A Comprehensive Search for Low-Energy Lines in BATSE GRBs

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A computer-based technique has been developed to search bright BATSE gamma-ray bursts for spectral lines in a comprehensive manner. The first results of the search are discussed and an example line candidate shown.

MOTIVATION

Prior to the launch of CGRO, and during the early days of the mission, the BATSE team expected that GRB lines would be common and easily identified. Our expectations were based upon the observations of KONUS\textsuperscript{13}, HEAO A-4\textsuperscript{[14]} and Ginga\textsuperscript{[10,17]}. Our early efforts were based upon these expectations: we searched bright bursts visually, examining consecutive spectra and also the spectrum of the entire burst\textsuperscript{[19]}. Our expectations were not met: no significant lines have been found\textsuperscript{[19,5]}.

While the failure to find lines in BATSE GRBs does not yet imply a serious discrepancy between the Ginga and BATSE results\textsuperscript{[13,5]}, it is disappointing. Previously, lines were interpreted as strongly supporting the theory that GRBs originate nearby from a disk population. Results from BATSE on the spatial distribution of GRBs demonstrate that only a minority of the bursts can originate from a disk population\textsuperscript{[16,12,7]}, so if the existence of lines is confirmed, their properties might indicate the presence of a disk subclass or give clues to the physics of halo or cosmological sources.

Is the failure to detect lines in the BATSE data because lines do not exist or is the failure due to some inadequacy in the visual search approach? To answer these questions a more systematic search is needed. We have therefore implemented an automatic, computer-based comprehensive line search. The goal of the search is comprehensiveness—a brute force approach is taken so that no significant line will be missed. The purpose of the search is to identify line candidates—the search need not perfectly evaluate their significances, which will be done later under direct human control. The computer-based
search has several advantages in addition to comprehensiveness: subjectivity is eliminated, there is no variation in detection threshold due to human exhaustion, there is no bias towards absorption or emission features, and the search will collect statistics on all trial lines.

COMPREHENSIVE SEARCH METHOD

The addition to the BATSE instrument of the eight Spectroscopy Detectors (SDs) was largely motivated by the KONUS results. Simulations and tests of the performance of the BATSE SDs show that they should be capable of detecting KONUS or Ginga-like GRB lines. Each SD is a NaI(Tl) scintillator crystal, 12.7 cm diameter and 7.6 cm thick, viewed by a photomultiplier tube of the same diameter. To limit the effort to a manageable level, the initial searches are restricted to lines below 100 keV, so only detectors in high-gain mode are useful. Typically, such detectors cover the energy range of about 10 keV to about 1400 keV, although analysis begins at about 15 or 20 keV due to an electronic artifact. Work to model this artifact continues, so that in the future we will be able to extend the analysis to lower energies. Analysis of the data is based upon an instrument response model which accounts for the detectors, nearby spacecraft material, and scattering from the Earth’s atmosphere. When a burst occurs, high-time resolution SHERB (Spectroscopy High Energy Resolution Burst) data are collected using a time-to-spill algorithm.

Since we do not know a priori when or how long a line will exist, we search essentially all time scales available. We search each single SHERB record, every consecutive pair, triple, and group of 4, 5, 6, 8, 10, 14, 20, ... records and the sum of all the SHERB records. Clearly, many overlapping intervals are searched, and thus the searched intervals are not all independent. Additionally, many intervals will have insufficient signal-to-noise ratio for a real line to be detectable—these intervals serve as controls. While not every possible consecutive combination of records is formed, enough combinations are searched so that no line should be missed, although its significance might not be optimized.

Similarly, we do not know a priori at what energies lines occur. Therefore, we first fit each spectrum with a continuum model, and then we perform continuum plus line fits using a closely spaced, fixed grid of trial centroids. Since the trial centroids are separated by one-third the detector resolution FWHM, no line candidate should be missed, although the exact centroid will not be found by the search.

Candidates are identified by large (> 20) changes in \( \chi^2 \). We have switched to using \( \Delta \chi^2 \) instead of the F-test because it is more appropriate when the errors are known. After a candidate is identified, other time intervals will be tried and the centroid will be made a free parameter in the fits.

To increase the robustness of the automatic nonlinear fits, we use a con-
FIG. 1. Results of the comprehensive line search for GRB 920627 (trigger 1676), SD 2. The figure shows the change in $\chi^2$ resulting from adding to the continuum model a narrow, additive Gaussian line. While SD 2 has useable data from 15–1240 keV, the search was made using the Comptonized continuum model and the restricted energy range 15–390 keV. The few points with $\Delta \chi^2 < 0$ are due to poor convergence.

The search results for GRB 940703 are quite different from those for GRB 920627. Only one high gain detector, SD 5, viewed the burst at an angle less than 100°. The data from SD 5 comprises 79 SHERB records, from which 917 spectra were formed. The largest value of $\Delta \chi^2$ identified in the search was 58.2 and many overlapping intervals had $\Delta \chi^2$ values approaching this value (see Fig. 2). When more careful fits are made, using the Band spectral form and the entire available energy range, the candidate is found to have $\Delta \chi^2$ of “only” 23.4. The difference in the values of $\Delta \chi^2$ is because for this very bright burst the Comptonized model is inadequate even over a restricted energy range.

Most of the line significance appears to come from a shorter interval which
excludes periods of weak emission, for which $\Delta \chi^2 = 28.1$. The spectrum of this interval is shown in Fig. 3—the candidate is seen to be an emission feature with an equivalent width of 2.1 keV. The line is narrow—allowing the width to vary does not significantly reduce $\chi^2$. For 3 additional parameters, the chance probability in any particular fit of such a large $\Delta \chi^2$, if no line actually exists, is $3 \times 10^{-6}$. Additionally, the residual plots show that adding the line to the model eliminates conspicuous runs of high, then low, residuals. Even considering the large number of spectra searched, the line is highly significant—the number of effectively independent spectra is well below 917 and the line is significant in more than one spectrum.

To date, 42 of the brightest GRBs have been searched by this technique. There was an average of 2.1 detectors per burst and 53 SHERB records per detector, for a total of 4729 SHERB records. From these records 51,651 spectra were formed and 861,372 fits performed. Partial examination of the results has identified 8 candidates with $\Delta \chi^2 > 20$. There are both absorption and emission candidates and their centroids range from 40 to 70 keV.

More work remains to be done. In most cases several high-gain SDs observe a gamma-ray burst. We can therefore usually test the reality of a line candidate by examining the data of the other detectors. If the lines are real, in all cases the data should be consistent and in some cases there should be confirmation: statistically significant detections in more than one detector. The ability to perform these tests is a major advantage of BATSE, but it is also time-consuming because there are many issues. Until we have completed these tests, the BATSE team considers the features identified by the comprehensive search to be line candidates rather than detections.

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FIG. 3. Data from SD 5, GRB 940703, for the interval 42.112–64.704 s. Top panels: Count rate data and fits, shown up to 100 keV. Bottom panels: Count rate residuals (data−model) in units of $\sigma$ for the entire energy range used in the fits. Left panels: A continuum-only fit, using the Band spectral form; $\chi^2 = 212.0$ with 199 degrees-of-freedom. Right panels: Added to the fits is an narrow, additive Gaussian line; $\chi^2 = 183.9$ with 197 degrees-of-freedom. The “hump” at 30 keV in the data and continuum model is expected from the detector physics (8,18). The contribution of atmospheric scattering to the counts in the line region is $\approx 4\%$.

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