, the redshift of this object has been determined as $z=0.695$, confirming its extragalactic nature. What is more, the required energies of isotropic GRBs at such distances are of the order of $10^{43}$ J or even as high as $10^{47}$ J, which is of the order of the rest mass energy of the Sun ($M_\odot \approx 2 \cdot 10^{47}$ J).

5 Models of gamma-ray bursts

While there have been many theoretical papers proposing a wide range of scenarios for GRBs, none provide a complete theory. That is, none have provided complete details specifying the site, the energy source, and an analysis of the energy emission processes. Perhaps the most difficult task has been deriving the observed burst properties from considerations of energy transport. For example, the intense gamma radiation would be expected to heat the neutron star surface, producing an intense thermal x-ray component, which has not been observed. So the challenge to theorists is to put this much energy into a burst with nonthermal spectrum of almost exclusively gamma rays, lasting of the order of 10 seconds.

The first models trying to explain GRBs were based on supernova explosions. Because of short durations and high luminosities, the emitting regions must be very small and photon densities very high which is easily achieved in a SN explosion. The energy emitted during a supernova is approximately of the same order of magnitude as the total energy emitted by a GRB. However, there are two major differences between the two phenomena. The energy in a GRB event is released much more rapidly than in a supernova, and the supernova radiation is thermalized. Because of these differences it was a surprise when the supernova SN1998bw was found in the error box of GRB 980425. The supernova occurred within $\pm 1$ day of the GRB event and lies in a galaxy at $z = 0.0085$. If the GRB was at this distance, its luminosity would be about $10^5$ smaller than that of a normal GRB. Another hint to a connection between SN and GRB events is based on photometric curves of optical afterglow of GRB980326. Some researchers believe that it reflects an underlying supernova (Fig. 10 Left). These results suggest that at least a fraction of GRBs may originate from a collapse of a supermassive star.

The SN model mainly explains the afterglows. In the standard model of GRB afterglows it is expected that after some kind of explosion, a relativistically ($\Gamma \sim 10^2 - 10^3$) expanding jet of plasma is formed - fireball. The GRB itself is thought to be produced
by a series of internal shocks due to collisions amongst layers expelled with different velocities that are being caught up by each other (Fig. 10 Right). When the fireball runs into the surrounding medium, a shock ploughs into the medium (this is called external shock scenario), and sweeps up the interstellar matter, decelerating to non-relativistic velocities and producing an afterglow at frequencies gradually declining from X-rays to radio wavelengths. However, the calculated spectra obtained in the framework of such a model are much softer than observed. On the contrary the afterglow emission can well be due to external shocks [9].

Another model that needs to be discussed is the tidal disruption model. In this model a star passes by a supermassive black hole and gets disrupted by tidal force. However, two conditions must be met for the disruption to occur. First, the star with a mass \( m \) and radius \( r \) must approach the black hole of mass \( M_{BH} \) to less than the Roche radius \( r_R \):

\[
r_R = \left( \frac{M_{BH}}{m} \right)^{\frac{1}{3}} r,
\]

and second, the Roche radius must lie outside the Schwarzschild radius\(^9\). Therefore a solar type star may be disrupted only by black holes less massive than \( 10^8 M_\odot \). If the black hole is more massive than that, the Roche radius lies beyond the horizon and the star is swallowed as a whole.\(^{10}\)

\(^9\)Schwarzschild radius is \( R_{Sch} = \frac{2M_{BH}G}{c^2} \). For Sun it is 2.96 km, and for Earth 8 mm.

\(^{10}\)More massive black holes may still strip the atmospheres of giant stars.
Simulations of encounters between a solar type star and a supermassive black hole have been made very recently [2]. Simulations show that large luminosity variations occur on timescales of a few \( M \) to a few \( 100M \).\(^{11}\) It was determined that gravitational lensing plays a very important role in determining the shape of the light curve. When lensing takes place the relevant part of the star is imaged into an Einstein disk making the apparent luminosity to increase manyfold (Fig. 11).

![Figure 11: A tidally disrupted star as seen edge on.][2]

Although in this model all particle interactions were neglected, the calculated timescales and energies are remarkably similar to the measured ones, but the spectra would still be thermal.

### 6 Conclusion

Gamma-ray bursts are very powerful and short events which are detected approximately once a day. They are classified into four types based on time profiles. The duration distribution of bursts is bimodal with peaks at around 0.3s and 70s and a minimum at 2s. The nature of this bimodality is still unknown.

Bursts have simple, non-thermal continuum spectrum. Although there were some reports of spectral lines, they were not verified by other detectors. Most of the energy emitted is above 50 keV and changes from burst to burst - shorter bursts tend to have harder spectra.

Probably the most important question was, whether bursts are at cosmological distances or in the halo of our Galaxy. With BATSE experiment, the halo hypothesis was severely challenged because the experiment showed the bursts to be distributed

\(^{11}\)For a \( 10^6M_\odot \) black hole these correspond to time spans from \(~5\) s to \(~10\) min, for a black hole with mass \( 10^{10}M_\odot \) the times are from \(~10\) hrs to few months.
isotropically. Also the test of homogeneity was performed indicating that bursts are not homogeneously distributed. The final confirmation of extragalactic origin of bursts came with the discovery of afterglows at cosmological distances.

Most models put supermassive black holes at the centre of burst sources. One such model is the tidal disruption model. In this model the star, which passes by the black hole, is tidally disrupted, thus exposing the inner hot regions. This model is in very good agreement with observations as far as the timescales and energies are concerned. The spectra, however, would still be thermal.

Until now no models can satisfactorily explain all of the observed features of GRBs.

References


