Gamma-Ray Burst–Supernova relation

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There is growing evidence that long and hard gamma-ray bursts (GRBs), discovered at redshifts between 0.4 and 3.4, are related to some type of supernova (SN) explosions. The GRB ejecta are ultra-relativistic, and possibly beamed. There is a possibility that some SN ejecta are also beamed and/or relativistic. Prospects for further advances guided by expected and unexpected observational developments are very good. The prospects for developing a sound and quantitative GRB theory any time soon are rather modest, if histories of quasars, radio pulsars and supernovae are used for reference. However, the current progress in the understanding of GRB afterglows (which are relativistic) and remnants (which are non-relativistic) is likely to continue, as these appear to be simpler than the GRBs.

According to the current analysis of GRB 970508 the energy of gamma rays released by this event was about the same as the total energy of explosion. If correct, this result is difficult to reconcile with the internal shock models. It also implies that the global energy generation rate by GRBs is four orders of magnitude lower than the rate due to ordinary supernovae, which makes it very unlikely that the highly energetic supernova remnants were created by GRBs.

1. Introduction

The most dramatic recent breakthrough in our understanding of gamma-ray bursts (GRBs) was made by the *BeppoSAX* team, which discovered the first X-ray afterglow (Costa et al. 1997). That was quickly followed with the discovery of optical (van Paradijs et al. 1997) and radio (Frail et al. 1997) afterglows, and the determination of the first optical redshift (Metzger et al. 1997). By now about two dozen afterglows were detected, almost all within fraction of an arc second of very faint galaxies, with typical R-band magnitudes 24–26. Approximately ten redshift were measured. Gradually evidence emerged that GRBs appear to be associated with star forming regions (Paczyński 1998, Kulkarni et al. 1998, Galama et al. 1998). In several cases a direct association with a supernova (SN) appeared: GRB 980425–SN 1998bw (Galama et al. 1998), GRB 980326 (Bloom et al. 1999, Castro-Tirado & Gorosabel 1999), and GRB 970228 (Reichart 1999, Galama et al. 1999).

We should keep it in mind that all this exciting development is for the long duration GRBs, as these were the only type for which accurate coordinates became available within hours of the burst. The rest of this paper is about the long gamma-ray bursts only.

Until recently the most popular models of gamma-ray bursts (GRBs) were related to merging neutron stars, and neutron stars merging with stellar mass black holes. However, these would be located far away from star forming regions, and far away from parent dwarf galaxies. This does not seem to be the case for the location of GRB afterglows, and this is the reason why an association of bursts with explosions of massive stars became popular.

Throughout this paper I shall adopt popular assumptions and terminology. The bursts with strong high energy spectra require very large bulk Lorentz factors, $\Gamma > 300$, to reconcile their rapid variability with their huge luminosities and no evidence for spectral cut-off due to pair creation (Baring & Harding 1996). During its activity GRB's intensity varies rapidly. Several seconds or minutes after the beginning of the burst an afterglow becomes dominant, as recently shown by Burenin et al. (1999). The afterglows fade smoothly, usually as a broken power law of time, and they are almost certainly due to

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the interaction between the relativistic ejecta and ambient medium. Their emission is non-thermal, and thus it is fundamentally different form a thermal emission of a non-relativistic supernova. When the ejecta decelerate to non-relativistic expansion a GRB remnant is created, and at this stage it may resemble a supernova remnant.

2. Rates

I adopt Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1} throughout this paper.

According to Wijers et al. (1998) the energy generation rate due to GRBs is at present epoch (i.e. $z = 0$) equal

$$\epsilon_{\rm GRB,0} \approx 10^{52} \ {\rm erg \ Gpc^{-3} \ yr^{-1}} \quad , \tag{2.1}$$

assuming that the GRB rate follows the star formation rate as a function of redshift. Note, that this number is independent of beaming of GRB emission. If there is beaming the energy per GRB is reduced, but the number of GRB explosions increases, so that the product, i.e. $\epsilon_{\rm GRB,0}$ remains unchanged. Using a very different analysis Schmidt (1999) obtained the GRB energy generation rate about the same as Wijers et al. (1998).

The rate of all types of supernovae is approximately 1.5 per 10^{10} $L_{B,\odot}$ per century (van den Bergh & Tammann 1991). The mass density of the universe is probably $\Omega_m \approx 0.25$, and the average mass to blue light ratio is $M/L_B \approx 200$ M$_\odot$/L$_\odot$ (Bahcall et al. 1995). Therefore, the blue luminosity within one cubic gigaparsec is $\sim 1.6 \times 10^{17}$ L$_\odot$, and the local supernova rate is

$$n_{\rm SN} \approx 2.4 \times 10^5 \ {\rm Gpc^{-3} \ yr^{-1}} \quad . \tag{2.2}$$

Adopting 10^{51} erg of kinetic energy per supernova we obtain the overall energy generation rate (at $z = 0$)

$$\epsilon_{\rm SN,0} \approx 2.4 \times 10^{56} \ {\rm erg \ Gpc^{-3} \ yr^{-1}} \quad . \tag{2.3}$$

It appears that global energy release rate is more than 4 orders of magnitude higher for supernovae than it is for gamma-ray bursts (Wijers et al. 1998, Schmidt 1999). Obviously, both rates are uncertain. It is possible that kinetic energy of GRB ejecta is considerably higher than their gamma ray output (Wijers et al. 1998 Kumar 1999). It is also possible that the actual supernova rate is much higher, as intrinsically faint explosions, like SN 1987A, are difficult to discover, yet they release about as much energy as ordinary SN Ia or SN II. While both, $\epsilon_{\rm GRB}$ and $\epsilon_{\rm SN}$, may well be higher than the estimates given with the eqs. (2.1) and (2.3), it is likely that the ratio $\epsilon_{\rm SN}/\epsilon_{\rm GRB} \gg 1$. If this seemingly obvious conclusion is correct it has consequences for finding GRB remnants.

There is no generally accepted quantitative model of GRB emission at this time, and we may only guess what is the ratio of gamma-ray energy to kinetic energy of the ejecta. While it is common to think that this ratio is small (Wijers et al. 1998, Kumar 1999), it may just as well be much larger than unity, i.e. the kinetic energy may turn out to be much smaller than gamma-ray energy. This possibility follows from the recent analysis of the non-relativistic radio remnant of GRB 990508 by Frail, Waxman and Kulkarni (1999), who find that the total energy is only 5×10^{50} erg. At the same time Rhoads (1999b) finds that GRB 970508 was not strongly beamed, as its afterglow had unbroken power law decline for over 100 days. The total gamma-ray emission was at least 3×10^{50} erg for this burst (Rhoads 1999b). If these claims are correct then for this burst gamma-ray and kinetic energies were comparable, and this rules out the popular 'internal shock' models, which are very inefficient in generating gamma-rays (e.g. Kumar 1999).

Of course, GRB 970508 was not a typical gamma-ray burst. Its afterglow was the only one which first increased in luminosity for about 2 days, and later declined as unbroken

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power law for over 100 days. This is also the only event for which quantitative estimates were made for both: gamma-ray and kinetic energies. We have no direct information for the ratio of these two energy forms for any other burst.

3. GRB and SN remnants

The global energetics of supernovae and gamma-ray bursts has direct implications for the extra energetic supernova remnants. Recently, several suggestions were made that these may be remnants of gamma-ray burst explosions (Efremov et al. 1998, Loeb & Perna 1998, Wang 1999). However, if a typical GRB generates a factor f more energy than a typical supernova then the GRB rate must be lower than the supernova rate by a factor $10^4 f$, and correspondingly the number of GRB remnants must be vastly smaller than suggested by the number of very energetic remnants. Therefore, it is unlikely that the very energetic supernova remnants are related to gamma-ray bursts, unless GRBs generate vastly more kinetic energy than gamma-ray energy.

Let us suppose that the energetic remnants were caused by single explosions. We know that some rare supernovae are much more powerful than average. For example, SN 1998bw has released $\sim 20 \times 10^{51}$ erg (cf. Woosley et al. 1999, Iwamoto 1999, and references therein, but a much less energetic explosion has been proposed by Hoflich et al. 1999). It may well be that some stellar explosions are even more powerful than SN 1998bw. However, there is no obvious reason why the most powerful stellar explosions should be related to gamma-ray bursts. A classical GRB with a hard spectrum requires ejecta with the bulk Lorentz factor ~ 300, or more. Nobody knows how to generate outflow so highly ultra-relativistic, and it is not clear that the total energetics of the explosion has to be extraordinarily large, as a strongly beamed explosion may appear to be much more energetic that it really is. In other words: the ability to generate hard gamma-ray emission and the overall energetics of an explosion may be correlated with each other, or just as well the two may be uncorrelated. As long as we do not have a sound quantitative model there is no justification for either assumption; a semi-empirical approach may be more promising than theoretical speculations.

4. GRB and SN beaming

The possibility that highly relativistic GRB explosions may be jet-like was considered for a very long time and I do not know who was the first to make a suggestion. Some similarity between the GRBs and the blazars is so striking that a term 'micro-quasar' was suggested some years ago (Paczyński 1993). Similarities of these two classes of objects were recently analyzed by Dermer & Chiang (1998). If these are taken seriously a very strong beaming of GRBs follows, with a drastic reduction of the energetics compared to a spherical explosion. Recently, the breaks in the rate of decline of several afterglows were interpreted as evidence for beaming (Kulkarni et al. 1999, Stanek et al. 1999, Harrison et al. 1999). If GRB emission is confined to a very narrow beam they may not need much more energy than the 'standard' $\sim 10^{51}$ erg of an ordinary supernova. At this time there is no robust estimate of the degree and the possible range of GRB beaming (e.g. Rhoads 1997, 1999a,b).

More than a decade ago observations of a 'mystery spot' near SN 1987A were reported by Karovska et al. (1987) and Matcher et al. (1987). Piran & Nakamura (1987) suggested that this might have been a jet generated by the supernova. Not knowing about SN 1987A Cen (1998) suggested that supernovae may create relativistic jets, which may give rise to gamma-ray bursts. This idea gained some support when the new analysis of

SN 1987A data provided stronger evidence for the original 'mystery spot', and in addition provided evidence for a second spot on the opposite side of the supernova, suggesting relativistic jets (Nisenson & Papaliolios 1999). Evidence for a strong non-sphericity of SN 1998S was reported by Leonard et al. (1999). Hoflich et al. (1999) claim that the explosion of SN 1998bw was highly non-spherical.

Jets in supernovae became popular (e.g. Khokhlov et al. 1999, Cen 1999, Nagataki 1999), and often suggested to be associated with a beamed gamma-ray emission. A schematic picture may involve a quasi-spherical and non-relativistic supernova explosion with a narrow ultra-relativistic jet streaming along the rotation axis.

The possibility that some supernovae may generate jets is very interesting, and it should be possible to test it with the VLBA observations of very young radio supernovae. However, there is no reason to expect that all jets must generate gamma-ray bursts, as this would require all outflows to reach the huge Lorentz factor $\Gamma \sim 300$. It seems much more likely that there is a broad range of jet velocities, and only some are capable of GRB-like emission.

5. Hypernova

While the term 'hypernova' became popular recently, it was been sporadically used in the past (e.g. Wilkinson & Bruyn 1990). It does not have a clear, universally accepted meaning. The following are several examples.

1. Hypernova is just a name. The optical light curve of GRB 970508 was several hundred times brighter than any SN ever discovered. The absolute luminosity of several other afterglows, e.g. 990123, 971214, 990510, was higher by another factor ~ 100 (cf. Norris et al. 1999). So, rather than call it a super-super-nova, or a super-duper-nova, the term hypernova seems reasonable as a description of the phenomenon, with no implications for its nature.

2. Hypernova is a special type of a supernova explosion. At least some optical afterglows appear to be associated with star forming regions. Note that GRBs are many orders of magnitude less common than supernovae, and there may be an almost continuous transition from a typical massive SN to a typical GRB; the SN 1987A with its relativistic jet and GRB 980425–SN 1998bw may be examples of intermediate explosions. The link between the GRBs and the deaths of massive stars does not specify the mechanism for a GRB, and it is testable without a need for theoretical models. A question: 'are GRBs in star forming regions?' can be answered observationally. In this context a 'hypernova' is an explosion of a massive star, soon after its formation. Soon, means several million years, not a delayed explosion of the merging neutron star type.

3. Hypernova is a rotationally driven supernova. The idea that at least some supernovae explosions are driven by a rapid rotation of a compact core has been around for several decades (e.g. Ostriker & Gunn 1971). A qualitative reasoning proceeds as follows. A spherical collapse of a massive stellar core transforms $\sim 3 \times 10^{53}$ erg of gravitational energy into thermal energy of a hot neutron star, and 99.7% of that energy is lost in a powerful neutrino–anti-neutrino burst, with the remaining $\sim 10^{51}$ erg used to power a supernova explosion. If a pre-collapse core is rapidly rotating, than additional $\sim 3 \times 10^{53}$ erg may be stored in the rotation of the collapsed object. Some rotational energy is lost in gravitational radiation, but a large fraction cannot be readily disposed of. If an ultra strong magnetic field is generated by the differential rotation then it may act as the energy transmitter from the spinning relativistic object to the envelope, powering an explosion, perhaps in a form of a relativistic jet. The more rotation there is, the more jet-like explosion results, and the more relativistic the jet. This is just a speculation at

this time, recycled in dozens, perhaps hundreds of theoretical papers, with terms like a 'micro-quasar' (Paczyński 1993) or a 'failed supernova' (Woosley 1993) used at least as often as a 'hypernova' (Paczyński 1998).

6. Pessimistic conclusions

It is useful to put theoretical work on gamma-ray bursts in a broader perspective of other exotic objects and phenomena in order to asses the prospects for a short term progress.

There is almost universal agreement that GRB emission is non-thermal. Several important correlations were found for various GRB properties (e.g. Fenimore et al. 1995, Liang & Kargatis 1996, Beloborodov et al. 1998, Stern et al. 1999, Norris et al. 1999), but is not clear how to incorporate them in a theoretical model. This is not surprising. It is very difficult to prove which specific physical processes are responsible for the operation of a non-thermal source—consider current theories of quasars and radio pulsars. Well into the fourth decade of their development, and no serious ambiguity about the relevant distance scales, there are no generally accepted theories that account for either quasar or pulsar non-thermal emission. There is no reason why GRBs should be easier to understand.

For several decades there has been a consensus that Type Ia supernovae result from explosive carbon burning in white dwarfs close to the Chandrasekhar limit, while all other supernovae are related to core collapse of various massive stars. However, the detailed physics is so complicated that there is still no satisfactory and quantitative model that could describe the propagation of the nuclear burning front in SN Ia, without introducing free, adjustable parameters. There is also no agreement how $\sim 0.3\%$ of energy released in core collapse is channeled to drive the explosion of a SN II. As far as I can tell, if there were no observations of SN II it would be impossible to predict them from the first principles, even though hundreds of sophisticated papers were written on the subjects. The guidance provided by the observations of GRBs and their afterglows is less clear than it has been for supernovae. In my view there is no way to prove with theoretical models that either merging neutron stars or hypernova explosions should generate gamma-ray bursts. It is hard to believe that the puzzle of the central engine can be solved for GRBs more readily than for supernovae.

There is plenty of observational evidence that a huge diversity of rotating objects generates either bipolar outflows or jets—the phenomenon is obviously natural, as it appears so commonly in nature. Yet, there is no quantitative theory of the phenomenon that could explain (without ad hoc assumptions and ad hoc free parameters or free functions) what outflow velocities, or what rates of mass loss, should be associated with any particular object. The same applies to gamma-ray bursts and the current attempts to explain why their ejecta are likely to be beamed.

There is no theory that could predict the outflow velocity of any jet, but it seems natural to expect that only very specific conditions make it possible to reach the outflow with the Lorentz factor $\Gamma \sim 300$, as needed for HE bursts. There may be many more jets with more modest values of $\Gamma \sim 30$, 3, or non-relativistic at all. There is no direct evidence for a large Lorentz factor for the NHE bursts, which appear to have no photons above ~ 300 keV (Pendleton et al. 1997), and the pair creation argument does not apply to them. Perhaps the NHE GRBs are driven by non-relativistic explosions.

7. Optimistic conclusions

In spite of all theoretical problems there was a spectacular progress in our understanding of gamma-ray bursts. The statistics of GRB distribution obtained with BATSE on *Compton Gamma Ray Observatory* (Meegan et al. 1992, Paczyński 1995, and references therein) provided a very strong argument for a cosmological distance scale to the majority of GRBs. The obviously explosive nature of gamma-ray bursts provided the basis for the theoretical prediction of the afterglows as the products of interaction between GRB ejecta and ambient medium (Paczyński & Rhoads 1993, Katz 1994, Mészáros & Rees (1997). This prediction was confirmed with the discovery of afterglows with *BeppoSAX* (Costa et al. 1997), and soon provided the proof for the cosmological distance (Metzger et al. 1997). The observed distribution of the afterglows with respect to host galaxies indicated that GRBs are associated with star forming regions, and therefore with the explosions of massive stars, rather than with merging neutron stars (Paczyński 1998, Kulkarni et al. 1998, Galama et al. 1998). There is evidence that at least some bursts are directly associated with explosions of some supernovae (Galama et al. 1998, Bloom et al. 1999, Castro-Tirado & Gorosabel 1999, Reichart 1999, Galama et al. 1999).

There is every reason to expect more progress along similar lines: observations and their analysis providing more and more hints about the nature of the bursts. The following are some of the likely lines of progress in our understanding.

The new GRB instruments will provide hundreds of accurate positions within seconds of the burst's beginning, for long as well as for short bursts. We may expect that the distribution in distance will soon be known not only for the long HE bursts, but also for the NHE bursts and for the short bursts. It may well be that in several years some GRB will be the redshift record holder. If GRBs trace massive star formation rate, then they may become a new probe of the process in very dusty regions, or at very high redshifts.

While old GRB remnants may be difficult to distinguish from SN remnants, there is a possibility that a clear signature of the effect of non-thermal emission from a GRB and its afterglow may be detected in the interstellar medium (e.g. Perna et al. 1999, Draine 1999, Weth et al. 1999), and it may turn out to be a powerful new diagnostics for these events. The importance of the interstellar scintillation for the estimates of radio afterglow expansion has already proven to be an important research tool (Goodman 1997, Frail et al. 1997).

If GRBs are related to explosions of massive stars then we expect that circumstellar gas is left over from a strong stellar wind, as all massive stars appear to have winds. Currently there is mixed evidence from afterglow studies, with some events consistent with ambient gas density falling off as $1/r^2$, as expected of wind environment, while in some the ambient gas density appeared to be constant (Chevalier & Li 1999a,b). With many more afterglows followed with multi-band studies it will be possible to determine which environment is more common, and to make inferences about the nature of the exploding object.

At a cost much lower than any GRB space mission a super-super ROTSE or a super-super-LOTIS may be developed to follow up on the experience of ROTSE (Akerlof et al. 1999) and LOTIS (Williams et al. 1999). At a cost less than $\$10^6$ it should be possible to implement an all sky optical monitoring system sensitive to optical flashes of ~ 1 minute duration, like the one discovered by ROTSE (Akerlof et al. 1999), detectable without any GRB trigger. There may be many more optical flashes than gamma-ray bursts if less extreme Lorentz factors are sufficient for generating optical flashes. Rather obviously, a major difficulty is not hardware but software.

We already know that some supernovae (SN 1998bw) eject some matter at a relativistic or sub-relativistic velocity (Waxman & Loeb 1999). There is a fairly strong case for a relativistic jet from the SN 1987A (Nisenson & Papaliolios 1999). We may expect (or at least hope) that other cases of relativistic motion will be discovered in other SN. For supernovae within $\sim$ 100 Mpc it may be possible to detect anisotropy in their ejecta, perhaps even superluminal jets, using VLBA. If jets are detected in many cases it will be possible to study the distribution of jet velocities.

When the number of recorded supernova explosions will exceed 10^4 we shall know more about the high energy tail of their power distribution, and we may learn if there is a sharp maximum, or is there an extended tail, to the explosions in the 10^{53}–10^{54} erg range.

The ever more vigorous searches for distant (i.e. faint) supernovae will discover optical afterglows without a need for the GRB alert (Rhoads 1997). There may be a rich diversity of SN-like or afterglow-like events, perhaps even optical transients from merging neutron stars (Li & Paczyński 1998).

If the past can be used as a guide for the future than the most spectacular breakthroughs in the observations and understanding of gamma-ray bursts will be unexpected, just as the most recent *BeppoSAX* breakthrough was. An example may be the recent empirical finding of a very tight correlation between photon energy-dependent lags and peak luminosities of gamma-ray bursts (Norris et al. 1999).

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Observations of Gamma-Ray Bursts

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Gamma-ray bursts (GRBs) are now recognized as the most luminous known objects in the Universe. Their brief, random appearance in the gamma-ray region had made their study difficult since their discovery, over thirty-five years ago. The recent discoveries of GRB afterglow radiation in other wavelengths and observations of their faint host galaxies have provided the long-sought breakthrough in the direct determination of their distance and luminosity scales.

The observed time profiles of GRBs are very diverse and their durations cover a wide range. Their general spectral characteristics are summarized, primarily from data obtained from the BATSE experiment on the *Compton Gamma-Ray Observatory*. With over 2500 GRBs now observed, these temporal and spectral signatures, as well as population studies and global properties of GRBs, can now be described with greater accuracy than previously possible.

1. Introduction

This paper describes some of the distinguishing features of GRBs, with particular emphasis on recent observations with the BATSE experiment on the *Compton Gamma-Ray Observatory* (Figure 1). BATSE has been in operation since its launch by the Space Shuttle Atlantis in April 1991 and it is planned to continue operation for at least another five years.

About once per day, a burst of gamma-rays appears from a random direction on the sky. Often, the burst outshines all other sources of gamma-rays in the sky, combined. The serendipitous discovery of GRBs resulted from the cold-war space program of the 1960s. The *Vela* series of spacecraft were developed by the Los Alamos National Laboratory to detect clandestine nuclear explosions above the atmosphere. The orbits of these spacecraft were greatly elongated in order to simultaneously view a large fraction of the earth. Occasional bursts of gamma-rays were seen coming from random directions in space. It was several years later that the observed GRBs were determined to be of cosmic origin (Klebesadel, Strong, & Olson 1973). In the first years after their discovery, GRBs were observed at the rate of about 10 to 15 per year.

Now, with more complete coverage and larger detectors, GRBs are detected at the rate of over 300 per year. At this sensitivity, the all-sky burst rate is about 800 per year, corrected for sky exposure.

The field of gamma-ray bursts has undergone a dramatic change since BATSE. This has resulted primarily from more sensitive observations of the gamma-ray burst intensity and sky distributions (Meegan et al. 1992). Prior to these observations, the source of gamma-ray bursts were considered by most workers in the field to be relatively nearby neutron stars in the Galactic plane (cf. Higdon & Lingenfelter 1990). Another revolution in GRB research is now underway, made possible by the rapid, precise locations from the *BeppoSAX* spacecraft (Piro et al. 1999).

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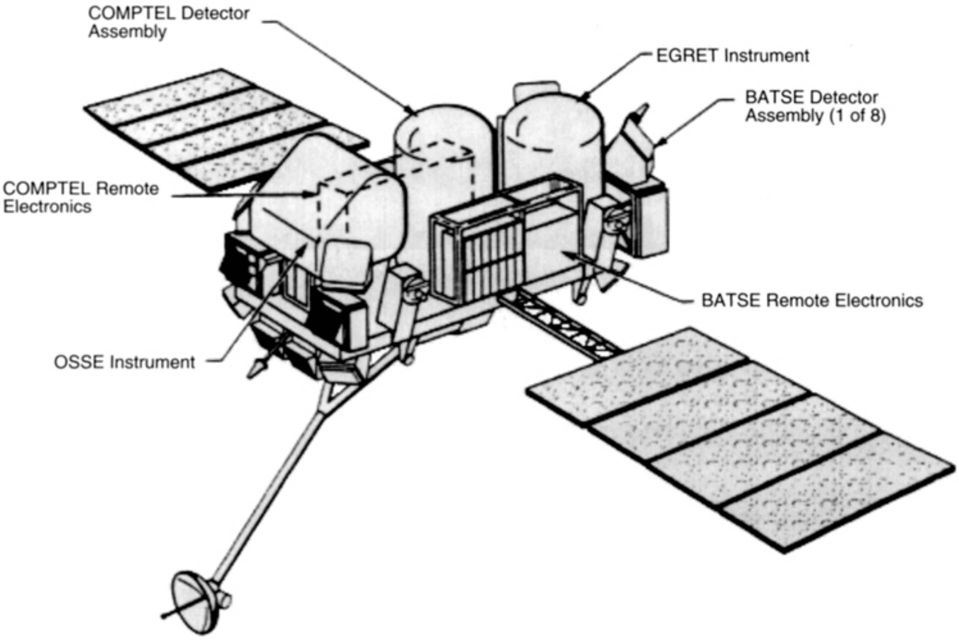

FIGURE 1. The *Compton Gamma-Ray Observatory*, showing the placement of the BATSE detector modules in the corners.

2. Temporal characteristics

The most striking feature of the time profiles of gamma-ray bursts is the diversity of their time structures and the wide range of their durations. Coupled with this diversity is the difficulty of placing many GRBs into well-defined types, based on their time profiles. Many bursts have multiple characteristics and many other bursts are too weak to classify. Some burst profiles are chaotic and spiky with large fluctuations on all time scales (Figure 2), while others show rather simple structures with few peaks (Figure 3). No periodic structures have been seen from gamma-ray bursts. There is, however, one general characteristic of the profiles: at higher energies, the overall burst durations are shorter and sub-pulses within a burst tend to have shorter rise-times and fall-times (sharper spikes). Most bursts also show an asymmetry, with the leading edges being of shorter duration than trailing edges. This feature is also evident when pulses from large numbers of GRBs are superposed (Mitrofanov et al. 1998). There are many bursts which have similar shaped sub-pulses within the burst. Numerous examples of GRB characteristics may be found in the latest BATSE GRB catalog (Paciesas et al. 1999). These characteristics are also summarized in a recent review (Fishman & Meegan 1995).

The wide diversity of GRB profiles has been known since the earliest observations. While several burst morphologies (e.g. smooth or spiky) are easy to identify, there are numerous gradations of these, as well as many complex forms. Examples of GRBs with well-defined, separated episodes of emission are also seen (Figure 4) but not accounted for by most emission models. Attempts to quantify these structures have been largely unsuccessful.

The range of the duration of gamma-ray bursts spans over five decades, from a few milliseconds to over a thousand seconds. The double peaked distribution of the duration, first noted many years ago (cf. Kouveliotou et al. 1993), is now much more evident with