Statistical studies of gamma-ray bursts

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The classical gamma-ray bursts (GRB) from the BATSE 3B catalog are analyzed on the basis of their time duration, fluence, spectral and shape parameters. Correlations between these parameters are derived and an attempt is made to describe the GRB population with a single variable, based on these correlations. A bimodal distribution of these events is seen with one generic group exhibiting shorter time duration and harder spectra compared to the other more populated sample. There is an indication of anisotropy in a sub-class belonging to the first group of events. Marginal evidence for repeating events in this sub-class is seen with two sets of gamma-ray bursts displaying quite similar properties.

1 Introduction

Cosmic gamma-ray bursts (GRB) represent one of the most perplexing phenomena observed in the Universe. Despite being studied for the last thirty years, we still do not have clear leads as to their origin and physical processes controlling prodigious outpourings of energy that they apparently represent in settings of either galactic or extra-galactic production models. The diversities in the time histories and energy spectra and the lack of direct knowledge of distance for most of the burst events complicate the study of these sources. Sensitive searches for burst counterparts in other spectral regions have been carried out from radio to X-ray ranges and the most promising development in this regard has been the recent detection of optical transients for a few (~13) GRB whose measured redshifts indicate that these bursts are of extra-galactic origin. However, the number of these presumably optically identified events is as yet too few to characterize GRB globally with respect to the nature of their sources or by the wide range of properties exhibited by them. Hence statistical studies of GRB properties will continue to play an important role in seeking additional leads in understanding this complex astrophysical phenomenon.

Several statistical studies of GRB properties have been made in the past using data provided by the BATSE experiment. Attempts have been made to bifurcate GRB into two groups on the basis of the bimodality, apparent in their temporal and spectral characteristics. An analysis of the burst-duration distribution, as obtained from the BATSE 1B catalog, was carried out by Kouveliotou et al. which showed possible evidence for two burst populations. Belli has divided the GRB into two classes on the basis of their distribution in the duration-hardness plane and has suggested a galactic origin for both the event classes. More recently, Balazs et al. have again separated the GRB into short and long classes and have concluded that, while the short ones are distributed somewhat anisotropically, the long ones have an essentially isotropic distribution. They believe that both the sets of events are consistent with a cosmological origin.

In this paper, the BATSE 3B catalog has been analyzed on the basis of the GRB time-duration, fluence, softness ratio and shape parameters, and we have searched for a possible evidence for distinct groups of GRB events. These parameters have been examined for likely correlations and to classify the GRB in a model-independent way. With this independent methodology, it has been possible to divide the GRB into two distinct classes on the duration-softness plane. Furthermore, a sub-class of short and hard events displays an anisotropy at a marginal significance level. The present work also points to the presence of two sets of possible 'repeater' events in this sub-class of GRB. Presently, the 4B catalog is also available. Analysis of the same would not substantially change the results presented here if the same methodology is adapted.
2 Details of analysis

This analysis has been performed using the data of BATSE 3B catalog\(^2\). The following parameters are selected for the present investigation.

(i) Time duration, \(T_{60}\)—It is the duration in which the observed counts accumulate from 5% to 95% of the total counts. Such a definition yields a burst duration which is, to a first order, independent of the intensity.

(ii) Total fluence, \(F(t)\) (in ergs cm\(^{-2}\)) of the burst—It is the sum of fluences in the four BATSE energy channels, namely, 20-50 keV, 50-100 keV, 100-300 keV and greater than 300 keV.

(iii) Softness ratio, \(SR\)—It is the ratio of the fluence recorded by the BATSE in its second energy channel (50-100 keV) to that in the third energy channel (100-300 keV).

(iv) Shape, \(Sh\), of the burst—It is the ratio of the difference in the peak time in the 64 ms timescale, \((T_p)\), and the start of \(T_{90}\), \((T_{90})\), to the duration \(T_{90}\) of the burst and is given by \(Sh = (T_p-T_{90})/T_{90}\).

Defined this way, the shape parameter \(Sh\) gives information about the relative rise-time of the event. Thus, for \(Sh < 0.5\), the rise-time of the burst is faster than the fall-time and \(\sim 63\%\) of the total bursts (807) fall in this category. This conclusion will not generally hold good for multi-peaked bursts, but we retain this parameter as a model-independent measure of the shape of the burst.

The \(T_{90}\) distribution for the 834 GRB, obtained from BATSE 3B catalog, is shown in Fig. 1. Figure 1 shows a bimodality on the logarithmic time-scale \(T = \log(T_{90})\), with broad peaks centered at \(T_{90} \sim 0.32\) s and 31.6 s and a minimum at \(T_{90} \sim 2\) s. This bimodality has, in fact, been one of the features identified at quite an early phase of the GRB studies and the robustness of this feature has prompted us to use \(T_{90}\) as the base parameter and seek its possible correlation with other above-referred GRB parameters. Since the range of values covered by each of these parameters is very wide (for example, the observed fluence values span 5 orders of magnitude), these parameters are expressed on a logarithmic scale to investigate correlations and hence onwards \(\log(F(t))\), \(\log(SR)\) and \(\log(Sh)\) are referred to \(F\), \(S\) and \(P\), respectively.

Among several possible pairs of parameters three pairs show significant correlations. As is evident from Table 1, the parameters \(F\), \(S\) and \(P\) individually exhibits statistically significant correlations with the reference parameter \(T\). Since most of these parameters may be mutually correlated, detection of a correlation between two parameters could be the result of possible correlations with the other parameters. To investigate this effect and to extract the independent correlations, we have applied the Spearman partial rank correlation test\(^3\). In this test, Spearman \(\rho\) represents the correlation coefficient, \(Pr_{spea}\) is the probability that this correlation is due to a random fluctuation, while the parameter \(D\) gives the probability in terms of standard deviations, and that the correlation is not due to the effect of the third parameter\(^3\). The results of this study are summarized in Table 2. It can be seen from the Table 2 that the

![Fig. 1—Distribution of \(T = \log(T_{90})\) for GRB obtained from the BATSE 3B catalog (A bimodality is seen with a minimum at \(T_{90} \sim 2\) s)](image-url)
Spearman partial rank correlation coefficients between $T$ and $F$ and between $T$ and $S$ are positive, while it is negative between $T$ and $P$. From this analysis, it is inferred that the correlations between $T$ and any one of the 3 other parameters, $F$, $S$ and $P$, are largely independent.

Next, when we project the 785 GRB events on the $F$-$T$, $S$-$T$ and $P$-$T$ planes, along with their corresponding best-fit regression lines, we find that the GRB distribution in the $F$-$T$ plane (Fig. 2) is more or less a continuous one, whereas two islands of population are seen in the distribution of GRB in the $S$-$T$ plane (Fig. 3). To get a clear-cut classification of two GRB populations as is seen in the $S$-$T$ plane, we take advantage of the underlying correlation between the parameters $S$ and $T$ and define a 'length' parameter $L$. This length parameter represents the geometrical distance between a fixed point $(S_0, T_0)$ on the best-fit regression line to the GRB position $(S, T)$ on the $S$-$T$ plane. Thus, for every point $(S, T)$ representing a GRB, its distance to this fixed point, called the length $L$, can be calculated as $L=\sqrt{[(S-S_0)^2+(T-T_0)^2]}$.

Defined this way, and since $S$ and $T$ are correlated, smaller $L$ means bursts with shorter duration and harder spectra (i.e., both $T$ and $S$ small), while larger $L$ implies bursts with longer durations and softer spectra. We note here that the choice of the reference point, $(S_0, T_0)$, to calculate the length will not change the conclusions, provided this point is on the best-fit regression line and sufficiently far away from the data points. Here, the reference point has been chosen to be about twice the distance from the midpoint on the best-fit regression line.

The GRB distribution for the length determined for the $S$-$T$ plane, $L_{ST}$, is shown in Fig. 4. A clear bimodal distribution is evident which is more pronounced as compared to the GRB distribution for $T_0$ alone (see Fig. 1.). It can be seen that the GRB gets divided into two distinct populations of events, with population $A$, corresponding to shorter duration and harder spectra ($\sim$197 events) and the other, population $B$, with relatively longer duration and softer spectra ($\sim$588
events). Similar GRB distributions for the other length parameters, namely, that between the fluence and the time duration (LST) and the shape parameter and time duration (LTST), have also been investigated. Quite remarkably, the bimodality is found to be most pronounced only for the LST distribution.

To explore whether the two-population picture of Fig. 4, obtained using the length parameter LST, has any underlying signature of a positional (galactic) preference, we have subjected the related GRB events to an anisotropy analysis. After binning the overall length LST suitably to have a reasonable sample size per bin (>35 events), the two standard anisotropy parameters, namely, the dipole moment \( d = \langle \cos \theta \rangle \) and the quadrupole moment \( q = \langle \sin^2 \theta - 1/3 \rangle \) have been calculated for each LST bin (here \( \theta \) is the space angle of a given GRB with respect to the galactic centre and \( b \) is the galactic latitude of the burst location). The anisotropy parameters are plotted against LST in Fig. 5 along with the corresponding statistical errors evaluated as \( 1/N(3N) \) for \( d \) and \( 2/\sqrt{(45N)} \) for \( q \), where \( N \) is the total number of GRB in each bin\(^4\). It is also noted here that, because of the choice of galactic coordinate-based statistics, the derived anisotropy values are not much affected by the non-uniformity in the BATSE sky-exposure. This is so, because the ecliptic plane crosses the galactic plane at a large angle\(^5\).

It is interesting to note that the sub-class of the shortest and hardest events (37 in number with \( L_{ST} < 4.5 \)), corresponding to the first bin in Fig. 5, has a non-zero quadrupole moment \( q \) with a statistical significance of \(-3\sigma\) and a non-zero dipole moment \( d \) with a significance of \(1.5\sigma\). More specifically, when we examine these events in the galactic co-ordinates, they are found to be predominantly concentrated in the galactic plane. When the latitude distribution of the sub-class of 37 GRB events was done it was seen that 15 out of 37 events are located within the galactic latitudes \( |b| \leq 10^\circ \). Assuming an isotropic distribution of GRB sources on the celestial sphere, 6 events from 37 are expected to be at \( |b| \leq 10^\circ \) on an average. The formal Poissonian probability of finding 15 events, when only 6 are expected, is \( < 10^{-5} \). It is also interesting to note that the longer and softer events do not show any deviations from isotropy (see Fig. 5).

The number of events which show anisotropy is rather small compared to the total number of GRB (37 out of 785) indicating that a small fraction of GRB could have a galactic origin, while the other group of events could be of extra-galactic (cosmological origin). To investigate whether the galactic populations that we have identified show any signs of repeating, we have examined them for spatial association. It is found that two pairs of GRBs come within \( 4^\circ \) of each other (when only 0.5 are expected). Though the significance of this spatial association is not very high, we find that the properties of these two pairs are quite similar. These properties like the fluence, the peak flux and their time durations are listed in Table 3. It can be seen that the observed properties are rather similar to each other for the two pairs of GRB.

### 3 Discussion

The idea that GRB may not represent a monolithic population is not new. Several workers\(^{16,17}\) have suggested it, and others have found signs of a bimodal behaviour in the temporal and spectral characteristics of GRB. In this paper, the GRB events from the BATSE 3B catalog have been analyzed on the basis
of four parameters characterizing their time duration, total fluence, softness ratio and shape. It has been found that the last three parameters are independently correlated with the first one, i.e. the burst duration parameter. Taking advantage of this correlation, a 'length' parameter has been devised, which has enabled us to bring out the GRB dichotomy more clearly. A clear bimodality is seen in the $T_{90}$ duration distribution which gets enhanced in the $L_{SR}$ distribution (Fig. 4). Two populations of GRB are suggested, the first comprising shorter and harder bursts (~197) and the second made up of longer and softer bursts (~588). These groups (population A and B, respectively) have been examined for a possible anisotropy using the $L_{SR}$ parameter. The first $L_{SR}$ bin, representing the sub-class of 37 short and hard events from the population A, shows non-zero quadrupole and dipole moments of 3$\sigma$ and 1.5$\sigma$, respectively. Furthermore, this sub-class of events is found to show a preference for galactic latitudes $|\beta| \leq 10^\circ$ and galactic longitudes between 90$^\circ$ and 180$^\circ$. Referring to Fig. 5, it is evident that the population B events, represented here by $L_{SR} > 5.5$, have essentially zero quadrupole and dipole moments. This implies an isotropic angular distribution for the vast majority of GRB which is in agreement with the results obtained by recent observations of optical afterglows for some of these events (suggestive of an extra-galactic origin).

An important additional realization which follows from the present work is that the bimodality of the GRB distribution and the apparent anisotropy for the sub-class, identified above, do not get significantly enhanced with the inclusion of additional burst parameters like the burst shape $P$ and the fluence $F$. This is so, because the correlation between $T$ and $F$, although more pronounced than that between $T$ and $S$, is more or less continuous unlike the latter case, where it displays largely a two-island population distribution. These differences can be seen by an examination of the GRB distribution in the $T-F$ and $T-S$ planes. It is suggested that the $T-F$ correlation is due to some observational effects (like, for example, for bursts of given intrinsic luminosity and shape, farther events will look shorter and have lesser fluence). On the other hand, the correlation between $T$ and $S$ appears to be more fundamental, thereby helping to divide the GRB into two main classes more clearly.

4 Conclusions

The analysis of spectral and temporal properties of GRB reveals that these events divide themselves into two well-separated populations on the $S-T$ plane. A small sub-class of short and hard events in the first population shows marginal evidence for an anisotropic distribution. There is an indication from the present work that some of these hard and short
bursts may be repeaters. The second population of events are compatible with an isotropic distribution and going by recent evidences, these events are suggestive of an extra-galactic (cosmological) origin.

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