

# Gamma-Ray Bursts and Cosmology

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**Abstract** A general review of the study of Gamma Ray Bursts (GRB) in the cosmological context is provided. The GRB, which distance was unknown since a few years ago, are now among the different astrophysical sources the most promising tool for doing cosmology.

**Key words:** gamma-rays: bursts – cosmology: observations

## 1 INTRODUCTION

The mystery of GRB origin, debated since their discovery in 1973 (Klebesadel et al. 1973) is in the right direction to be solved due to the confirmation of their cosmological distance (Costa et al. 1997, Metzger et al. 1997). The solution of what is the source that causes these intense flares of gamma-rays is still debated. However, their cosmological distance is now generally accepted. There is also a growing consensus that GRB could be powerful tools to study cosmology, mainly because of their instanteneous luminosity and their association with death of massive stars in star forming galaxies. The expected results coming from new satellites such as Swift will improve the knowledge in this field. In this review we describe the connection of GRB with cosmology, taking into account the first studies based on global properties, the observations of GRB with determined redshift and the expectations for the new satellites. Here we follow the description of GRB that could be found in the excellent reviews on the subject proposed by Piran (1999) and Hurley et al. (2003).

## 2 GENERAL PROPERTIES

Gamma-ray bursts (GRB) are intense non-thermal bursts of  $\sim 100\text{ keV} - 1\text{ MeV}$  photons. Observed durations vary from several milliseconds to several thousand seconds (Fishman & Meegan 1995).

The shortest burst, detected by the BATSE experiment on board the CGRO, had a duration of 5 ms with sub-structures of 0.2 ms (Bhat et al. 1992). The longest so far, was detected in the GeV range by EGRET on CGRO one and a half hours after the main burst (Hurley et al. 1994). The distribution of burst durations is bimodal. The distribution can be divided into two sub-groups: long bursts with duration longer than 2 s and short bursts with total duration less than 2 s (Kouveliotou et al. 1993). The GRB time profile vary considerably from one burst to

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another. In most bursts, the typical variation takes place on a time-scale significantly smaller than the total duration of the burst.

GRB are characterized by emission in the few hundred keV ranges with a non-thermal spectrum. Most bursts are accompanied by a high energy tail which contains a significant amount of energy. GRB940217, for example, had a high energy tail up to 18 GeV (Hurley et al. 1994). Recently a high energy component was discovered in GRB941017 (González et al. 2003).

The spectrum is normally fit by two power law smoothly joined around  $E_{\text{peak}}$  where the source emits the bulk of its luminosity (Band et al. 1993). The distribution of  $E_{\text{peak}}$  derived from BATSE data is quite narrow (Mallozzi et al. 1995) peaking around a few hundred keV, which is surprising considering the great diversity exhibited by most other GRB characteristics. The GRB spectrum varies during the bursts. For bursts with multiple peak emission, later spikes tend to be softer than earlier ones.

The most recent breakthrough in the understanding of GRB came from the detection of the afterglow, a long duration emission in longer wavelengths. It was first detected in the X-rays by the BeppoSAX satellite in 1997 (Costa et al. 1997). Then it was confirmed for many bursts from the optical to the radio band (van Paradijs et al. 2000). The detection of the afterglow decaying flux, which timescale is longer than the prompt GRB gamma-ray emission, led to the detection of the host galaxies and then the determination of the GRB cosmological distance (Metzger et al. 1997).

The cosmological origin of GRB immediately implies that they are the most luminous sources in the sky. They release  $\sim 10^{51} - 10^{53}$  ergs or more in a few seconds. In the generic picture of a cosmological GRB model (e.g. Sari & Piran 1997; Mészáros & Rees 1997) the observed  $\gamma$ -rays are emitted when an ultra-relativistic energy flow is converted to radiation. Possible forms of the energy flow are kinetic energy of ultra-relativistic particles or electromagnetic Poynting flux. This energy is converted to radiation in an optically thin region, as the observed bursts are not thermal. It has been suggested that the energy conversion occurs either due to the interaction with an external medium, like the ISM or due to internal process, such as internal shocks and collisions within the flow (for a review see Piran (1999)).

The “inner engine” that produces the relativistic energy flow is hidden from direct observations. However, the observed temporal structure reflects directly this engine activity. This model requires a compact internal engine that produces a wind – a long energy flow (long compared to the size of the engine itself) – rather than an explosive engine that produces a fireball whose size is comparable to the size of the engine. Not all the energy of the relativistic shell can be converted to radiation (or even to thermal energy) by internal shocks. The remaining kinetic energy will most likely dissipate via external shocks that will produce an afterglow in different wavelength (for a review see Mészáros (2002)) .

Recent observations (Hurley et al. 2003) suggest that possibly they are related to collapses and subsequent explosions of massive stars. Their energetics is similar to supernovae, to which they may indeed be related in some cases.

### 3 GRB AND COSMOLOGY IN THE “BATSE” ERA

The universe and our Galaxy are optically thin to low energy  $\gamma$ -rays. Thus GRB constitute a unique cosmological population that is observed practically uniformly on the sky. Most of these objects are located at  $z \approx 1$  or greater. Thus this population is farther than any other systematic sample. GRB are, therefore, an ideal tool to explore the Universe. One of the most remarkable findings of BATSE was the observation that the angular distribution of GRB positions on the sky is perfectly isotropic. It was generally believed, prior to the launch of BATSE, that GRB were associated with galactic disk neutron stars. It has been expected that more sensitive detectors would discover an anisotropic distribution that would reflect the planar structure of

the disk of the galaxy. BATSE's distribution is instead, within the statistical errors, in complete agreement with perfect isotropy (Briggs et al. 1995). BATSE observations of the isotropy of GRB directions, combined with the deficiency of faint GRB, ruled out the galactic disk neutron star model and make a convincing case for their extra-galactic origin at cosmological distances (Fishman 1995)

The peak intensity distribution has been used to give an estimate to the distance of GRB (Piran 92). The limiting fluence observed by BATSE is  $\approx 10^{-7}$  erg/cm<sup>2</sup>. The actual fluence of the strongest bursts is larger by two or three orders of magnitude. A plot of the number of bursts vs. the peak flux depicts clearly a paucity of weak bursts. The peak count distribution is incompatible with a homogeneous population of sources in Euclidean space. It is compatible, however, with a cosmological distribution (Piran 1996, Katz & Canel 1996). A homogeneous count distribution, in an Euclidean space should behave like:  $N(C) \propto C^{-3/2}$ , where  $N(C)$  is the number of bursts with more than  $C$  counts per second. The observed distribution is much flatter and is compatible with a cosmological distribution of sources. A homogeneous cosmological distribution displays the observed trend - a paucity of weak bursts relative to the number expected in a Euclidean distribution. In a cosmological population four factors combine to make distant bursts weaker and by this to reduce the rate of weak bursts: (i) K correction - the observed photons are red-shifted. As the photon number decreases with energy this reduces the count rate of distant bursts for a detector at a fixed energy range. (ii) The cosmological time dilation causes a decrease (by a factor  $1+z$ ) in the rate of arrival of photons. For a detector, like BATSE, that measures the count rate within a given time window this reduces the detectability of distant bursts. (iii) The rate of distant bursts also decreases by a factor  $1+z$  and there are fewer distant bursts per unit of time (even if the rate at the comoving frames does not change). (iv) Finally, the distant volume element in a cosmological model is different than the corresponding volume element in a Euclidean space (Piran 1999).

Another cosmological effect was discussed prior to the direct measurement of GRB distance, the time-dilation. Norris et al. (Nemiroff et al. 1994, Norris et al. 1995) examined 131 long bursts (with a duration longer than 1.5s) and found that the dimmest bursts are longer by a factor of  $\approx 2.3$  compared to the bright ones. Fenimore and Bloom (1995) find that when the fact that the burst's duration decreases as a function of energy as  $\Delta t \approx E^{-0.5}$  is included in the analysis, the measured time dilation corresponds to larger distances.

#### 4 GRB AND COSMOLOGY IN THE "AFTERGLOW" ERA

One of the main problems in resolving the GRB mystery was the lack of identified counterparts in other wavelengths. This has motivated numerous attempts to discover GRB counterparts. The search for counterparts is traditionally divided to efforts to find a flaring (burst), a fading or a quiescent counterpart.

The breakthrough came in early 1997, when the Italian-Dutch satellite BeppoSAX obtained their first accurate positions of GRB (several arcminutes). This allowed rapid follow-up observations which led to the discoveries of X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997), millimeter (Bremer et al. 1998) and radio (Frail et al. 1997) counterparts of GRB. These observations quickly settled the distance controversy. Detection of absorption features in the optical transient spectrum of GRB 970508 (Metzger et al. 1997) established that this event was at a redshift greater than  $z = 0.835$ . Starting with this first redshift measurement, which unambiguously demonstrated the cosmological nature of GRB there are now over 30 redshifts measured for GRB hosts and/or afterglows. The median redshift is  $\langle z \rangle \approx 1.0$ , spanning the range from 0.25 (or 0.0085, if the association of GRB 980425 with SN 1998bw is correct) to 4.5 (for GRB 000131). These discoveries revolutionized GRB studies.

Most cosmological models suggest that GRB are in a host galaxy. If so, then deep searches within the small error boxes of some localized GRB localized should reveal the host galaxy to which they belong. Until the discovery of GRB afterglow these searches have yielded only upper limits on the magnitudes of possible hosts. This situation has drastically changed with afterglow observations and the “no host” problem disappeared. These observations have allowed an accurate position determination and led to the identification of host galaxies for several GRB. Most of these host galaxies are dim. The missing cases are at least qualitatively consistent with being in the faint tail of the observed distribution of host galaxy magnitudes. The magnitude and redshift distributions of GRB host galaxies are typical for the normal, faint field galaxies, as are their morphologies (Bloom et al. 2002)

Within the host galaxies, the distribution of GRB-host offsets follows the light distribution closely (Bloom et al. 2002), which is roughly proportional to the density of star formation (especially for the high- $z$  galaxies). It is thus fully consistent with a progenitor population associated with the sites of massive star formation.

Besides of the possibility to localize the GRB, the detection of the afterglow led to other interesting results. First of all there is a growing evidence that the gamma-radiation is strongly beamed, within a cone whose opening angle is only several degrees (Frail et al. 2001) and thus that the total energy emitted in the prompt phase is more or less two orders of magnitude smaller than previously estimated. The burst rate was estimated in the BATSE era, with the use of the cumulative brightness distribution (the  $\log N - \log S$  curve), to about  $10^{-7}$  bursts per year per galaxy (Schmidt 1999; Schmidt 2001). However, if the emission is collimated to  $\Omega \ll 4\pi$  then we do not see most of the events. The true event rate is then larger than that measured by BATSE by a factor of  $4\pi/\Omega$ .

The most intriguing recent result however is the confirmation of the association of GRB with supernovae. The first such event was GRB980425 (Galama et al. 1998), a burst whose position and time of occurrence were both consistent with those of an optical supernova, 1998bw. In other cases, supernova-like bumps in the afterglow light curves have been identified and attributed to underlying supernovae (Bloom et al. 1999). The recent detection of GRB030329 associated with the 2003dh is the first undoubted association of GRB with supernovae (Stanek et al. 2003). This will open the most interesting use of GRB in cosmology as probes of the early phases of star and galaxy formation, and the resulting reionization of the universe at  $z \sim 6 - 20$ . If GRB reflect deaths of massive stars, their very existence and statistics would provide a unique probe of the primordial massive star formation and the initial mass function. (see, e.g., Lamb & Reichart 2001; Loeb 2002; Loeb 2003). There are two lines of argument in support of the existence of large numbers of GRB at  $z > 5$  or even 10. First, a number of studies using photometric redshift indicators for GRB suggests that a substantial fraction (ranging from  $\sim 10\%$  to  $\sim 50\%$ ) of all bursts detectable by past, current, or forthcoming missions may be originating at such high redshifts, (Reichart et al. 2001; Lloyd-Ronning et al. 2002). Second, some modern theoretical studies suggest that the very first generation of stars, formed through hydrogen cooling alone, were very massive, with  $M \sim 100 - 1000 M_{\odot}$  (Bromm et al. 2001; Bromm et al. 2002; Abel et al. 2002). It is also not yet completely clear that the end of such an object would generate a GRB, but that too is at least plausible (Fryer et al. 2001). Thus, there is some real hope that significant numbers of GRB and their afterglows would be detectable in the redshift range  $z \sim 5 - 20$ , spanning the era of the first star formation and cosmic reionization (Bromm & Loeb 2002).

Finally, absorption spectroscopy of GRB afterglows is now becoming a powerful new probe of the the interstellar matter in high redshift galaxies. The key point is that the GRB almost by definition (that is, if they are closely related to the sites of ongoing or recent massive star formation) probe the lines of sight to dense, central regions of their host galaxies This opens

the interesting prospect of using GRB absorbers as a new probe of the chemical enrichment history in galaxies (Hurley et al. 2003)

## 5 CONCLUSIONS

Due to recent observations now it is generally accepted that GRB occur in a star-forming region of a galaxy at a redshift  $z \approx 1$ . In currently popular models, it is caused by the collapse of a massive star ( $\approx 30$  solar masses). While interesting on their own, GRB are now rapidly becoming powerful tools to study the high-redshift universe and galaxy evolution, thanks to their apparent association with massive star formation, and their brilliant luminosities.

The cosmological evolution of luminous matter and gas in the universe could be studied with different methods. Studies of GRB could be useful in most of them. Their hosts could be detected directly. Secondly the afterglow radiation could either be absorbed by the host galaxy or by the intervening interstellar matter (Hurley et al. 2003).

The new satellites, such as Swift<sup>1</sup> will give new insights in this field giving a very rapid distribution of precise localizations and allowing the detection of bright associated transients even at cosmological distances.

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<sup>1</sup> <http://swift.gsfc.nasa.gov>

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