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# A THIRD CLASS OF GAMMA-RAY BURSTS?

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## ABSTRACT

Two classes of gamma-ray bursts have been identified so far, characterized by $T_{90}$ durations shorter and longer than approximately 2 s. We show here that the BATSE 3B data allow a good fit with three Gaussian distributions in log $T_{90}$. The $\chi^2$ statistic indicates a 40% probability for two-Gaussian fits, whereas the three-Gaussian fit probability is 98%. Using another statistical method, it is argued that the probability that the third class is a random fluctuation is less than 0.02%.

*Subject headings:* gamma rays: bursts — methods: statistical

## 1. INTRODUCTION

In the BATSE 3B catalog (Meegan et al. 1996) there are 1122 gamma-ray bursts (GRBs), of which 834 have duration information. Kouveliotou et al. 1993 have identified two types of GRB based on duration, for which the value of $T_{90}$ (the time during which 90% of the fluence is accumulated) is respectively smaller or larger than 2 s. This bimodal distribution has been further quantified in another paper (Kouveliotou et al. 1995), where a two-Gaussian fit is made. To make further progress in quantifying this classification, one of the issues that needs to be addressed is evaluating the probabilities associated with a bimodal, or in general, multimodal, distribution. In this paper we make a first attempt at this, evaluating the probability that the two populations are independent, and consider in addition whether a third group of bursts can be identified.

## 2. GAUSSIAN FITS IN $\log T_{90}$

For this investigation we have used a smaller set of 797 burst durations in the 3B catalog because these have peak flux information as well as duration information, and we use the $T_{90}$ measures provided in this data set. For a one-Gaussian fit the $\chi^2$ probability is less than 0.1%, so the one-Gaussian null hypothesis can be rejected. A lognormal two-Gaussian fit using 52 time bins with bin size 0.1 in the log (Fig. 1) has a 40% probability. This indicates that this null hypothesis cannot be rejected (Press et al. 1992). However, in the middle we have three consecutive bins that have extremely large deviations.

The three bins have 3.2 $\sigma$, 4 $\sigma$ and 2.5 $\sigma$ deviations (Fig. 2). The probability of getting such deviations in 52 bins is 6.3%, 0.3%, and 58%. Because we obtained these in three consecutive bins, the probability that these deviations are random is $\sim 10^{-4}$.

Such deviations are interesting if they are in one/two/etc. consecutive bins. This raises the probability approximately by a factor of 5. These three bins contain 64 GRBs. The two-Gaussian fit would account for 19, leaving 45. The difference between these two numbers is more than 5 $\sigma$, which corresponds to a probability of less than $6 \times 10^{-7}$. We can ask what is the probability of there being an excess in $n$ ($n$ small) consecutive bins located somewhere else. The number of trials is of the order of the number of possible locations of excess *times* the number of possible widths of excess, which is roughly $50 \times 6 = 300$. Therefore, if the GRB duration distributions are lognormal, then the probability that there is a deviation in these three bins from a two-Gaussian fit is more than 99.98%.

Because the durations distribution of the two previously known classes of GRB are nearly lognormal, we made a fit including a third Gaussian. The three-Gaussian fit (with nine parameters) has $\chi^2 = 24$, which implies a 98% probability (Fig. 3). Table 1 contains the parameters of this fit. Looking at the goodness of the three-Gaussian fit, one might conclude that there is an "intermediate" type of GRB. This is in agreement with the results of Mukherjee et al. 1998, who used a multivariate analysis and found that the probability of there being two clusters rather than three is less than $10^{-4}$.

Both the two- and three-Gaussian fits have acceptable $\chi^2$ values; therefore neither can be rejected as an inappropriate fit. If we view the problem as one of model comparison, then, if the third Gaussian does not exist, the change in $\chi^2$ between the two fits from adding the three-parameter third Gaussian should be distributed as $\chi^2$ with 3 degrees of freedom (Band et al. 1997). The change in $\chi^2$ of $46.8 - 24.0 = 22.8$ implies a probability of less than $10^{-4}$, indicating that a three-Gaussian fit is a highly significant improvement over a two-Gaussian fit.

If we had considered six bins in the intermediate region, the two-Gaussian fit would show an excess of 61 GRBs. We may estimate that the intermediate group contains more than 50 but less than 70 GRBs, which would represent $\sim 8\%$ of the GRB population.

## 3. SYSTEMATICS

The BATSE on-board software tests for the existence of bursts by comparing the count rates to the threshold levels for three separate time intervals: 64, 256, and 1024 ms. The efficiency changes in the region of the middle area because the 1024 ms trigger becomes less sensitive as burst durations fall below about 1 s. This means that at the intermediate timescale a large systematic deviation is possible. To reduce the effects of trigger systematics in this region we truncated the data set to include only GRBs that would have triggered BATSE on the 64 ms timescale.

Using the current BATSE catalog "CmaxCmin" table [1], we choose GRBs with numbers larger than one in the second column (64 ms scale maximum counts divided by the threshold count rate). Because this process reduced the

[1] Available at http://www.batse.msfc.nasa.gov/data/grb/catalog/

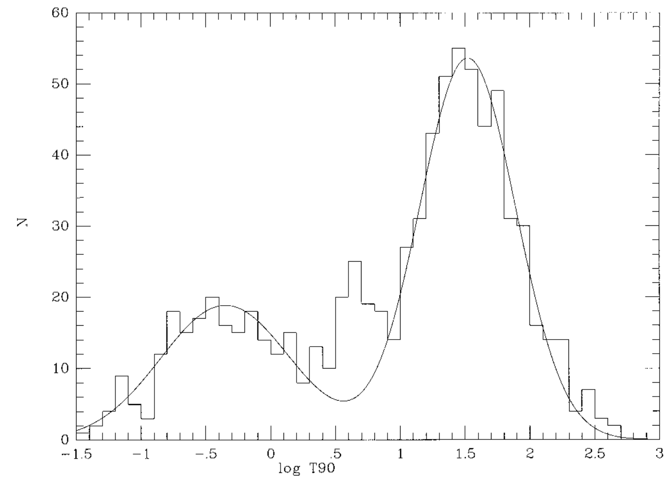


FIG. 1.—Distribution of log $T_{90}$ for 797 bursts from the 3B catalog. The solid line represents a fit of two lognormal Gaussians using 6 parameters and 52 bins. The best fit $\chi^2 = 46.8$, which implies a 40% probability.

number of bursts very much, we used the 4B catalog (Paciesas et al. 1998) data. In the 4B catalog there are 1234 GRBs that have duration information; unfortunately, only 605 of these satisfied the above condition. In the three interesting bins we have 35 GRBs. The two-Gaussian fit would account for 13, leaving 22. Therefore 63% of the population are still a "deviation" (note that in § 2 it was 70%).

This is still a 4–5 $\sigma$ deviation, depending on whether one uses the expected number or the observed one. Therefore,

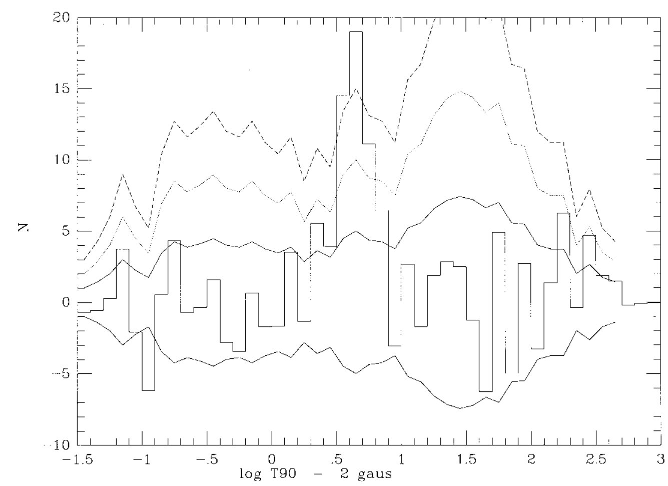


FIG. 2.—Difference between the two lognormal Gaussian fit and the log $T_{90}$ distribution. The solid lines represent 1 $\sigma$ errors of the $T_{90}$ bins. Dotted line and dashed line mean 2 and 3 $\sigma$. Except for the three middle bins, only one bin has a $\gtrsim 2\,\sigma$ deviation, and seven bins have $\gtrsim 1\,\sigma$.

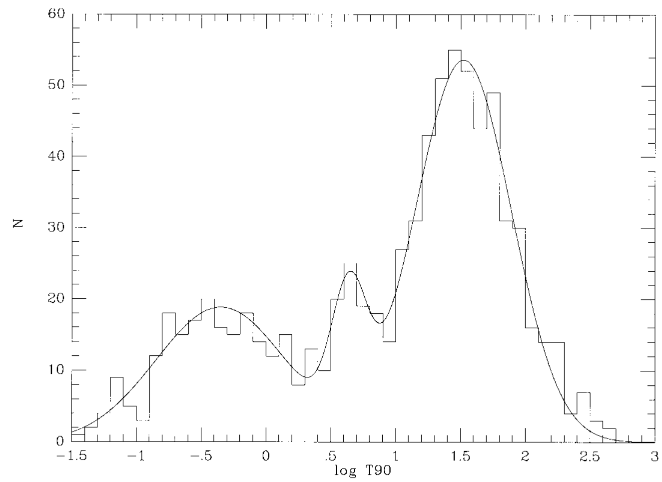


FIG. 3.—log $T_{90}$ distribution. The solid line represents a fit of three lognormal Gaussians. The $\chi^2$ value implies a probability of 98%.

after neglecting some systematics, the probability that there is a deviation from a two-Gaussian fit in these three bins is approximately 99.8%–99.98%.

## 4. log *N*–log *P*

In Figure 4 we show the log *N*–log *P* distribution of the two previous classes of GRB (see also Kouveliotou et al. 1995 and Horváth et al. 1996) and compare this with the log *N*–log *P* in Figure 5 for the intermediate class of bursts, consisting of 74 events (log $T_{90} = 0.4$–0.8). The log *N*–log *P* distributions of the $T_{90} < 2.5$ s range and the $T_{90} > 6.3$ s range are shown in Figure 4. The former has a Euclidean part, and the left portion goes over into a $-1.05$ slope. The

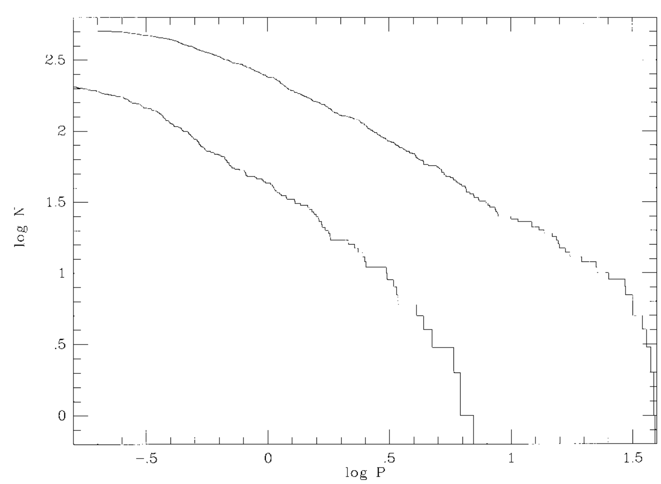


FIG. 4.—The log *N*–log *P* distributions of the two types of GRBs. The left curve is for $T_{90} < 2.5$ s (223 GRBs), while the right curve is for $T_{90} > 6.3$ s (508 GRBs).

TABLE 1

THE PARAMETERS OF THE THREE-GAUSSIAN FIT OF GAMMA-RAY BURSTS

| GRB (1) | Average Duration (lg $T_{90}$) (2) | $\sigma$ (lg $T_{90}$) (3) | Members (4) | Group Population (%) (5) | $T_{90}$ (s) (6) |
|---|---|---|---|---|---|
| First ........ | $-0.35$ | 0.50 | 236 | 30 | <5 |
| Second...... | 1.52 | 0.37 | 497 | 62 | >4 |
| Third ....... | 0.64 | 0.14 | 61 | 8 | 2.3—8 |

NOTES—Col. (2): Average duration (lg $T_{90}$). Col. (3): width of the Gaussian ($\sigma$) (lg $T_{90}$). Col. (4): Members of the group. Col. (5): population of the group (%). Col. (6): Border of the group in $T_{90}$ (unfortunately they overlap).

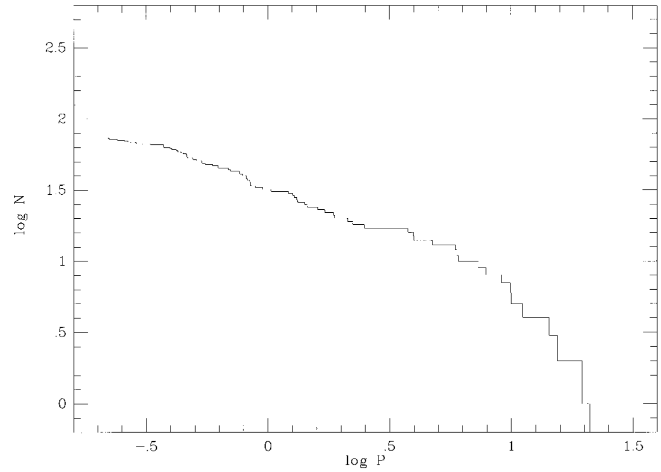


FIG. 5.—log $N$–log $P$ distribution of the intermediate type ($2.5 < T_{90} < 6.3$) GRBs. The slope of $-0.65$ is substantially different from that of the two other types of GRBs. This is compatible with the intermediate GRB being a separate class of objects.

second group has a $-1.06$ slope. This corresponds to the results of Kouveliotou et al. 1995.

The log $N$–log $P$ distribution of the intermediate-type GRBs (Fig. 5) may be different, but this is questionable.

## 5. HARDNESS RATIOS

The average hardness ratios of the short and long bursts are 4.5 and 2.5. The intermediate type has a 2.2 average hardness ratio. If this group were a random mix of some *shorter* long-type bursts and some *longer* short-type of bursts, the expected value should have been between the two average hardness ratios. The actual value differs significantly from this, being close to (and even somewhat smaller than) the hardness ratio of the long bursts. However, it does not seem possible purely from the point of view of the hardness ratio to distinguish the intermediate bursts from the long ones, and thus the hardness information does not support, but also does not contradict, the intermediate burst class hypothesis.

## 6. CONCLUSION

It is possible that the three-log normal fit is accidental and that there are only two types of GRBs. However, if the $T_{90}$ distribution of these two types of GRBs is lognormal, then the probability that the third group of GRBs is an accidental fluctuation is less than 0.02%. The log $N$–log $P$ distribution and hardness ratio are also suggestive of the fact that the intermediate-duration ($T_{90} = 2.5$–7 s) bursts represent a third class of GRBs.

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