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MeV measurements of γ-ray bursts by CGRO-COMPTEL: Revised catalog

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MeV Measurements of γ-Ray Bursts by CGRO-COMPTEL: Revised Catalog

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Abstract. The imaging COMPTEL telescope has accumulated 0.1–30 MeV spectra, time-histories, and positions of more than forty γ-ray bursts within its $\sim$ 3 sr field of view in the eight years since its launch. CGRO-COMPTEL measures in both imaging "telescope" and single detector "burst spectroscopy" mode. In an ongoing collaboration with BACODINE/GCN, bursts are imaged automatically, with localizations relayed to a global network of multiwavelength observers in near real time ($\sim$ 10 minutes). We have updated our burst search procedure in two ways: 1) using more sensitive search algorithms; and 2) using data from more detectors. The first are double change-point algorithms. With these we can find regions of significant excess flux with no assumptions on the wide range of burst time-scales (e.g., rise-times or decay-times) or intensities, and only one adjustable parameter (the time-averaged count-rate of the detectors). This makes it simpler to combine information on burst time-histories from the larger effective area (but cruder time bins) burst spectroscopy detectors, and hence better pinpoint the best times for imaging each burst. We report the eight bursts detected during 1998–1999.

CGRO-COMPTEL Rapid Burst Response

The imaging Compton telescope COMPTEL, on board the Compton γ-Ray Observatory, has special capabilities for measuring transient events such as γ-ray bursts [1]. Not only are they detected in double-scatter "imaging" or "telescope" mode (0.75–30 MeV, 0.125 μs timing); but two NaI detectors act as independent 0.1–1.6 MeV and 0.6–10 MeV spectrometers (single-scatter "burst-mode"). Upon receiving

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an on-board burst trigger from BATSE, these burst spectrometers read out spectra at a faster cadence (every $\sim$1 s for 6 s; then every 4 s for several minutes), before reverting to the default "background" integration time of 140 s. COMPTEL's Rapid Burst Response (COMPTEL RBR) [2], an ongoing project with BACODINE [3,4] to broadcast $\sim 1^\circ$ COMPTEL positions of MeV-bright bursts in near-real time ($\geq$ 7 minutes), had so far made use of only the telescope data. Here we report on upgrading the process to incorporate the lower time resolution but higher effective area burst spectroscopy data. These contain effectively no imaging information but do allow us to more accurately constrain both ends of the burst light curve and whether the burst was visible above 0.5 MeV at all. This can improve the signal-to-background ratio for imaging and reduce the false trigger rate. However, properly including these data forced us to rederive methods for finding the start and end time of a burst (or other transient) from first principles.

To Catch a Burst: Change Points + Bayes

Previous methods of determining burst (or flare) start and end times ranged from finding it by eye (BATSE-LOCBURST [5]) to requiring the counts per pre-set time bin to be greater than $n\sqrt{counts}$ above a running average for the background (BACODINE [3]). COMPTEL had used a Negative Double Difference (NDD) algorithm, on the telescope data alone. NDD weights and smooths the data within specified time windows; numerically determines a second derivative; and checks to see if this curvature is beyond threshold. All parameters were empirically determined and carefully crafted to the telescope count rates and likely burst time scales [2]. Unfortunately, upgrading to include burst-mode data was difficult with NDD due to the involved parameter-tuning, which change drastically with count-rate and burst duration. By contrast, this was simple with change-point models. Scargle ([6] "Bayesian Blocks") first pointed out this simplicity, using it on GRB light-curves with drastically varying time-structures. Models for these are built up one at a time from piece-wise constant components. The 'change points' are the times at which these components switch, and are estimated by a straightforward Bayesian likelihood calculation. (change points are one of a number of aproaches well-known to statisticians but not to astronomers.) For catching γ-ray bursts, we use double change points: one each for the burst start and end.

Building the Algorithm

In theory, a properly constructed Bayesian likelihood ratio should be the best measure of the "distance" between two hypotheses ([7] and references therein). We built and tested likelihood ratios for several different kinds of change-point algorithms, using the standard Bayesian calculus. These all compared models of three segments delineated by two change points (i.e., two background segments separated by a burst block) with models of only one segment and no change points (i.e., background only). Here we briefly sketch the process (for details see [8]). We used constant or exponential rates μ_i for the segments (see below). For all, the sampling statistic assumed a Poisson process (binned or unbinned), given the model: $\exp(-\mu_i \delta t_i)(\mu_i \delta t_i)^{Y_i}/Y_i!$, with Y_i the counts in the i^{th} time bin with width δt_i. The priors on the average rates were chosen to be exponential, with scale factor β given by the inverse of the long-term average detector count-rate $\langle r \rangle$: $\pi(\mu_i|I) = \exp(-\beta\mu_i)/\beta$, with $\beta = 1/\langle r \rangle$. The prior on the exponential model scale factor was a broad Gaussian centred at zero; while that for the change-point times was uniform over the interval sampled.

The burst models tested included: **1)** Three constant pieces (1st background, burst, 2nd background) versus one (only background); **2)** Three constant pieces with rate before and after the burst constrained to be equal; **3)** Three exponential pieces; **4)** Three exponential pieces with the rate before and after the burst constrained to be the same exponential model; **5)** Two exponential pieces plus one constant "burst block" in the middle; and **6)** Two exponential pieces plus one constant "burst block" in the middle, with the rate before and after the burst constrained to be the same exponential model. The marginalized posterior for these was compared to those for two background models: **1)** One constant piece (for Models 1 and 2); and **2** One exponential piece (for Models 3–6).

Let Y_i represent the total counts and T_i the total livetime in the i^{th} segment, with t_0 and t_1 be the burst start and end times respectively (i.e., the end of the 0^{th} and 1^{st} segments; with segments 0 and 2 being background and 1 the burst). Then, the Bayes likelihood ratio for t_0, t_1 (after marginalizing over the unknown rates μ_0, μ_1, μ_2, and dividing by the similarly marginalized likelihood for no change points) can be written as the ratio of the priors (on the rates and change points) times the ratio of the (marginalized) sampling statistics. For Model 1 (constant background, burst, background) this is:

$$\lambda_{3C}(t_0, t_1) = \frac{1}{\beta} \frac{\beta^3}{(N_T - 3)(N_T - 2)} \times \frac{(\beta + T_T)^{Y_T + 1}}{(Y_T!)} \prod_{i=0}^{2} \frac{Y_i!}{(\beta + T_i)^{Y_i + 1}}$$

For Model 2 (constant background, burst, same background) it is similar, but the product is taken over only two segments(0+2 and 1). Bayes likelihood ratios for the exponential models were the same but were multiplied by terms for marginalizing over the exponential scale parameter. Finally, to find global (or total) Bayes odds for each model, we marginalized over all change points.

Tests and Results

These were compared on BACODINE-generated COMPTEL data for 44 BATSE burst triggers in COMPTEL's field of view from Jan 1, 1999 though May 31, 1999. For COMPTEL detections, we required that the total Bayes Odds ratio >10:1, and that the odds at the maximum likelihood change points exceed $\sim 25\%$ of this.

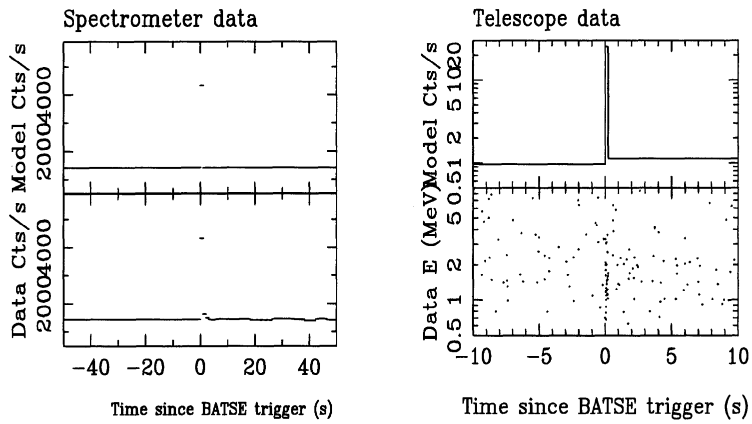

FIGURE 1. GRB980706: Light-curves and Model 1 for burst (*left*) and telescope (*right*) data.

TABLE 1. Results from Automated Timing Analysis

	Burst Spectrometer				Telescope Events			
GRB	Log Bayes Odds		Best times (s)		Log Bayes Odds		Best times (s)	
DAY	Total	Peak	Start[a]	Length	Total	Peak	Start[a]	Length
980124	1092.	1095.	+4.1	6.1	69.2	29.7	+4.2	3.3
980329	462.3	465.6	+3.1	7.1	5.64	10.8	+7.3	0.63
980706	823.1	826.5	+0.0	1.0	69.9	28.1	+0.0	0.23
980828	57.16	60.58	+0.0	2.0	4.49	9.99	+0.8	1.43
990105	167.7	171.1	+0.0	54.4	40.2	1.25	−0.2	0.88
990123	3645.	3649.	+22.2	20.1	64.7	24.8	+20.0	25.39
990728	199.0	202.3	+2.1	40.3	50.5	58.1	−1.9	31.64
990915	754.9	758.3	+0.0	10.1	67.1	26.7	+0.1	1.61

[a] With respect to BATSE trigger time.

We found: 1) Using an exponential to model a burst gave an indeterminant end-time. 2) Background variations gave too many false triggers unless the 3-piecewise-constant or exponential models were used. 3) Models 1 and 6 worked best; the exponential model for the background worked about as well as the 3-constant-components model, but was rather slower. Hence, Model 1 was preferred. 4) Using the change points determined from burst-spectrometer data to set a *window* in which to search for burst start and end times in the telescope data reduced the false trigger rate; increased the signal-to-noise ratio; and increased the speed of the search. 5) We also added a "minimum COMPTEL imaging" criterion: that the burst block must have at least 10 events.

After testing, Model 1 was run on all bursts for which we had BACODINE datasets, from 1996 through the present. For NDD: 8 false triggers, 9 real bursts found, 3 missed. For Model 1: 0 false triggers, 10 real bursts found, 2 missed; plus higher significance detections (and better position contours) for several of the bursts. We illustrate the change-point algorithm with GRB 980706, a very short

TABLE 2. Results from Automated Imaging Analysis

GRB DAY	Peak likelihood ratio	COMPTEL R.A ° 2000	COMPTEL Decl ° 2000	COMPTEL Azimuth °	COMPTEL Zenith °	2σ error °
980124	67.28	285.61	78.69	208.48	21.88	1.57
980329[a]	**	**	**	**	**	**
980706	60.22	161.82	57.53	67.51	46.75	1.84
980828	27.11	141.86	22.44	91.83	21.69	3.00
990105	21.67	307.73	1.28	320.92	22.09	3.12
990123	99.88	225.41	44.96	277.72	53.49	2.00
990728	241.4	211.96	−57.83	27.69	4.09	0.82
990915	61.97	96.89	71.68	280.24	50.69	2.50

[a] Below threshold for the automated algorithm, but was imaged by hand.

burst missed by the NDD algorithm but found by the CP algorithm (Fig. 1).

In sum, through a confluence of Bayesian methods, a classical statistics tool (change points), and knowledge of the COMPTEL instrument, we constructed more robust "burst-catching" algorithms. We have eight new candidates for the COMPTEL burst catalog. We show their timing results and preliminary positions in Tables 1 and 2. These bursts will go through standard COMPTEL processing before final acceptance.

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