Bull. Astr. Soc. India (1993) **21**, 223-233

Cosmic gamma ray bursts—recent developments

M. N. Vahia
Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005

Abstract. The Gamma Ray Bursts (GRB) have been observed for the last 20 years by a large number of satellites. However, till recently, comprehensive analysis was difficult in view of varying techniques used by different satellites. The launch of the Gamma Ray Observatory (GRO), has produced a large data base of more than 250 GRB that is now available for detailed analysis. The GRO/BATSE observations have catalogued GRBs fainter by three orders of magnitude compared to the previous observations. However, in spite of this large database our understanding of the GRBs remains as poor as ever. This is primarily because (1) no other specific class of objects can be seen in GRB error boxes and in some very well localized GRBs, very deep searches have shown no object; (2) the Log (Number) to Log (Power) distribution indicates that the number of objects increases more slowly with depth than would be expected by geometric considerations; (3) the source distribution remains isotropic even for very faint GRBs and (4) the bursts themselves have a very involved time structure which varies dramatically from burst to burst.

Key words : gamma ray bursts—gamma ray observations

1. Introduction

The origin of the Gamma Ray Bursts (GRB) has been an enigma ever since they were discovered two decades ago. Their general properties are listed in table 1. These transient gamma ray events with durations varying from a fraction of a second to several hundred seconds have been marked by poor repetition rate, very complex time profiles and confusion over absorption lines. The matters are further complicated by the fact that no specific class of objects can be associated with the GRB positions (cf. Atteia *et al.* 1987 and references therein and Vahia & Rao, 1988 (Paper I hereafter)). The absence of any specific class of objects in the GRB error boxes led several scientists to propose that some kind of activity on neutron stars was responsible for these events, in spite of severe theoretical problems associated with this suggestion. However recent results have indicated very strongly that the neutron stars are not the cause of the GRB, even though lack of association with any known objects continues. In fact, recent results have thrown doubt on even the possible location of the sources, in that we are not even sure if the GRB sources are galactic or extragalactic. We discuss all these aspects below.

Table 1. General properties of gamma ray bursts (Vahia & Rao 1987)

Property	Observed value
Intensity	10^{-7} to 10^{-3} ergs cm^{-2}
Luminosity	10^{37}(d/100 pc)^2 ergs s^{-1}
Energy	10^{38}(d/100 pc)^2 ergs
Duration	0.1–100 s
Recurrence rate	≥ 8 years (for hard GRB)
Spectral features	Possible emission feature at about 400 keV and absorption features at about 40 keV possible break in spectral index in some events
Sources	Typically no candidate of $m_v \leq 22$ mag
Space distribution	Isotropic but falling with distance

Until 1990 the GRBs were studied by a network of interplanetary satellites that decided the position by triangulation from the delay in the arrival of the signal in different satellites. The spectral information were taken from individual satellites. The studies were done with up to 9 satellites using different techniques. This method, though the best available at that time suffered from several problems. The primary one was that the energy band of different satellites was different and even within the same satellite, the time structure varied depending on the energy band taken for the study (cf. Golenetskii *et al.* 1985; Atteia *et al.* 1987; Paper I).

Since the launch of the Gamma Ray Observatory (GRO), a collaborative satellite between Germany and USA, the picture has changed significantly as far as the quality of data is concerned. However, the interpretive uncertainties have remained as acute as before. We discuss both groups of observations, the problems posed by them and the interpretation of the observations.

2. Method of study of the GRB

The method of studying of GRB has been as complex as the results themselves. This is because, unlike in other branches of Astronomy, there is no consensus yet on the best detector techniques for studying gamma-rays. Hence, different groups have used different types of detectors and procedures to study the GRB. Also, since GRB are an infrequent phenomena, it is necessary to have large area detectors for this work. Each technique used has its own limitations and advantages. We discuss below the most general methodology of data reduction and for want of space we avoid discussions on the instrumentations.

2.1. *Spatial distribution*

2.1.1. LOCALIZATION IN PLANE

It is not practicable to make accurate pointing from a single detector because the GRBs are infrequent phenomena. Hence the source localization is done by several detectors using the time difference in the arrival or difference in intensity of the signal in any two detectors. Any pair of detectors defines an annulus of the possible arrival direction and a pair of annuli define two possible locations. If more than 3 detectors are available, a more accurate positioning of the GRB is done (Cline *et al.* 1984; Atteia *et al.* 1987). Mazets *et al.* (1981) have used the angular dependence of several detectors on a single satellite to localize the GRB positions.

2.1.2. VARIATION WITH DEPTH

If the objects are distributed uniformly with distance, assuming that they are mono luminous, their power (P) seen by us should be related to the distance d as (Vahia, Rao and Singh, 1992)

$$P \propto \frac{I}{d^2} \qquad \ldots (1)$$

where I is the intensity of the source. On the other hand their number density ($N(I)$) would increase with distance as

$$N(I) \propto d^3 \qquad \ldots (2)$$

purely by arguments of geometry and volume of a sphere. Putting equations (1) and (2) together then, we get that

$$\log(N(I)) \propto \frac{-3}{2} \log(P). \qquad \ldots (3)$$

Thus, the so called –3/2 distribution and the deviation from it are used to determine the radial distribution of sources.

2.2. *Spectra and time evolution*

The spectral and timing analysis is done for the satellite that observes the strongest signal and has a large band width and fast time response. From the observations of such a satellite, the characteristics of the event are deducted.

2.3. *Other wavelength observations*

Since neither the location of GRB nor their repetition rates are known, pre planned simultaneous observations are not feasible. GRB alerts have been used to observe GRBs at other wavelengths soon after they are recorded in gamma rays. However, most of these observations have had no success. There have however been reports of soft X-ray observations around GRBs (cf. Paper I and Meegan *et al.* (1992)) which are the only indications that there is a small amount of soft X-ray activity probably preceding the GRB.

3. Highlights of studies before the GRO

The mode of study of the GRB until recently has been the collection of simultaneous observations using several (up to a maximum of 9) satellites. These results, with the flux sensitivity of 10^{-3} to 10^{-5} ergs/cm^2 have catalogued about 400 GRBs over a period of about 25 years. The main results of the studies done through the interplanetary network are summarized in Atteia *et al.* (1987) (see also Vahia & Rao 1988 (Paper I)). These are :

1. *Isotropic distribution* (Atteia *et al.* (1987) : Though the GRB error boxes derived from a group of satellites has often been large, one of the most interesting aspect of the GRB has been that they are isotropically distributed except some indications of anisotropy for GRB with flounce around 10^{-5} ergs/cm^2 based on data from *Venera* 13 and 14 (cf. Atteia *et al.* 1991) (figure 1).

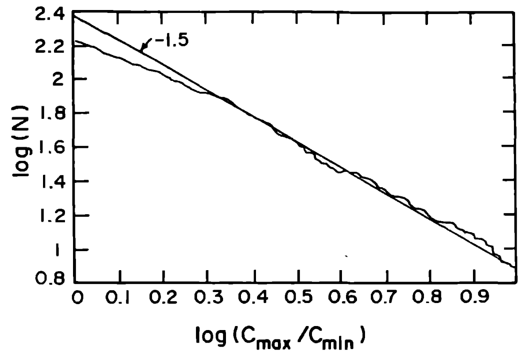

Figure 1. log (*N*)–log (N)–log (C_{max}/C_{min}) distribution of GRB before the GRO/BATSE observatory was launched. This is same as log (N)–log (P) distribution but not normalized to absolute numbers. The data shown here is from the *Venera* 13 and 14 (from Atteia *et al* 1991).

2. *Very complex time structures* (Mazets *et al.* 1981; Atteia *et al.* 1987) : This is one of the most intriguing aspect of the GRB observations. The time profile of the GRB has been markedly complex showing several maxima in more complex burst and to just one maxima in some cases (figure 2). FFT detailed studies of these bursts do not show a fixed period (Paper I) making it likely that these are not related with the nature of objects but with the physical process that results in the gamma ray emission.

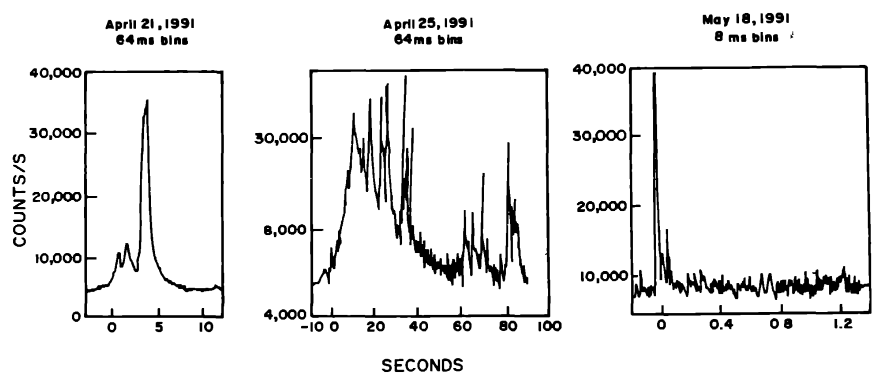

Figure 2. Three typical GRB light curves seen by GRO/BATSE in the energy range of 50-300 keV.

3. *Variable time structures on milli second time scales and absorption features* (Mazets *et al.* 1981; Murakami *et al.* 1991) : A group of Soviet Satellites in the eighties made an extensive catalogue of the GRB with milli second time resolution and found that there are apparent absorption features which are seen in the initial stages of the GRB which seem to disappear when the entire event was integrated. However, since by and large the photon flux was not sufficient to establish a firm feature this had remained a possible observation only. The Japanese GINGA satellite found clear and statistically significant absorption lines in

some four of the eighty GRB catalogued by them. These remain the only observations of an absorption feature in the GRB.

4. *Few simultaneous identifications in other wave bands* (Paper I; Schaefer, 1987) : Several near simultaneous as well as archival searches have been done in the GRB error boxes but these have failed to reveal any specific class of objects in the GRB error boxes.

4. Improvements brought about by GRO

The GRO launched in 1991 has had a specific experiment BATSE dedicated to studying the bursts and transient sources and this has brought about a qualitative change in the GRB data. The data have become more reliable as far as detector response, trajectory errors, and time delay corrections are concerned. Also, the detectors are the most sensitive flown so far and this has also increased the volume and the band width of the database. The main features of the GRO results are given below. Even though some of the results discussed below have been published, a large amount of the data has been analyzed by us by downloading the raw data from the NASA/GSFC computer which has made this data base freely available to the community. Hence, even though the results that are given are a result of the work done by us, in principle, these results are available with anyone interested in this field.

1. *Improved sensitivity to* 10^{-7} *ergs/cm*^{2}*/sec* (Fishman *et al.* 1989) : One of the most significant improvements in the GRO/BATSE detector has been to improve the sensitivity by two orders of magnitude.

2. *Increased the catalogue size by 250 new observations* : As a result of increased sensitivity, the BATSE detector has catalogued more than 250 GRBs in less than a year compared to about 450 GRBs catalogued in the previous two decades. The distribution of the error box size is given in figure 3. As can be seen from the figure, the typical error box size is about 3 degrees.

3. *Increased the time resolution to microseconds* (cf. Bhat *et al.* 1992) : The ability to measure the GRB with very fast time interval has also shown that the GRB have time

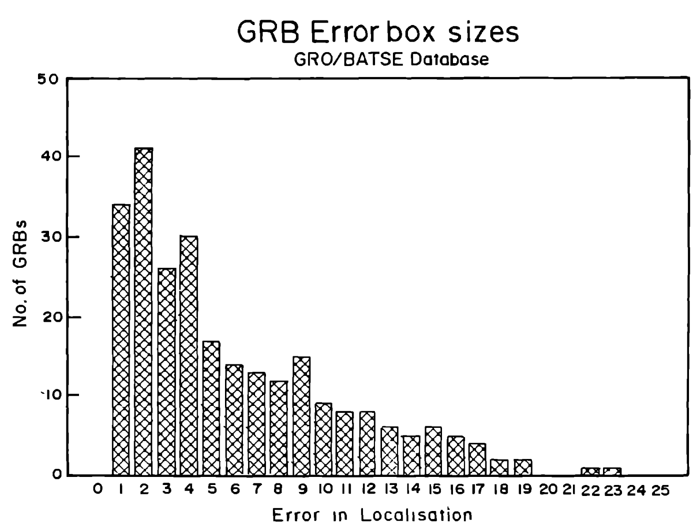

Figure 3. Error box size distribution of the GRBs observed by GRO/BATSE.

structures that vary over a few microseconds putting an upper limit on the size of the objects that emit the GRB.

4. *Increased the band width of observations* (Johnson 1989) : Even though the BATSE detector itself has a small energy band (20 keV to 1 MeV), along with other detectors on the GRO observatory, it is possible, in some cases to observe the GRB structure over the energy band of a few tens of keV to several tens of GeV.

These studies have revealed important pointers to the origin of the GRB. These are :

1. *The degree of isotropy is very high* (Meegan *et al.* 1992) : The sky distribution of the GRB is shown in figure 4. As can be seen from the figure the sky distribution is very uniform. The dipole moment of the GRB distribution is –0.002 ± 0.006 indicating a very high degree of uniformity. Similarly the quadrapole moment is also very small.

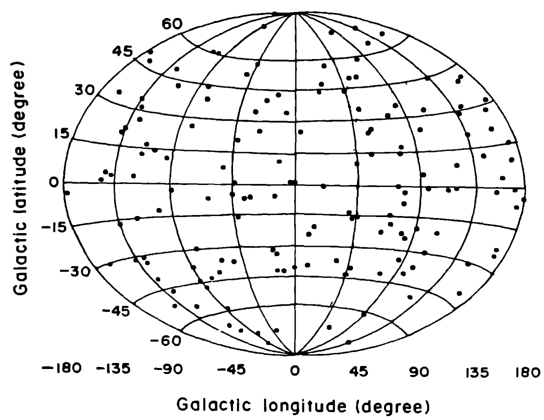

Figure 4. Space distribution of GRB as seen by GRO/BATSE (Meegan *et al.* 1992).

2. *Clear deviation from –3/2 law* : The log (*N*) log (*P*) distribution of the BATSE observations is compared with the older observations in figure 5. As can be seen from the figure, the BATSE distribution deviates very significantly (3σ) from the distribution expected from uniform distribution indicating a clear fall in the number of sources with depth.

3. *No association with other known objects* : (Lingenfelter & Higdon (1992) have compared the BATSE catalogue with several standard catalogues and found no statistically significant association with any objects.

4. *No spectral absorption features* : Unlike the tentative reports of Mazets *et al.* (1981) and Murakami *et al.* (1991) from the earlier generation of satellites, the BATSE observations show no absorption features in spite of systematic searches. However Schaefer *et al.* (1992) have reported a clear break in the spectral index in some intense bursts which could be analyzed in detail. However, this break is also not universally seen.

5. *Brighter GRBs are harder* : In figure 6 we have plotted the fluence of GRB in 50-100 keV versus the fluence in 20-50 keV and 100-300 keV. It can be seen from the figure that the slope for the correlation between 50-100 keV versus 100-300 keV is much larger than the corresponding value for the 50-100 keV versus 20-50 keV fluences indicating that the brighter GRBs have flatter spectra.

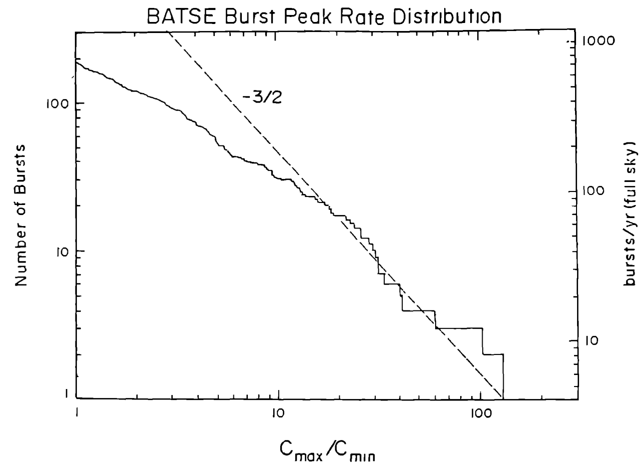

Figure 5. log (N)–log (C_{max}/C_{min}) distribution of GRB as seen by GRO/BATSE observatory. This is same as log (N)–log (P) distribution but not normalized to absolute numbers (Meegan *et al.* 1992).

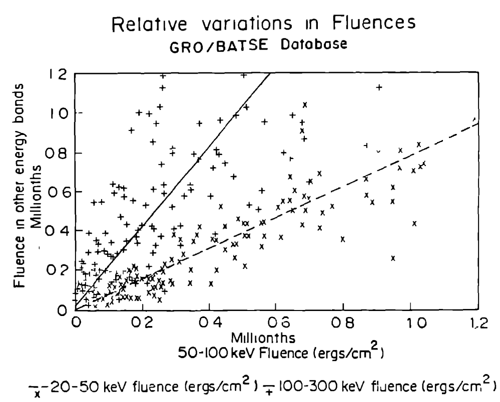

Figure 6. Variation in fluences of the GRBs as a function of variation in the 50-100 keV fluence. The × indicates fluence in 20-50 keV (visual best fit is shown by a dotted line) and the + 100-300 keV fluence of 100-300 keV (visual best fit is joined by a continuous, line). All fluences are in ergs cm^{-2}.

We have some analysis done with the unpublished but publicly available GRO/BATSE GRB catalogue that has become available for about a month. This analysis, though not published anywhere is essentially a straight forward study and in principle is known to all the laboratories that are interested in the GRB mystery. In particular, the GRO/BATSE have a typical error bar of about 3 degrees with very few GRBs showing larger errors. This, combined with the fact that the GRO/BATSE database is more cohesive, should give much more stringent tests to the models for GRB. For our study we looked for GRB in close spatial association with each other and found that some 33 per cent more GRB tend to be in the neighbourhood of each other than expected by chance. Also, these so called repeaters are more significantly associated with southern galactic plane than expected by chance (Figure 7a, 7b). These repeating GRBs are clearly concentrated in the southern galactic latitudes as can be seen from their β distribution.

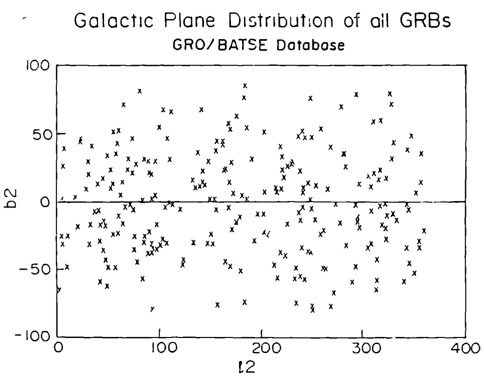

Figure 7a. Sky distribution of all GRB seen by GRO/BATSE. This is the same as figure 4 except that it is plotted on a rectangular scale for comparison with figure 7b.

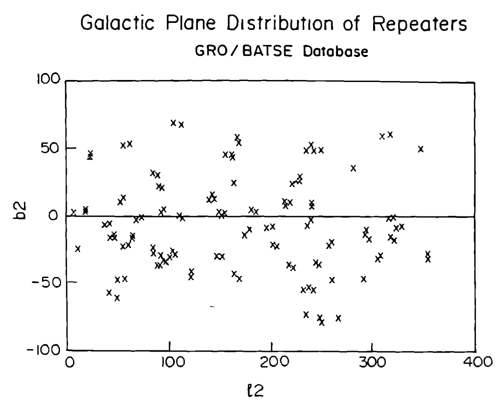

Figure 7b. Sky distribution of the repeaters seen by BATSE.

5. Interpretations of the results

These studies have thrown up several unanswered questions :

5.1. *Isotropy and homogeneity (Fenimore el al. 1992; Lingenfelter & Higdon 1992; Vahia, Rao & Singh 1992; Meegan et al. 1992)*

In the case of the GRB, the Log (N) – Log (P) distribution deviates significantly from an isotropic distribution clearly showing that the number of sources falls significantly with distance (figure 8). The data for high fluence is from PVO and the low fluence data is from GRO/BATSE (from Fenimore *et al.* 1992). The isotropy and the lack of homogeneity imply that while the sources are uniformly distributed in the sky, their number falls significantly

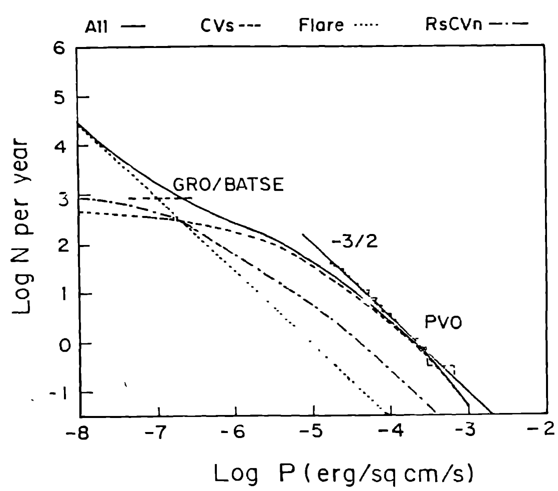

Figure 8. log (N)–log (P) distribution of GRB from PVO and GRO/BATSE (Fenimore *et al.* 1992) fitted to the suggestion that they are flares on stars (Vahia, Rao & Singh 1992).

with distance. If the sources are of a single type, then this type of distribution is not possible for galactic objects since galactic objects tend to show a distinct distribution in the galactic plane and for extragalactic objects the fall from the –3/2 law is difficult to achieve (Mao & Paczenski). However, Chuang *et al.* (1992) have reported some degree of anisotropy based on the results from *Pioneer Venus Orbiter* in the flux range lower than 10^{-5} ergs/sec.

5.2. *Problems of errors in localizations not properly studied (Paper I)*

Though the catalogue of GRB error boxes claim very high degree of localizations, there is internal inconsistency in the GRB localizations depending on the combination of satellites used and these doubts have not been satisfactorily resolved, though the GRO database does not have this problem.

5.3. *No special sources in the GRB error boxes (Lingenfelter & Higdon (1992))*

Even very deep CCD searches in the GRB error boxes in very well localized GRB error boxes have revealed no source, though there are claims that in the proximity of the GRB error boxes magnetically active objects predominate beyond statistical expectations. Even searches of archival plates have not revealed any activity in GRB error boxes in the past.

5.4. *The nature of the absorption feature is uncertain*

If it is assumed that the absorption feature, seen for a very short duration in some of the observations from Venera, and claimed as a distinct feature in some 4 of the 80 GRB observed by GINGA, if taken as a synchrotron absorption, gives source magnetic fields to be of the order of 10^{12} Gauss which are difficult to achieve in Astrophysical sites that satisfy other observational characteristics of GRBs. None of the 250 GRBs seen by the more sensitive GRO detectors have shown any spectral features.

5.5. *Absence of activity in other wave bands within the GRB error boxes*

Near simultaneous observations have revealed no activity in any energy bands whatsoever, though X-ray flares from the neighbourhood of the GRB error boxes have been revealed (Paper I, Murakami *et al.* 1991).

6. Models

By and large neutron star scenarios are preferred because the sources seem to disappear at quiet times (Narayan & Ostriker 1990; Harding & Leventhal 1992; Li & Dermer 1992; Bailyn 1992; Higdon & Lingenfelter 1990; Fenimore *et al.* 1992). However, the GRO/BATSE results have severely constrained these models since the log (N)-log (P) distribution differs very significantly from what can be expected from any expected distribution of neutron stars. These suggestions have revolved around (a) Starquakes, (b) Star Comet, Collisions, (c) Some magnetic activity on neutron stars, (d) High velocity neutron star or, (e) Neutron star binary coalescence. However, all these models have yet to find acceptance because the spatial distribution of GRBs remains isotropic as well as shows time structures of several seconds which is difficult to reproduce for neutron star related activity. The expected number of coalescences of GRB also do not agree with other observations of the galaxy.

A number of extragalactic scenarios have also been suggested but any such source would have to show a significant amount of evolution in order to fit the data (cf. Fenimore *et al.* 1992). These include the suggestions of space time manifestation of galactic strings or some unknown extragalactic objects. However this amounts more to pushing the problem beyond the realm of observability.

The scenario that is the favourite of the author suggests that the GRB are large flares on magnetically active stellar systems (MASS) (cf. Paper 1, Vahia, Rao & Singh (1992)). The model suggests that the GRB error boxes in the older catalogues are over constrained and that if a small error in the error box estimates is accepted then there is a significant association between the GRB error boxes and the MASS. This can also satisfactorily account for the energy budget of the GRB as well as explain the log (*N*)-log (*P*) distribution (figure 8) (Vahia, Rao & Singh 1992). The authors are still working on the new GRO/BATSE catalogue to look for positional associations.

7. Conclusions

The Gamma Ray Bursts (GRB) have been observed for the last 20 years by a large number of satellites. The launch of the Gamma Ray Observatory (GRO), has produced a large database of more than 250 GRB of unprecedented quality that is now available for detailed analysis. The GRO/BATSE observations have catalogued GRBs fainter by three orders of magnitude compared to the previous observations. However, in spite of this large database our understanding of the GRBs remains as poor as ever. This is primarily because :

1. No other specific class of objects can be seen in GRB error boxes and in some very well localized GRBs, very deep searches have shown no object.
2. The Log (Number) to Log (Power) distribution indicates that the number of objects increases more slowly with depth than would be expected by geometric considerations.
3. The source distribution remains isotropic even for very faint GRBs.
4. The Bursts themselves have a very involved time structure which varies dramatically from burst to burst.

Acknowledgements

The author wishes to acknowledge the helpful discussions and assistance of Dr A. R. Rao and Dr R. K. Singh in preparing this talk. The author also wishes to thank Prof. P. C. Agrawal for giving him an opportunity to convey the excitement in this field to the participants of the meeting.

References

Atteia J. L. *et al*, 1987, ApJS, 64, 305.

Atteia J. L. *et al*, 1991, Nature, 351, 296.

Bailyn C., 1992, Nature, 359, 478.

Bhat P. N., Fishman G. J., Meegan C. A., Wilson R. B., Broch M. N., Paciesas W. S., 1992, Nature, 359, 217.

Chuang K. W., White R. S., Klebesadel R. W., Laros J. G., 1992, ApJ, 391, 242.

Cline T. L. *et al*, 1984, ApJ, 286, L15.

Fenimore E. E. *et al.*, 1992, Nature, 357, 140.

Fishman G. J. *et al.*, 1989, In : Proc. Gamma Ray Observatory Science Workshop, ed. W. N. Johnson, NASA/GSFC, Greenbelt, Maryland, USA.

Golenetskii S. V., Mazets E. P., Aptekar R. L., Guryan Y. A., Ilynskii V. N., 1985, Sov. Astr. Lett., 11, 381.

Harding A. C., Leventhal M., 1992, Nature, 357, 388.

Higdon J. C., Lingenfelter R. E., 1990, ARA&A, 28, 401.

Johnson W. N. (editor), 1989, In : Proc. Gamma Ray Observatory Science Workshop, NASA/GSFC, Greenbelt, Maryland, USA.

Lingenfelter R. E., Higdon J. C., 1992, Nature, 356, 132.

Li H., Dermer C. D., 1992, Nature, 359, 514.

Mao S., Paczeński B., 1992, ApJ, 389, L13.

Mazets E. P. *et al.*, 1981, Astrophy. Space Sci., 80, 3.

Meegan C. A. *et al.*, 1992, Nature, 355, 143.

Murakami T., Inoue H., Nishimura J., van Paradijs J., Fenimore E. E., Ulmer A., Yoshida A., 1991, Advances in Space Research, 11, no 8, (8)119.

Narayan R., Ostriker J. P., 1990, ApJ, 352, 222.

Schaefer B. E., 1987, Advances in Space Research, 6, no 4, 471.

Schaefer B. E. *et al.*, 1992, ApJ, 393, L51.

Vahia M. N., Rao A. R., 1988, A&A, 207, 55 Paper I.

Vahia M. N., Rao A. R., Singh R. K., 1992, In : Proc. Advances in Solar and Stellar Coronal Physics, Palermo, Italy.