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GAMMA-RAY BURSTER RECURRENCE TIMESCALES **

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ABSTRACT

Three optical transients have now been found (Schaefer 1981 and Schaefer et al. 1984) which are associated with gamma-ray bursters (GRBs). The deduced recurrence timescale for these optical transients (τ_{opt}) will depend on the minimum brightness for which a flash would be detected. We present a detailed analysis using all available data of τ_{opt} as a function of E_{γ}/E_{opt}. For flashes similar to those found in the Harvard archives, the best estimate of τ_{opt} is 0.74 years, with a 99% confidence interval from 0.23 years to 4.7 years. It is currently unclear whether the optical transients from GRBs also give rise to gamma-ray events. One way to test this association is to measure the recurrence timescale of gamma-ray events (τ_{γ}). We examine here a total of 210 gamma-ray error boxes and have found that the number of observed overlaps is not significantly different from the number expected from chance coincidence. This observation can be used to place limits on τ_{γ} for an assumed luminosity function. We find that $\tau_{\gamma} \gtrsim 10$ yr if bursts are monoenergetic. However, if GRBs have a power law luminosity function with a wide dynamic range, then our limit is $\tau_{\gamma} \gtrsim 0.5$ yr. Hence, the gamma-ray data do not require τ_{γ} and τ_{opt} to be different.

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I. INTRODUCTION

In the decade since GRBs were discovered (Klebesadel, Strong, and Olson 1973), many models have been proposed to explain the GRB phenomenon (Ruderman 1975). Part of the difficulty in distinguishing between the models is that they typically make few predictions which are either distinctive or verifiable. One of the few verifiable predictions of many models is the recurrence time scale, τ_γ. For example, some models (Woosley 1981) predict $\tau_\gamma \sim 1$ yr, while some models (Colgate and Petschek 1981; Van Buren 1981; Michel 1984; and Hameury et al. 1982) predict $\tau_\gamma \sim 10^6$ yr, and others (Zwicky 1974; Grindlay and Fazio 1974; Baan 1982; Teller and Johnson 1980; Brecher 1981) predict no recurrences at all.

Jennings and White (1981) have analyzed the LogN(>S)-LogS curve and concluded that $\tau_\gamma < 10^5$ yr. Indeed, two GRBs have been observed (Mazets and Golenetskii 1982 and Golenetskii, Ilyinskii, and Mazets 1984) with $\tau_\gamma \lesssim 1$ yr. One of these GRBs (GBS0520-66) is highly unusual for many reasons (Cline 1981), and may represent a separate class of GRBs. For this reason, the sixteen bursts from this source have been ignored in the analysis below.

One method to measure τ_γ is to look for possible cases of recurrence as indicated by overlapping error boxes. Our analysis is composed of three procedures: (1) We have searched through known error regions for cases where the error regions overlap; (2) We have determined how many overlaps are expected by chance coincidence alone; and (3) We have calculated how many overlaps are expected due to recurrence for various assumed τ_γ and luminosity functions.

II. GAMMA-RAY RECURRENCE TIMESCALE

The 210 error regions which we used for procedure (1) were obtained from a variety of sources (Mazets et al. 1981; Klebesadel et al. 1982; Terrell et al. 1982; Nishimura et al. 1978; Hueter 1983; Mazets 1983; Baity, Hueter, and Lingenfelter 1984; Ozel, Kiziloglu, and Tokdemir 1983; Ubertini et al. 1982; Strong, Klebesadel, and Olson 1974; Sommer and Muller 1978; Katoh et al. 1984; Desai 1984; and Klebesadel et al. 1983). We found one case where ten error regions overlapped and several cases where nine error regions overlapped. We also found several cases where four thin (width < 1°) annuli intersected. Roughly half of the 210 error regions are annuli on the sky derived from detections with only two spacecraft. Clearly, any two error regions with annulus shapes are quite likely to intersect. When all 210 error regions are considered, the number of annulus/annulus overlaps is much larger than the number of overlaps expected to be caused by recurrence for any $\tau_\gamma > 0.1$ yr . Therefore, we have searched a number of subsets of the 210 error regions for the subset which places the greatest restriction on τ_γ. We find the most restrictive subset is defined as consisting of those regions which subtend an area less than 200 square degrees and which entirely fit inside a circle of 20° radius. For bursts with two separated yet equally likely error regions, the later criterion was applied to each alternate area separately. For this subset of 89 error regions, the 37 overlaps which occur (fourteen double overlaps and three triple overlaps) are tabulated in Table 1.

A number of these overlaps, possibly all, are due to chance superposition of error regions from unrelated GRBs. Procedure (2) consists of calculating this number by means of a Monte Carlo analysis. In each of 100 Monte Carlo runs, the error regions are randomly scattered over the sky before the number of overlapping error regions is evaluated. For all subsets of error regions, we find that the observed number of overlapping error regions is not significantly different from that expected from chance superposition alone. For example, the subset of 89 regions defined above has 37 overlaps whereas 39.3 ± 8.5 are expected from coincidence. For the entire collection of 210 regions, several 9x overlaps and 10x overlaps are expected, as are a number of overlaps involving four or more thin annuli. These results indicate that the bulk of observed overlaps are not due to recurrence.

The number of expected overlaps caused by recurrence is model dependent. We have assumed that bursts from an individual GRB have a Poisson distribution in time with a mean of τ_γ. We assume (as has Jennings, 1982) that the number of bursts with a given gamma-ray energy $n(E_\gamma)$, has a power law distribution;

$$n(E_\gamma) = \frac{\alpha n_0 E_\gamma^{\alpha-1}}{E_2^\alpha(1-\zeta^\alpha)},\ 0 < E_1 < E_\gamma < E_2,\ \zeta \equiv E_1/E_2.$$

Note that as ζ approaches unity, the luminosity function becomes monoenergetic. Jennings (1982, 1984) finds that $-1.5 \lesssim \alpha \lesssim 0$ and $\zeta \lesssim 0.04$ are consistent with the gamma-ray longN(>S)-logS observations. The sixteen bursts from GBS0520-66 (Golenetskii, Ilyinskii, and Mazets 1984) closely follow the power law luminosity function with $\alpha \sim -0.4$ and $\zeta \sim 10^{-3.5}$, although we remind the reader that these sixteen bursts are not used in the analysis in this paper. Belli (1984 and private communication) has demonstrated that $\alpha \sim -2.5$ and $\zeta < 10^{-3}$ for the population of bursts in the Konus catalogue (Mazets _et al_. 1981). We have evaluated our model for values of α between 0.5 and -1.5 and for values of ζ between 1 and 10^{-7}. Finally, we have assumed that the probability that a given burst will both be detected and be positioned is a function of the burst's fluence and date of occurrence. This probability was determined empirically by dividing the LogN(>S)-LogS curve for the bursts included in the subset of error regions by the LogN(>S)-LogS curve for all bursts. A separate determination of the probability was made for each of five intervals of time since 1969 over which the probability is roughly constant (see Table 2).

With these assumptions, the expected number of observed recurrences can be calculated by means of a Monte Carlo analysis. For each trial run, a number of GRB distances, burst times, and burst luminosities are generated. Each burst is then determined to be "positioned" or "not positioned" based on the probability of positioning for a given date and fluence. The number of overlaps caused by recurrence can then be tallied by finding the number of multiple bursts from a given GRB which are positioned.

Allowance must be made for the possibility that error regions which are overlapping because of recurrence can also be overlapping with the error regions from other GRBs. To correct for this effect, the fraction of sky covered by error regions must be known. Ninety-one percent of the sky is covered by our 210 total error regions, while only eight percent is covered by the subset of 89 regions.

The results of the Monte Carlo analysis are presented in Figure 1 and Table 3 for the subset of 89 error regions. The total number of expected overlaps (due to both recurrence and chance overlaps) is also presented. This number is to be compared to the 37 observed overlaps. It can be seen that a monoenergetic luminosity function ($\zeta = 1$) is consistent with observation only if $\tau_\gamma \gtrsim 10$ yr. However a luminosity function with a wide dynamic range ($\zeta \lesssim 10^{-3}$) is consistent with a recurrence timescale as short as 0.5 yr.

III. OPTICAL RECURRENCE TIMESCALE

Schaefer et al. (1984) have estimated that $\tau_{opt} \sim 1$ yr. This estimate is based on the sum of exposure times of the archival plates examined. However, some of these plates are not sensitive enough to detect a flash which has a gamma-ray to optical energy ratio (E_γ/E_{opt}) similar to those of the three detected flashes (i.e., 10^3). The exposure times for these plates should not be used in calculating τ_{opt} for bursts with $E_\gamma/E_{opt} = 10^3$. Similarily, more sensitive plates can be used to limit τ_{opt} for flashes with a larger maximum E_γ/E_{opt}. If estimates of τ_{opt} are stated as a function of E_γ/E_{opt}, then effects due to the differing GRB distances will be scaled out.

In Table 4, we have presented 99% confidence limits on τ_{opt} for flashes in a given range of E_γ/E_{opt}. The data used in preparing Table 4 was compiled from a number of studies (Gehrels et al. 1983; Schaefer, Seitzer, and Bradt 1983; Pedersen et al. 1983; and Schaefer et al. 1984) in addition to the archival plate search (Schaefer 1984). In each of these studies, it is known how many hours of observations are capable of detecting a brief flash of any given optical fluence. With the measured E_γ, the effective duration of observations can be stated as a function of E_γ/E_{opt}. In the second column of Table 4, the exposure for all bursters for the above mentioned studies were summed for each E_γ/E_{opt} bin. Note that the limits on τ_{opt} are for the average of the τ_{opt} for each of the dozen or so GRB positions examined in these studies. For example, the best estimate for τ_{opt} for flashes with $E_\gamma/E_{opt} \sim 10^3$ is 0.74 yr (with a 99% confidence interval of 0.23 yr $< \tau_{opt} <$ 4.7 yr).

Table 4 was created with the assumption that the E_γ value of any burst from a given GRB would always be proportional to the fluence of one specific burst from that GRB reported by the instrument on board the Pioneer Venus spacecraft (Klebesadel et al. 1983). This assumption is valid only if GRBs are monoenergetic. However, even if the assumption is false, the ratio of E_γ to E_{opt} still represents the best available means to construct a distance independent measure for comparing E_{opt}.

IV. DISCUSSION

We conclude that τ_{opt} is consistent with the best current estimates of τ_γ if $\zeta \lesssim 10^{-3}$. Hence, we cannot yet answer such questions as: (1) Do the optical and gamma-ray events occur simultaneously on GRBs? (2) Is the archival E_γ/E_{opt} ratio a constant (cf. Schaefer et al. 1984)? (3) Is τ_γ so small that many GRB models can be rejected?

GRB detectors onboard the recently launched Venera-13 and -14 satellites, as well as the continuously operating Solar Max, Pioneer Venus, and ICE instruments, are expected to yield a number of new gamma-ray error regions. However, these new error regions are not likely to be greatly improved in either number or positional accuracy when compared to the earlier results that include Venera-11 and -12 data (Mazets et al. 1981). In such a situation, the new observation may not greatly change our limit on τ_γ, because the models with $\zeta \lesssim 10^{-3}$ will still predict that the number of recurrence caused overlaps will be comparable to or smaller than the uncertainty in the number of chance overlaps. The Gamma Ray Observatory (Fishman et al. 1984), however, is expected to produce several hundred error regions with an area of order 10 square degrees, and hence will yield a much stronger limitation on τ_γ than we present in this paper.

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TABLE 1

OBSERVED OVERLAPS OF GRB ERROR REGIONS

R.A.	δ	DATES OF OVERLAPPING BURSTS		
117°	-67°	71/03/18	73/06/10	81/10/16
116°	-63°	73/06/10	79/09/25	
99°	-42°	78/03/30	79/08/26	79/10/14
294°	-40°	74/07/23	76/12/09	
338°	-32°	76/12/20	79/07/12	
33°	-21°	78/10/25	79/07/28	
59°	-13°	78/10/25	79/09/10	
94°	-11°	76/08/16	79/04/12	
310°	- 8°	79/02/13	82/03/03	
164°	0°	79/01/16	79/10/03	
287°	5°	79/03/24	79/03/25	79/03/27
68°	8°	71/03/18	73/06/10	
106°	8°	76/01/28	77/07/08	
92°	15°	77/07/08	79/10/06	
227°	32°	78/09/18	78/10/19	
57°	54°	73/03/02	79/11/15	
190°	79°	72/05/14	79/10/16	

TABLE 2

PROBABILITY OF POSITIONING A GRB

logS	1969.6 to 1973.6	1973.6 to 1976.0	1976.0 to 1978.7	1978.7 to 1980.1	1980.1 to 1982.3
>-3.5	0.50	0.40	0.50	1.0	0.50
-4.0 to -3.5	0.50	0.20	0.50	1.0	0.25
-4.5 to -4.0	0.11	0.0[a]	0.10	1.0	0.0[a]
-5.0 to -4.5	0.0[a]	0.0[a]	0.018	0.37	0.012
-5.5 to -5.0	0.0017	0.003	0.0025	0.067	0.0[a]
-6.0 to -5.5	0.0[a]	0.0[a]	0.0025	0.014	0.0[a]
<-6.0	0.0[a]	0.0[a]	0.0[a]	0.0020	0.0013

[a] A zero probability merely means that no bursts with positional information were observed inside the indicated time and fluence bin.

TABLE 3

PREDICTED NUMBER OF OVERLAPS

τ_Y(yr)	α	ζ	Overlaps from Recurrence	Total Overlaps[a]
1.0	--	1	44.3 ± 13.9	83.6 ± 16.3
5.0	--	1	23.7 ± 7.7	63.0 ± 11.5
10.0	--	1	13.3 ± 4.7	52.6 ± 9.7
15.0	--	1	7.5 ± 3.7	46.8 ± 9.3
20.0	--	1	6.1 ± 2.6	45.4 ± 8.9
1.0	-0.5	10^{-4}	5.5 ± 1.2	44.8 ± 8.6
0.5	-0.5	10^{-4}	9.9 ± 2.2	49.2 ± 8.8
10.0	-0.5	10^{-4}	3.1 ± 2.2	42.4 ± 8.8
1.0	-1.0	10^{-4}	2.6 ± 0.9	41.9 ± 8.5
1.0	0.0	10^{-4}	21.6 ± 5.3	60.9 ± 10.0
1.0	-0.5	10^{-3}	12.4 ± 4.6	51.7 ± 9.7
1.0	-0.5	10^{-5}	4.3 ± 1.8	43.6 ± 8.7

[a] The model predictions in this column are to be compared with the observed number of 37 overlaps.

TABLE 4

OPTICAL RECURRENCE TIME SCALE

log (E_γ/E_{opt})	Observing Time (hr)	Number Flashes Observed	99% conf. limit on τ_{opt} (yr)[a]
1.75 to 2.25	28300	0	> 0.70
2.25 to 2.75	24400	0	> 0.61
2.75 to 3.25	19500	3	> 0.23, < 4.7
3.25 to 3.75	12000	0	> 0.30
3.75 to 4.25	5680	0	> 0.14
4.25 to 4.75	2040	0	> 0.051
4.75 to 5.25	650	0	> 0.016
5.25 to 5.75	176	0	> 0.0044
5.75 to 6.25	46.0	0	> 0.0011
6.25 to 5.75	44.3	0	> 0.0011
6.75 to 7.25	38.4	0	> 0.00095
7.25 to 7.75	8.2	0	> 0.00020

[a] For Poisson statistics, if zero events are observed, then there is a 99% probability that the average number of events observable for identical experiments is less than 4.6. Similarly, if three events are observed, then there is a 99% probability that the mean will be between 0.47 and 9.5.

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FIGURES

Figure 1. Predictions of Overlaps Due to Recurrence.

This figure shows a contour plot of the number of overlaps caused by recurrence which should be observed for the subset of 89 error regions. The model predictions are given as a function of the α and ζ parameters in the luminosity function. A monoenergetic luminosity function occurs when ζ equals unity. One of this paper's conclusions is that the majority of observed overlaps are due solely to chance coincidence. In this case, the number of recurrence overlaps must be small compared to the uncertainty in the number of chance overlaps. The diagram indicates that τ_γ = 1 yr is acceptable if the luminosity function has $\alpha < -0.3$ and $\zeta < 10^{-3}$.

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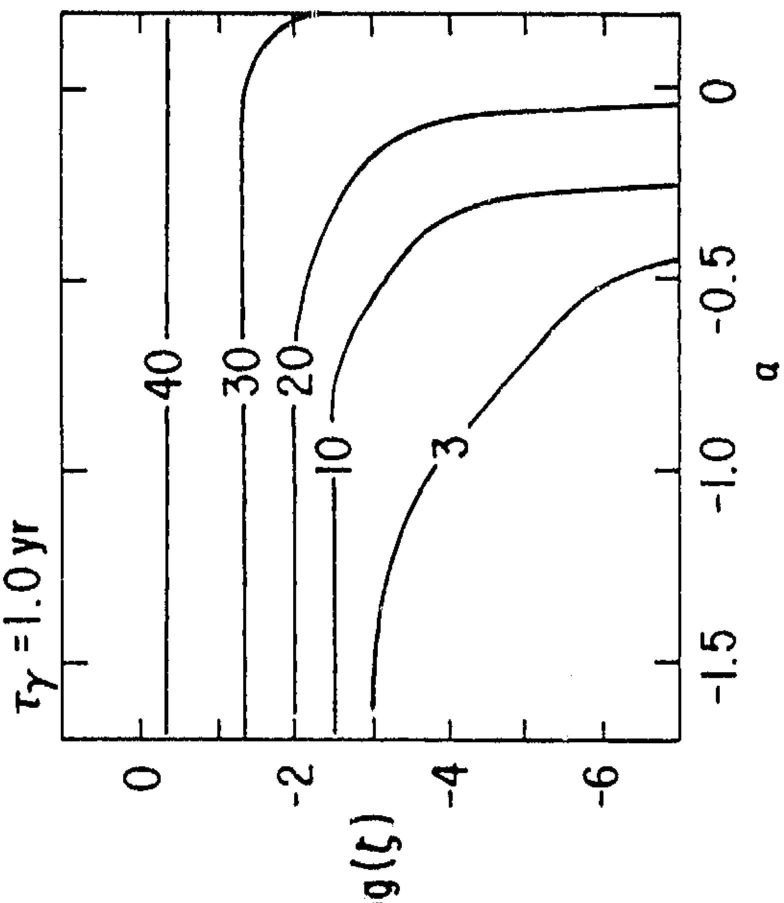

Figure 1