ANALYSIS OF LINE CANDIDATES IN GAMMA-RAY BURSTS OBSERVED BY BATSE

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ABSTRACT. A comprehensive search of BATSE Spectroscopy Detector data from 117 GRBs has uncovered 13 statistically significant line candidates. The case of a candidate in GRB 930916 is discussed. In the data of SD 2 there appears to be a emission line at 46 keV, however the line is not seen in the data of SD 7. Simulations indicate that the lack of agreement between the results from SD 2 and SD 7 is implausible but not impossible.

KEYWORDS: gamma-ray bursts; spectra.

1. INTRODUCTION

A primary goal of adding the Spectroscopy Detectors (SDs) to BATSE was the detection of low-energy spectral features in gamma-ray bursts. At the time, the reported low-energy lines were interpreted as resonant cyclotron scattering in intense magnetic fields of neutron stars in our Galaxy. While the former theoretical explanation of spectral features is now untenable unless there are two populations of GRB sources, the observational status of spectral features is still important.

Each of the eight BATSE modules contains one SD, which consists of a 12.7 cm diameter by 7.6 cm thick crystal of NaI(Tl) viewed by a single 12.7 cm photomultiplier tube. Compared to the BATSE Large Area Detectors, the SDs have better energy resolution and a higher probability of full-energy absorption of incident gamma-rays, but a smaller area.

After the failure of our manual search to discovery a single line [1], we developed an automatic computer search to comprehensively search the data of bright bursts [2]. Because we do not a priori know the energy, starting time, or duration of spectral features, the procedure searches a wide range of centroid energies and timescales. Many combinations of consecutive spectra are examined: all singles, pairs, triples, and groups of 4, 5, 7, . . . spectra, up to the entirety of the high time resolution SD data. The presence of a line is tested by fitting each spectrum twice, first with Band’s “GRB” continuum function, then with the same continuum function plus a narrow line. A change in $\chi^2$ of more than 20 identifies a line candidate. The present search is limited to low-energy features, so a closely spaced grid of trial centroids extending up to 100 keV is used. The LLD is typically just below 20 keV and, after requiring a continuum interval below the first search centroid, lines are tested starting above 20 keV.
The search was applied to 120,700 spectra from 117 GRBs. Because of the examination of trial spectra with a sliding starting time and a wide range of durations, many of these spectra have substantial overlap. Additionally, most of the spectra have very low signal-to-noise ratios and consequently a real spectral feature could not have been detected; these spectra were searched as controls. Thus the number of independent spectra with sufficient photons to support the detection of a real feature is much lower, below about 1000.

2. RESULTS

The comprehensive search identified 13 candidates. The $\chi^2$ improvement from adding a line ranges from 20, the candidate threshold, to 50, corresponding to chance probabilities of $4 \times 10^{-5}$ to $10^{-11}$. The probabilities are calculated for adding two-parameters (line intensity and centroid; the intrinsic width is assumed to be narrow) to the spectral fit to a single spectrum. The energy range searched contains about five resolution elements; the number of independent spectra of sufficient intensity searched is below about 1000. Consequently at most one of these candidates might be a chance fluctuation in the ensemble.

An advantage of BATSE is the observation of bursts by several detectors, thereby enabling further tests of the reality of a candidate. Is the candidate detected with high statistical significance in the second detector? This would be confirmation of the reality of the feature. Confirmation might not be achieved for several reasons. If the feature is not highly significant in the second detector but a sensitivity analysis shows that this is reasonable based upon the line strength and the viewing angle of the detector, then the data are consistent. However, a contradiction obtains if a sensitivity analysis indicates that the feature should have been detected in a second detector but the feature was not detected.

We have previously reported details on two of the candidates. For GRB 940703 (trigger 3057), only SD 5 had a suitable gain and viewing angle. A highly significant 44 keV emission line ($\Delta \chi^2 = 31.2, P = 2 \times 10^{-7}$) was observed in a portion of that burst [2]. Because of the gains or viewing angles of the other SDs, no consistency tests are possible for this candidate. The other candidate previously described, GRB 941017 (trigger 3245), was usefully observed by SDs 0 and 5 [3]. An apparent emission line at 43 keV was discovered in the data of SD 0. A less significant feature appears in SD 5 at a strength consistent with that feature seen in SD 0. This appears to be one of the best cases for detecting a line: the data from two detectors are consistent and a joint fit of their data has $\Delta \chi^2 = 28.6 (P = 6 \times 10^{-7})$ for adding a line.

An interval of data from SD 2 for GRB 930916 (BATSE trigger 2533) which contains the peak and trailing portion of the event appears to have a significant line ($\Delta \chi^2 = 24.1, P = 6 \times 10^{-6}$). Because of the coarser time resolution of the data from SD 7, a slightly different interval must be used to compare the results from SD 2 and 7. Using the revised interval, the significance of the feature in SD 2 is slightly reduced to $\Delta \chi^2 = 23.1$ (Fig. 1).
FIGURE 1. Data from the interval 22.144 to 83.200 s after the BATSE trigger of GRB 930916. The plot shows the count rate data (points) and count rate models (histograms). The count rate models are obtained by folding the photon models through a model of the detector response. The ‘bump’ at 30 keV is expected from the K-edge of the iodine in NaI. Left panel: best continuum-only fit to the data of SD 2. The data show a clear excess above the model from 41 to 51 keV. Right panel: A narrow spectral feature is added to the model: an emission line at 45 keV improves $\chi^2$ by 23.1. The width of the feature is due to the detector resolution. The solid histogram depicts the total count model; the dashed histograms show the continuum and line portions separately.

There is no evidence for the feature in the data of SD 7 (Fig. 2). Not only does adding a line to the model result in no improvement in $\chi^2$, imposing a line at the strength expected according to SD 2 results in a $\chi^2$ increase of 9.7 (Fig. 2, right).

A quantitative sensitivity or consistency analysis is required to decide whether the failure to detect the candidate in SD 7 is reasonable because of some difference between the detectors. The two detectors have the same gain and viewing angles of 31° for SD 2 and 64° for SD 7. Because of the detectors are almost as thick as their diameters, the effective area has only a small dependence on burst angle.

We have performed simulations to quantitatively test the consistency of the two detectors. We use the joint fit to the data of the detectors that viewed the burst as the best compromise between the line strengths prefered from the data of each detector. Then, using the parameters of the joint fit photon model and the detector response model, 1000 simulated count rate datasets are made for each detector. These simulated spectra are fit to determine the range of line significances expected. A simulated significance above the observed significance for SD 2 ($\Delta \chi^2 = 23.1$) is obtained in 9% of the simulations, indicating that the observed significance is slightly better than expected. However, a simulated significance $\Delta \chi^2$ below 0.1 is obtained in only 2% of the simulations of SD 7, indicating that the observation is only marginally consistent with expectations.
3. CONCLUSIONS

Consistency between the results obtained from several detectors is required for a believable result. In the case of GRB 930916, the consistency is marginal. The event could be understood as a 9% probable fluctuation towards high significance in SD 2 and a 2% probable fluctuation towards insignificance in SD 7. If this were the only such case, such an explanation would be plausible. There are several other such cases among the 13 candidates, raising the possibility of a systematic error that invalidates the statistical significances. We have performed many tests of the reliability of the SDs [5] and for systematics in the line analysis [4]: the SDs and the data pass all tests. Until we have a better understanding of these apparent inconsistencies between the data collected from different detectors, the reality of all of the BATSE line candidates is unclear.

A key lesson is the power of observations from more than one detector for testing the reality of a possible line feature. Agreement would be powerful confirmation; disagreement might indicate a systematic error.

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