A Possible Explanation for The Peculiar Correlations in The Angular Distribution of γ-ray Bursts

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ABSTRACT

It has been recently discovered that the angular autocorrelation function of \(\gamma\)-ray bursts exhibits sharp peaks at angular separations of \(\theta \lesssim 4^\circ\) (Quashnock and Lamb 1993), and at \(\theta \gtrsim 176^\circ\) (Narayan and Piran 1993). These results were based on the publicly available BATSE catalogue. While an excess of very close pairs of bursts can naturally arise from burst repetition or from a spatial correlation of the burst sources, a physical explanation for an angular correlation on a scale of \(\simeq 180^\circ\) seems inconceivable.

We show that the sharp peaks in the correlation function, both at very small and at very large angular separations, can be explained by a possible bias in the determination of the burst positions. A generic way is described in which the suggested bias can be introduced into the burst localization procedure, either through instrumental imperfection or through the software analyses.

We apply Monte Carlo simulations to show that the observed correlation function can be reproduced by the suggested effect. We demonstrate that the results can nicely agree with the observations even if only a fraction of the bursts are subject to the bias.

We emphasis that the only motivation for suggesting the existence of this bias are the features found in the angular autocorrelation function. It does not rule out the possibility that bursts repeat. The natural way in which such bias, if it exists, explains both sharp peaks, and the various conceivable causes for the origin of this bias, make the bias hypothesis worth considering.

*Subject headings:* Gamma-rays: bursts
1. Introduction

In a recent analysis of the publicly available BATSE catalogue of γ-ray bursts Quashnock and Lamb (1993) have found a significant excess of close pairs of bursts with angular separations \( \lesssim 4^{\circ} \). They suggested that this is evidence for burst repetition on a time scale of months, where the scale of \( 4^{\circ} \) reflects the localization error in the bursts’ directions, which is estimated to be of the same order (Fishman et al. 1993). In a subsequent study of the burst angular autocorrelation function, Narayan and Piran (1993) have discovered also a substantial correlation on angular separations in the range \( 176^{\circ} < \theta \leq 180^{\circ} \), comparable in significance to the peak at \( \theta \leq 4^{\circ} \) (Fig. 1). Lacking any physical explanation for the excess of pairs separated by \( \approx 180^{\circ} \) they suggested that the two peaks in the correlation function, both at very small and at very large angular separations, are either due to a statistical fluctuation or caused by some unknown selection effect.

A correlation on scales \( \lesssim 4^{\circ} \) can naturally arise from burst repetition or from a spatial correlation of the burst sources. In contrast, an astrophysical explanation for the angular correlation on \( \approx 180^{\circ} \) scale is inconceivable. The sharpness of this peak (Fig. 1) and the absence of any comparable excess of correlation in the entire range of \( 4^{\circ} < \theta < 176^{\circ} \) are especially puzzling.

In this paper we argue that the sharp peaks in the correlation function, both on the \( \lesssim 4^{\circ} \) and on the \( \gtrsim 176^{\circ} \) scales, can be explained by a possible bias in the determination of the burst positions. In §2 we demonstrate how points can be distributed on a sphere “almost randomly” while being strongly correlated at separations of \( \sim 0^{\circ} \) and \( \sim 180^{\circ} \), and on these scales only. In §3 we describe a generic way in which the suggested bias can be introduced into the burst localization procedure, either through instrumental imperfection or through the software analyses. In §4 we apply Monte Carlo simulations to show that the observed correlation function can be reproduced by the suggested effect, even if the bias is applied only to a fraction of the burst population.
2. Angular Distributions On Rings

First, let us discuss a purely mathematical problem which will be related to the peculiar correlations in the burst distribution in §3.

The angular two-point correlation function, $w(\theta)$, averaged over many realizations of randomly distributed points on the celestial sphere, is identically zero. It is easy to show that if, instead of an isotropic distribution, the points are randomly distributed only within an angular distance $\Delta \theta/2$ from a single great circle on the sky (hereafter, a ring of width $\Delta \theta$) then $w(\theta)$ will exhibit pronounced peaks at $\theta \leq \Delta \theta$ and at $\theta \geq 180 - \Delta \theta$. In fact, $w(\theta)$ would present such peaks even if the points were distributed within a set of an arbitrary number of randomly oriented rings. In order to demonstrate this we have constructed many Monte Carlo sets of points with such underlying distributions, using the following procedure: a) choose $k$ randomly oriented rings, each 4° in width. b) generate random positions on the sky and keep only those points which fall within at least one of the rings. We do it in such a way that the probability of selecting a point in a certain direction is proportional to the number of rings within which that direction is located, namely, there are higher probabilities to directions where rings overlap. For illustration, figure 2 presents one realization of randomly distributed points within 3 rings, and within 60 rings.

For any given number of rings, $k$, we have constructed many realizations of 260 points using the above scheme (there are 260 bursts in the available BATSE catalogue), and calculated $w(\theta)$ for each realization. For any value of $k$ we find that $w(\theta)$, when averaged over the ensemble of realizations, sharply peaks at angular separations of $\lesssim 4°$ and $\gtrsim 176°$. Figure 3 shows the results for $k = 20$, and $k = 60$. The effect remains, though with a lower significance level, even when $k$ is so large that the rings practically cover the entire sky. The reason is that any number of randomly oriented rings are extremely unlikely to cover the sphere uniformly, and the regions where rings overlap are typically $\sim 4°$ in size, which shows up in the correlation function.
It is not difficult to trace the origin of the two peaks: The correlation at $\theta \lesssim 4^\circ$ is due to the small width of the rings and due to the fact that the enhanced probability regions (where rings overlap) are of the same angular size. The peak at $\simeq 180^\circ$ is due to the ring-like structure of the underlying distribution, and due to the fact that if two rings cross at a certain point then they must cross also at the diametrically-opposed direction. Thus, the enhanced probability regions themselves (which are typically $\sim 4^\circ$ in size) are correlated on angular separation of exactly $180^\circ$.

Obviously, the underlying distribution function of any set of rings is symmetric in opposite directions. If rings cross at an angular distance $\phi$ from a certain position on the sphere, then their second crossing point is at a distance of $180^\circ - \phi$ from that position. Therefore, the autocorrelation function of distributions on rings must be symmetric, i.e., satisfy $w(\theta) = w(180 - \theta)$, a property which is indeed evident in Figure 3.

As we shall see in §4, the effect is weakened when such distribution is considerably diluted with a truly isotropic distribution, but it does not disappear altogether.

3. The “Ring Bias”

The peculiar correlations in the burst distribution (Fig. 1) can be understood if the bursts, or at least a substantial fraction of them, are somehow biased to lie within a set of narrow rings. We shall now argue that the structure of the BATSE instrument, the configuration of the spacecraft’s orientations, and the burst localization software allow considerable room for a systematic localization error which tends to slightly displace bursts, making their positions coincide with a certain configuration of rings. First, we mention the relevant basic characteristics of the instrument and then describe a simple generic way in which such a bias can be introduced, keeping in mind that the real cause for such bias, if it exists, is likely to be more complex.
The BATSE experiment (Fishman et al. 1989) consists of eight Large Area Detectors placed at the corners of the Gamma Ray Observatory spacecraft, with an octahedron geometry. The detectors are uncollimated and the location of a burst is determined by comparing the relative count rates from the separate detectors. A burst can be viewed by up to four detectors, but bursts are triggered on-board when the count rate in the 50-300 Kev energy range increases above the background by $5.5\sigma$ or more in at least two detectors simultaneously.

The response of BATSE’s detectors to incident flux is anisotropic, so the sensitivity threshold for detecting a burst varies across the sky. A weak burst at one location on the sky may create acceptable rates in BATSE’s detectors while an identical burst at another location will not (Brock et al. 1991). This known intensity-dependent effect is in GRO coordinates, but because of the many orientations of GRO for the various observation periods, this effect is believed to be averaged away when calculating dipole or quadrupole moments of the burst distribution. However, it may not average away when calculating the correlation function.

For example, many bursts are likely to produce the required $\geq 5.5\sigma$ signal only in two detectors, either because the direction of a burst is close to the plane defined by the two detectors (so the other detectors are at higher angles of incidence), or simply because the burst is weak (most bursts are weak ones). The important point is that if no other detector had fired (say, due to its high angle of incidence), or alternatively, if the burst localization software had ignored (or mistreated) a $<5.5\sigma$ signal from the other detectors, then the burst would be determined to lie in the plane defined by the two detectors. A burst’s direction would “collapse” into a ring, rather than into the exact plane, if, for example, the reason for the bias is that a low-amplitude signal in a third detector was not taken into account properly. The width of the ring would be $\simeq 4^\circ$, which is comparable to the already known localization errors due to statistical errors and imperfect modeling of the instrument.

Revealing the exact origin of such possible localization error requires a high level of
technical understanding of the instrument’s operation, and familiarity with the relevant software. The following are just a few conceivable causes which might be related to the suggested effect: a) an insufficient response of the detectors at incidence angles which approach $90^\circ$. b) differences in the thresholds of the eight detectors. c) the burst localization software ignores detectors which fire with low significance levels (or takes them into account incorrectly). d) some correlation between the spacecraft’s different orientations (see §4).

The suggested localization error slightly displaces bursts from their true positions and puts them within one or a few rings which have fixed orientations relative to the spacecraft. However, since GRO has changed its orientation $\sim 30$ times during the first year of observation, the relevant number of rings is larger by a factor of $\sim 30$ (but see §4). Furthermore, the rings should be unequally weighted since the GRO spent different periods of time in its various orientations. Therefore, we shall now derive the configuration of rings, based on the GRO orientations in the first year of observation, and check whether the discovered peaks in $w(\theta)$ can be reproduced by the suggested bias.

4. GRO’s Rings

During the time in which the first 260 bursts were detected (from April 21, 1991 until March 5, 1992) the GRO has changed its orientation 31 times, spending between 3 to 14 days in each orientation (the GRO’s pointing plan is publicly available). Suppose that there is only one plane in GRO coordinates towards which the positions of the bursts are shifted, and make, at the moment, the (too optimistic) assumption that the bias applies to all bursts. Instead of performing Monte Carlo simulations of 31 randomly oriented rings, we “attach” a plane to the spacecraft and derive the configuration of rings which corresponds to the set of orientations that this plane had portrayed during the year of observation (hereafter, the GRO rings). The orientation of the plane relative to the spacecraft is irrelevant as long as it is fixed during the entire year. Now we generate simulated sets of
260 points by drawing randomly from this specific set of rings as described in §2, but with a probability of drawing a point within each ring proportional to the time the spacecraft spent in the corresponding orientation. Obviously, the probability to draw a point in a certain direction is weighted by the total period of time that this direction had been located within a ring. The autocorrelation function for the GRO set of rings, averaged over many realizations, is displayed in figure 4.

We find that the sharp peaks at $\lesssim 4^\circ$ and at $\simeq 180^\circ$ are even higher than the expected from a randomly oriented set of 31 rings, and that there is also a marginally significant correlation on intermediate angular scales. We have examined the GRO pointing plan for the relevant period of time and found that the GRO orientations were not distributed at random. The spacecraft is usually oriented in ways that the other on-board (collimated) experiments, e.g., OSSE and COMPTEL, are pointed towards especially desirable targets like the Crab pulsar, the Galactic center, CYG X-1, etc. Furthermore, the pointing plan is optimized, for example, in a way that will enables the OSSE detector (which can move in the x-y plane of the spacecraft) to alternate between two targets when one of them is below the horizon (Eric Chipman, GRO Science Support Center; private communication). Choosing an orientation for the spacecraft is also constrained by the requirement that the collimated detectors will not point too close to the sun. Consequently, 6 of the GRO orientations are redundant, and the others are correlated in some non-trivial way. This, and the variance in the durations that the spacecraft spent in the different orientations imply that the number of rings is effectively lower than 25.

We have assumed so far that the “ring bias” applies to all bursts, but it is reasonable to expect that only some fraction of them would be subject to the effect. Lacking the exact mechanism which produces this bias (but see §3) we shall now show an example which demonstrates that even if a biased distribution is diluted with randomly (and isotropically) distributed bursts the observed features in $w(\theta)$ can still be reproduced. For that we have generated many simulated samples of 260 points, where the position of each point was
determined in the following way: a) draw a random location from an isotropic distribution and choose a random day within the year of observation. b) find the orientation of the plane (which is fixed to the spacecraft) at that time, and calculate the angular distance of the point from the plane. c) If the angular distance is less than 30° then the position of the burst “collapses” to the corresponding ring. Otherwise, the burst remains in its original position. Figure 5 presents the resulting $w(\theta)$, averaged over many such realizations. It is consistent with the observed autocorrelation function (Fig. 1).

We point out that the quadrupole and dipole moments for such distributions are not in conflict with the values obtained for the burst distribution.

5. Discussion

The main conclusion of this paper is summarized in the abstract so we avoid redundancy here. We shall just stress that the suggested bias, if it exists, does not rule out the possibility that burst sources repeat on a time scale longer than a year, and it does not necessarily imply that the dipole and quadrupole moments of the burst distribution are much different than their current values.

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Fig. 1 - The angular autocorrelation function of the bursts in the publicly available BATSE catalogue, binned into intervals of $4^\circ$ (Narayan and Piran 1993). The 1-$\sigma$ error bars were calculated using simulations of random isotropic distributions (the data for these plots have been kindly provided by Ramesh Narayan and Tsvi Piran). Notice the sharp peaks at $\theta \lesssim 4^\circ$ and at $\theta \gtrsim 176^\circ$. a) The full sample of 260 bursts. b) Only those 131 bursts which have formal position errors smaller than $4^\circ$.

Fig. 2 - a) An equal area projection of one realization of 260 points which are distributed randomly within 3 randomly oriented rings, according to the scheme described in §2. b) A similarly generated distribution but within 60 rings. Although a visual assessment cannot distinguish between this and a random isotropic distribution, the angular autocorrelation function for these distributions sharply peaks at very small and at very large angular separations (see Fig. 3).

Fig. 3 - The angular autocorrelation function, averaged over many realizations, for 260 points randomly distributed within 20 randomly oriented rings (a), and within 60 rings (b). The error bars reflect one standard deviation obtained from the ensemble of realizations. Notice the sharp peaks at $\theta \lesssim 4^\circ$ and at $\theta \gtrsim 176^\circ$, and the symmetry property $w(\theta) = w(180 - \theta)$ (see text). These functions appear smoother than those in figure 1 because they are the product of averaging $w(\theta)$ over many realizations.

Fig. 4 - The angular autocorrelation function for 260 points randomly distributed on the GRO set of rings (see text). The peaks in the first and last bins are even higher than the expected from a randomly oriented set of 31 rings, which indicates that the effective number of rings is smaller. Indeed, the various orientations of the spacecraft are not randomly distributed (§4), which is also reflected by the marginally significant variations of $w(\theta)$ on intermediate angular scales.

Fig. 5 - Similar to figure 4, but now the distribution is considerably diluted by a truly isotropic distribution (unbiased positions) (see text).