BATSE Evidence for GRB Spectral Features

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Abstract. We have developed an automatic search procedure to identify low-energy spectral features in GRBs. We have searched 133,000 spectra from 117 bright bursts and have identified 12 candidate features with significances ranging from our threshold of $P = 5 \times 10^{-5}$ to $P = 1 \times 10^{-7}$. Several of the candidates have been examined in detail, including some with data from more than one BATSE spectroscopy detector. The evidence for spectral features appears good; however, the features have not conclusively been shown to be narrow lines.

LINE SEARCH AND RESULTS

Narrow, low-energy ($< 100$ keV) spectral lines in GRBs have been reported using the data of several instruments (e.g., see review [4]). Based on these reports, the BATSE team expected lines to be easy to find and looked for them manually [7]. The reality was different: lines were not obvious in burst spectra. In order to be sure that the manual search had not missed any lines, we implemented a comprehensive, automatic computer search [5]. Bursts with at least one spectrum with a normed signal-to-noise ratio (SNR) [2] near 40 keV above 5.0 are searched. For each burst, we form spectra from each individual spectral record, every pair, triple, etc. The spectra so formed overlap in many cases. Once a burst is selected for the search, spectra are searched regardless of the presence of burst flux—low SNR spectra serve as controls. Each spectrum is fit with a continuum model and then a series of fits are made adding narrow lines at a closely spaced grid of line centroids extending to 100 keV. Line candidates are identified by a $\chi^2$ change $\Delta \chi^2$ of more than 20, corresponding to a chance probability in a single spectrum of $P = 5 \times 10^{-5}$. The probability is calculated for two line parameters, intensity and centroid, since the intrinsic width is assumed narrow compared to the detector resolution.

So far, 133,000 spectra formed from 12,000 spectral records from 117 bursts have been searched. Most of these spectra have SNR too low to support the detection of a line. Only 16,000 have normed SNR > 5, which our simulations show is needed
to have a reasonable sensitivity to lines similar to those found in the *Ginga* data [1].

The search identified several cases with $\Delta \chi^2$ values exceeding our significance threshold, but which we rejected either because they occur in background intervals or because they become insignificant when a better fit requiring a non-negative flux is made. These cases were located in spectra of low SNR, and because of the large number of low-SNR spectra, they are consistent with statistical fluctuations. Several possible candidates with angles between the burst direction and detector normal exceeding $70^\circ$ are inconsistent with the data of other detectors. We believe these cases to be due to inadequacies in the detector model and we have set them aside.

After these exclusions, our candidate list has 12 members with $\Delta \chi^2$ values ranging from the threshold of 20 to 31.8 ($P = 1 \times 10^{-7}$). The normed SNRs of the spectra in which these candidates are most significant range from 2.1 to 18.4, with 10 normed SNR values exceeding 5. These SNR values are reasonable for real features.

The number of independent trials is a nebulous concept. While there are roughly 16,000 spectra sufficiently bright for there to be a high probability of detecting a real line, many of these spectra overlap, e.g., starting a few records earlier or later, or differing in length by a few records. Consequently the number of bright, independent spectra is one or more orders of magnitude below 16,000. The number of independent energy resolution elements averages about 5 per spectrum. We estimate that the ensemble chance probability of the most-significant candidate is below $1 \times 10^{-3}$, and probably much lower than this value.

We therefore believe that few, if any, of these candidates are statistical fluctuations. Of the 12 candidates, in all but one the best line fit is an emission feature with a centroid near 40 keV. The twelfth candidate is an absorption feature at 60 keV. Typically the lowest energy of the data is about 20 keV, so we are unable to find lines much below 40 keV.

**EXAMPLE CANDIDATE**

We have previously presented results [5] for a candidate in GRB 940703 (trigger 3057) which was usefully observed by only one BATSE spectroscopy detector (SD). Observations are useful only from SDs in high-gain mode which point to within $70^\circ$ of the burst. Since that time we have searched more bursts and begun more detailed analyses of the nine candidates that were usefully observed by more than one SD.

These multiple-detector cases allow stringent tests of the reality of the candidates. Ideally, the data from another detector will confirm the feature found by the automatic search. While some features may not be confirmed by another detector due to differing SNRs between the detectors or from plausible statistical fluctuations, the data of all detectors must be consistent.
FIGURE 1. The time history of GRB 941017 as observed with SD 0. The automatic search found the greatest $\Delta \chi^2$ value, 20.8 ($P = 3 \times 10^{-5}$), for adding a narrow line for the interval $7.936$ to $22.464$ s, which is designated with the pair of vertical lines. The dotted line indicates the background model.

TABLE 1. Line fits to the common time interval, GRB 941017.

| Detectors | $\Delta \chi^2$ | $P$   | # of line param. | line intensity $\gamma$ s$^{-1}$ cm$^{-2}$ | centroid |
|-----------|-----------------|-------|-----------------|---------------------------------|----------|
| 0         | 19.1            | $7 \times 10^{-5}$ | 2                | 0.31±0.07                        | 43.8±1.2 |
| 5         | 9.3             | $1 \times 10^{-2}$ | 2                | 0.21±0.07                        | 42.2±1.7 |
| 5         | 8.5             | $4 \times 10^{-3}$ | 1                | 0.19±0.07                        | 43.8     |
| 0 & 5     | 26.5            | $2 \times 10^{-6}$ | 2                | 0.25±0.05                        | 43.1±1.0 |

GRB 941017 (trigger 3245) was usefully observed by SDs 0 and 5. The automatic search identified a candidate in the data of SD 0 during the rising portion of the burst (Fig. 1). A spectrum is not available for SD 5 for the time interval with the best $\Delta \chi^2$ value for SD 0. We therefore continued our analysis using spectra from a similar time interval ($9.728$ to $23.936$ s) which is available for both detectors. The results of fits to this interval are listed in Table 1. Because of the non-optimum time interval, the significance of the feature in the data of SD 0 is reduced. The line was discovered in the data of SD 0 so we may regard the centroid as a priori determined when we analyze the data of SD 5. A one parameter line fit yields a significance for the feature in SD 5 of $4 \times 10^{-3}$. The joint fit (Fig. 2) yields a significance of $2 \times 10^{-6}$, better than the value obtained with SD 0 alone despite the forced change to the common time interval. SD 5 provides evidence for the feature independent of the detector in which the feature was found by the automatic search.

We must also check that the data of the two detectors are consistent. For example, are the line strengths or significances obtained from each detector compatible with the values obtained with the other detector? We expect some differences due to statistical fluctuations. Therefore we have investigated this question with simulations based upon the parameters of the joint fit. Table 2 shows the data of the two detectors to be consistent.

To demonstrate the existence of a line, we must show that the data require a
FIGURE 2. Simultaneous fit to the data for GRB 941017 from SD 0 (crosses) and SD 5 (crosses with dots—shifted downwards by ×5 for clarity). The photon model has been folded through the detector responses to produce the count rate models (histograms). The dashed line shows the continuum portion of the model. The width of the feature in count space is due to the resolution of the detector. The ’hump’ at 30 keV is due to iodine in the detector [4].

TABLE 2. Simulation Results: Tail-probabilities of the fits to each detector assuming the parameters of the joint fit.

|                      | SD 0 | SD 5 |
|----------------------|------|------|
| Fraction with a greater line intensity: | 0.28 | 0.85 |
| Fraction with a greater $\Delta \chi^2$: | 0.24 | 0.88 |

FIGURE 3. Fit to the data of SD 0, GRB 941017 using an alternative continuum model. The continuum model used looks very similar to the Band ‘GRB’ form—in $\nu F_\nu$ space, the energy emission peaks at 600 keV. To this model we have added an additional break at 43 keV, for a total of 6 parameters (vs. the 4 parameters of the GRB function). The fit has $\chi^2 = 201$ for 189 degrees-of-freedom. The depiction of the data points in photon flux units is model-dependent.

The above fits were made using the standard ‘GRB’ continuum function of Band. However, if we use an alternative continuum model with a low-energy break in addition to the standard high-energy break, the significance of the line in SD 0 is reduced to $\Delta \chi^2 = 6.3$ ($P = 4\%$). While this model still involves a low-energy spectral feature (Fig. 3), it means that for this burst we cannot prove that the feature is a line.
CONCLUSIONS

Since our last report [5], we have completed the automatic search for bright bursts through May 1996. We have identified 12 line candidates and have begun detailed analysis. Because the 12 candidates appear as expected in the small fraction of spectra with high SNR, their probability of appearing in the ensemble by chance is low.

For all except one of the 12 candidates, the best line fit is an emission line with a centroid near 40 keV. Our simulations show that we have useful sensitivity to Ginga-like absorption lines at 40 keV [1,3], so the lack of detections of absorption lines gives a constraint on their frequency. However, with the small number of bright bursts seen by BATSE and Ginga, there is no significant discrepancy between the two instruments [2].

Observations made with multiple detectors have the strong advantage of redundantly verifying the existence of the features. We have now carefully investigated several candidate features, including some observed with multiple detectors. So far the evidence appears good for the existence of spectral features, however we do not want to make a blanket statement that BATSE has observed spectral features until we have carefully examined all 12 candidates.

Note that we are stating that the evidence appears good for the existence of spectral features. In the cases examined so far, we have not been able to demonstrate that the spectral features must be narrow lines—an alternative explanation is possible: a low-energy break in addition to the normal break in the few 100 keV to 1 MeV region.

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