Gamma-Ray Burst Lines

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Abstract. The evidence for spectral features in gamma-ray bursts is summarized. As a guide for evaluating the evidence, the properties of gamma-ray detectors and the methods of analyzing gamma-ray spectra are reviewed. In the 1980’s, observations indicated that absorption features below 100 keV were present in a large fraction of bright gamma-ray bursts. There were also reports of emission features around 400 keV. During the 1990’s the situation has become much less clear. A small fraction of bursts observed with BATSE have statistically significant low-energy features, but the reality of the features is suspect because in several cases the data of the BATSE detectors appear to be inconsistent. Furthermore, most of the possible features appear in emission rather than the expected absorption. Analysis of data from other instruments has either not been finalized or has not detected lines.

1. Introduction

Formerly, lines were widely believed to exist in GRB spectra and were regarded as strong evidence that GRBs originate on nearby neutron stars with intense magnetic fields. Currently, lines are unfashionable due to a lack of recent good observations and due to the strong evidence that most or all GRBs originate at cosmological distances. If the community once again becomes convinced of the existence of lines, there would probably be a vigorous debate between a nearby neutron star origin for a subset of GRBs and efforts to model line formation in fireballs at cosmological distances.

I will discuss the evidence for lines in the spectra of gamma-ray bursts, focusing on observations and analysis rather than physical or theoretical interpretation. Previous reviews include Teegarden (1982), Teegarden (1984), Harding, Petrosian & Teegarden (1986), Higdon and Lingenfelter (1990), Fishman and Meegan (1995) and Briggs (1996). While the problems involved in interpreting gamma-ray spectra and the accepted analysis procedures should be well known (e.g., Fenimore et al. 1983; Teegarden 1984; Fenimore et al. 1988; Loredo & Epstein 1989; Briggs 1996), I shall review these topics because they are crucial for interpreting the evidence for GRB lines.
2. Detector Properties

In optical astronomy, one uses a prism or grating to spread the photons out by wavelength—a line is simply detected as an deficit or excess in the intensity of photons at one wavelength compared to neighboring wavelengths. In contrast, gamma-ray detectors typically detect individual photons. Each photon may interact in the detector by a variety of processes: the photoelectric effect, Compton scattering, or pair production. The energy deposited in the detector by a photon is referred to as the “energy loss”—the great complication is that in some cases the energy loss may only be a fraction of the energy of the incident photon. A detected photon is referred to as a “count”: we can never be sure that the energy of a particular count equals the energy of the incident photon. The observed counts form an energy loss spectrum from which we must deduce the incident photon spectrum.

As an example, I will use the Spectroscopy Detectors (SDs) of BATSE. The principles described result from the physics of photon interactions and are broadly applicable to all gamma-ray detectors. The SDs are 12.7 cm diameter by 7.6 cm thick crystals of NaI(Tl) scintillator viewed by a single photomultiplier tube. When a particle interacts in the crystal, the resulting ionization is converted into scintillation light and amplified by the photomultiplier. The electronic pulse is further amplified and then digitized by the pulse height amplifier. The digital value is called the “channel” of the event. To first order, the scintillation light is proportional to the ionization, so that the channel value is nearly proportional to energy deposited in the crystal. Accurate analysis requires a calibration that accounts for nonlinearities in the emission of the scintillation light (e.g., Band et al. 1992 for the BATSE SDs).

Below about 200 keV, most photon interactions will be via the photoelectric effect (Fig. 1). Compton scattering is important above several hundred keV; pair production is important only for photons with energies of at least several MeV.

![Figure 1. The mass attenuation coefficient $\mu$ for gamma-rays in NaI: solid line: total coefficient; dotted line: the photoelectric effect; dashed line: Compton scattering; dot-dash line: pair production. The fractional transmission is $\exp (-\mu x)$, where $x$ is the quantity of NaI transversed in g cm$^{-2}$. The data are from Hubbell (1969). Other materials will differ in detail but will also have successive regions in which the photoelectric effect, Compton scattering and pair production dominate.](image-url)
In the case of the photoelectric effect, the gamma-ray energy is totally transferred to an atomic electron, typically an inner shell electron. An atomic cascade will result in which fluorescent X-rays or Auger electrons will be emitted. The left curve of Fig. 2 illustrates a simple case, the count spectrum expected for 20 keV photons incident on the crystal. The line detected from a beam of monoenergetic photons is broadened by Poisson fluctuations in the number of photoelectrons in the photomultiplier tube.

Even the simple photoelectric effect can result in a complicated energy deposition spectrum. The 20 keV photon of the previous example will typically interact with an electron of the L-shell of iodine—the K-shell is energetically forbidden. A photon with an energy greater than the 33.17 binding energy of the iodine K-shell, such as a 50 keV photon (bold curve, Fig. 2) will typically interact with a K-shell electron. The resulting cascade will usually involve a L, M or N to K shell transition and a fluorescence X-ray with an energy from 28.3 to 33.0 keV. If this fluorescence photon also interacts in the crystal, the entire energy of the 50 keV may be captured (right peak of the bold curve of Fig. 2). However, the energy fluorescence photon has a lower interaction cross-section than the 50 keV photon (Fig. 1), and may escape the crystal, resulting in incomplete energy deposition (left peak of the bold curve of Fig. 2).

Full energy deposition normally occurs for photons with energies below the 33.17 keV K-shell energy; photons with energies just above the K-shell energy will normally interact but have a substantial probability of incomplete energy deposition due to the escape of a fluorescence photon. A flat or hard incident photon spectrum will lead to a detected count spectrum with a deficit above 33 keV. This feature (Fig. 3) is a detector property and should not be mistaken for an astrophysical feature.

At energies of a few hundred keV to a few MeV, Compton scattering is the most likely process. As a scattering rather than absorption process, only a portion of the energy of the incident photon is transferred to the electron. Fig. 2 shows the energy loss spectrum of 500 keV photons (right curve). The
peak at 500 keV originates from cases in which the energy of the scattered photon is also captured in the detector from some combination of Compton scattering and photoelectric interactions. The maximum energy transfer to the scattered electron, 331 keV, occurs for the case that the incident photon is backscattered at 180°. Single scattering events with angles near 180° cause the peak at 310 keV, while the valley above 310 keV exists because single scattering events cannot create counts with energies above 331 keV. The minimum energy of the scattered photon, 169 keV, also occurs for 180° backscattering, so photons that interact outside the detector and scatter into the detector with scattering angles near 180° create the peak at 190 keV.

The result of the several interaction processes is that incident photons may deposit in the detector any energy from zero up to their entire energy. Mapping the expected count spectra as a function of incident energy (Fig. 4), partial energy deposition creates off-diagonal terms in addition to the desired diagonal response. Furthermore, Poisson fluctuations in the number of photoelectrons produced in the photomultiplier tube cause a broadening of the diagonal response, visible in Figures 2 and 4. These effects are included in a computer model of a detector by simulations using a standard Monte Carlo particle transport code and a description incorporating the geometry and materials of the detector (e.g., Pendleton et al. 1995 for the BATSE detectors).
Figure 4. A contour map of the response of a BATSE spectroscopy detector (logarithmically spaced contours). The units of the response are cm$^2$ keV$^{-1}$; for a fixed incident photon energy, integrating the response with respect to the detected count energy (channel) will yield the effective area, typically about 120 cm$^2$. The main grouping of contours, starting at photon energy of 8 keV and running diagonally across the figure, is the direct or full-energy loss response. It is broadened by Poisson fluctuations. The second diagonal group of contours, which starts at photon energy of 35 keV, represents cases in which a fluorescence photon escapes the detector. The remaining contours originate from other cases of partial energy deposition in the detector.

3. Methodology

The lack of a one-to-one correspondence between the energy of an incident photon and the energy of the detected count complicates understanding the observed energy loss or count spectra. The detected count spectrum cannot be simply inverted into a measured photon spectrum, as it can for optical photons. The energy of a single photon cannot be deduced from the energy of the observed count; if many counts are observed, the incident spectrum can be unfolded subject to certain limitations.

Several direct inversion techniques have been proposed (Loredo & Epstein, 1989), but practitioners have generally not found them to be useful. Instead, the ‘forward-folding’ deconvolution procedure is generally used: one assumes a photon spectral form and compares it to the data. A model photon spectrum is represented with a parameterized function, the model photon spectrum is converted into a model count spectrum using a computer model of the detector, and the model and observed count spectra are compared. The comparison is quantified by using a statistic such as $\chi^2$ or likelihood. The fit is optimized, subject to using the assumed spectral form, by varying the parameters of the function. If a sufficiently low value of $\chi^2$, or high value of likelihood, is achieved,
Figure 5. Two fits to the same data of GRB 940703 are shown (see Fig. 6 for the corresponding graphs of the count rate data). The curves show the photon model and its components (dashed lines). The points in photon flux units are obtained by scaling the observed count rate with the ratio of the model photon rate and model count rate. It should be obvious that the points in photon flux units are model dependent and should not be thought of as data.

one is said to have a ‘good’ fit. Other spectral forms might obtain similar or better values of the fitting statistic, so a ‘good’ fit can never be known to be the best fit, or to be the correct representation of the incident photon spectrum.

Sometimes the fitted photon function is used to scale the count rate data points into what appear to be photon flux points. These must be treated with great caution since what appear to be data points are actually model dependent. In particular, when lines with intrinsic widths comparable to the detector resolution are fit, the values of the photon points scaled from the count rate data points become strongly dependent on the model—the reality of a spectral feature should never be judged on a plot of deconvolved photon flux (Fig. 5). Properly speaking, the results of the deconvolution procedure are the parameter values of the assumed functional form and the value of the statistic measuring the quality of the fit.

If we can never prove a fit to be ‘correct’, how can one demonstrate the existence of a spectral line? The answer is two-fold: by viewing the problem as one of statistical model comparison and by using scientific judgment. The statistical approach used is model comparison: a potential line is viewed as an additional term added to the continuum model and we ask whether the fitting statistic (e.g., $\chi^2$) is sufficiently improved to convince us of the reality of the line. Traditionally, the F-test has been used, but statistical theory shows that the change in $\chi^2$, $\Delta \chi^2$, is better (this test is also known as the Maximum Likelihood Ratio test (Freeman et al. 1999a)). In practice, there is little different between the two statistics (Band et al. 1997). Bayesian analysis procedures have also been developed (Graziani et al. 1993, Freeman et al. 1999a). In principal, to demonstrate the existence of a line one must show that the line is significant.
for any continuum model. Scientific judgment can be used to limit the space of trial continuum models to all ‘reasonable’ models.

Some researchers believe that only continuum models justified for the particular spectrum should be used (Freeman et al. 1999a)—but if a reasonable continuum model explains that data without resort to a line, then we cannot be sure whether the line exists. Consider two continuum models, ‘A’ and a more complicated model ‘B’. Further suppose that both models have acceptable $\chi^2$ values when fitting a particular spectrum, and that adding a line creates a significant $\chi^2$ improvement for model ‘A’ but not for model ‘B’. Despite the line being significant if model ‘A’ is assumed, overall the line must be considered insignificant because model ‘B’ might be the correct model. Judgment enters the problem in deciding what the set of all reasonable continuum models is. Currently, the most popular continuum model is the four-parameter ‘GRB’ function of Band et al. (1993). This function fits the available gamma-ray data well. Most of the popular simpler models can be represented as special cases of the GRB function; depending on the SNR and energy range of a spectrum, it may not be possible to demonstrate that the four-parameter GRB function provides a statistically better fit compared to a simpler model. It may be sufficient to use just the GRB function as the set of all reasonable continuum models. However, a recent analysis of data extending below 20 keV indicates that in some cases the GRB function may fail in the X-ray range (Preece et al. 1996).

A final consideration is that recent experiments collect a large number of spectra from a large number of GRBs. If all of these spectra and the additional spectra formed by summing them are searched for lines, the possibility of a chance fluctuation mimicking a line is increased. This must be allowed for in calculating the overall significance of a possible line feature.

The preceding discussion is based on the assumption that the instrument works correctly, that the computer model of the detector is sufficiently accurate, and that the errors in the observed spectrum arise solely from Poisson fluctuations in the arrival of photons and their interaction in the detector. Systematic errors need to be limited by ground and space based testing of the detectors.

If multiple detectors observed a burst with a possible line feature, the feature needs to be tested by comparing the results from each detector. If the feature is a statistical fluctuation, a matching fluctuation in a different detector is improbable. Some types of systematics errors, e.g., hardware problems with one detector or failures of the detector model as a function of source angle, would also be revealed by discrepancies between the data collected with different detectors. After allowing for statistical fluctuations, the data of the detectors must be consistent; ideally more than one detector would detect the feature with statistical significance, thereby confirming the presence of the line.

In summary, the steps to demonstrate the existence of a gamma-ray line are:

- Deconvolve the spectra using the forward-folding technique,
- Show the model fit and the data in the units of observed energy loss (also known as count spectra), rather than in deconvolved photon flux units,
- Test the necessity of the line by comparing fits with and without the line,
- Test the significance of the line against all reasonable continuum models,
• Quantify the model comparisons by using a statistic such as $\Delta \chi^2$ or likelihood.
• If a large number of spectra have been examined, consider the increased probability of a chance fluctuation and appropriately degrade the significance of a line candidate.
• If several instruments or detectors observed an event, the datasets need to be analyzed for consistency.

4. The First Era

The work of the Mazets group created the field of GRB lines. In 1981 they reported absorption lines between 30 and 70 keV in numerous bursts in observations made with the Konus experiments on the Venera 11 and Venera 12 spacecraft (Mazets et al. 1981). Lines were reported to be a common characteristic of GRBs, with low-energy lines observed in 43 of 143 GRBs (Mazets et al. 1982). The Konus instruments consisted of six NaI(Tl) detectors, each 30 mm thick and 80 mm in diameter. Lines were also reported in the Konus instruments of Venera 13 and 14, which had similar detectors but improved electronics with better temporal and spectral resolution (Mazets et al. 1983).

The lines appear as large deviations in a few channels from the assumed continuum model. Most of the lines are absorption lines between 30 and 70 keV with equivalent widths of 10 to 20 keV. Only one low-energy feature appeared in emission. Most of the lines are seen in only a portion of the burst, and that portion is typically the beginning of the burst (Mazets et al. 1982). Excepting a single 45 keV emission line (Mazets et al. 1981), all of the emission lines are between 350 and 450 keV. In several GRBs high-energy emission lines are present in the fits to the data of both Venera 11 and 12 (Mazets et al. 1982). These high-energy lines have intrinsic widths of a few hundred keV and were interpreted as gravitationally redshifted annihilation radiation.

The analysis procedure was designed to minimize the computational effort: spectra were deconvolved with standard templates and then iteratively improved (Mazets et al. 1983). Almost all of the spectra are depicted in deconvolved photon units, making it difficult to judge the robustness of the features and their significance if a different continuum model were to be used. The paper best describing the analysis procedure (Mazets et al. 1983) includes a graph showing the observed count spectrum and the corresponding deconvolved photon spectrum for an interval of GRB820406b which appears to have an absorption feature at 45 keV. At the time, GRBs were nearly always modeled with a simple optically-thin thermal bremsstrahlung form, photon flux \( \propto E^{-1} \exp\left(-E/kT\right) \); this function was assumed for most of the Konus spectra. We now know that many GRB spectra have a high-energy power law, the “$\beta$-component” of the Band GRB function, which cannot be described by a function with an exponential cutoff, and that the low-energy portion of the spectrum (the $\alpha$ and $E_{\text{peak}}$ parameters) undergoes rapid spectral evolution. These improvements in our knowledge of the continuum function render interpretation of the Konus results difficult.

Efforts were made to validate the Konus results with the observations of other instruments. Most of the comparisons focused on the high-energy emission
lines. Observations with the SIGNE experiments on the Venera spacecraft were taken to show the presence of several lines in GRB 781104 and GRB 781119 (Barat 1983). Because of differing time intervals, the results were not directly comparable with the lines reported by Mazets et al. (1981). Data collected with the Gamma-Ray Spectrometer on the SMM spacecraft for GRB 811231 included a spectrum collected over an interval overlapping two intervals in which Konus data (Mazets et al. 1983) showed a high-energy emission line. The data from GRS is consistent with a power law above 300 keV (Nolan et al. 1981).

While there was some debate about the reality of the Konus lines, the matter was viewed by most as settled when line observations with the Ginga instrument were reported. The Gamma-Ray Burst Detector for the Ginga satellite covered the energy range 2 to 400 keV by using both a proportional counter (effective area 63 cm$^2$) and a NaI scintillator (1 cm thick, 60 cm$^2$ area) (Murakami et al. 1989). Harmonically spaced lines at 20 and 40 keV were seen at high significance in GRB 880205 and at lesser significance in GRB 870303 (Murakami et al. 1988, Fenimore et al. 1988). The harmonic spacing was seen at the time as powerful evidence in support of cyclotron resonant scattering, implying an origin on highly magnetized neutron stars. The analysis of GRB 880205 was carefully done using the forward-folding technique and using several continuum models, including a very flexible continuum model, a power-law with two breaks (Fenimore et al. 1988). The F-test indicates a significance of $9 \times 10^{-6}$ for the pair of lines in GRB 880205 (Wang et al. 1989).

Later analysis found lines at 26 and 47 keV in GRB 890929. Assuming harmonic spacing, a good fit was obtained with centroids of 24 and 48 keV (Yoshida et al. 1992). An additional interval with a 20 keV feature was found in GRB 870303 (Graziani et al. 1992). With lines in three GRBs of 23 observed (Yoshida et al. 1992), Ginga also showed low-energy lines to be a common feature of GRBs.

Two recent papers (Freeman et al. 1999a, Freeman et al. 1999b) have very detailed analyses of the statistical significance of the lines observed with Ginga in GRB 870303 and of their interpretation as cyclotron resonant scattering.

Lines were reported in the data of HEAO A-4 for three GRBs, but only in the case of GRB 780325 are the lines statistically significant (Hueter 1987). The HEAO A-4 instrument included three types of NaI detectors to cover the range 10 to 6200 keV. GRB 780325 lasted $\approx$ 50 s and consisted of two peaks: a 70 keV absorption feature was reported in the first peak and a 50 keV absorption feature in the second. The changes in $\chi^2$ were 14.0 and 16.5, respectively, corresponding to chance probabilities of $9 \times 10^{-4}$ and $3 \times 10^{-4}$. Most interestingly, the line is stated to be visible in the data of both detectors which observed the burst in the energy range of the line, however, only summed data is shown. Unfortunately, some approximations were used that cause the analysis to fall short of current standards: a exponential continuum model was fit to the data below 200 keV and a simplified detector model was used, created from the full detector model by assuming an $E^{-2}$ power law (Hueter 1987). A figure of the 50 keV feature for a slightly different time interval is available in Harding, Petrosian & Teegarden (1986).

A pair of absorption lines were reported in GRB 890306, based on data from Lilas (Barat 1993). The Lilas detector was a NaI crystal 5.3 cm in diameter.
and 3 cm thick covering the energy range 5 keV to 1 MeV. The intense burst GRB 890306 lasted more than 70 s; the line candidates appear in a spectrum accumulated over 68.5 s. The fitting is done using the forward-folding approach and the data but not the model are shown as an energy loss (count) spectrum. A fit to the sky background is shown to allay concern about possible systematics. A very flexible spectrum was assumed, a power law with two breaks. Adding two lines at 11 and 35 keV reduces \( \chi^2 \) from 132.2 to 43.2 for 26 degrees-of-freedom, with an implied chance probability of \( 2 \times 10^{-13} \) by the F-test. Possible concerns are the still-high value of \( \chi^2 \) and the possible impact of the unknown location of the burst.

The HEAO and Lilas results have received less attention than they deserve; both merit reanalysis using forward-folding fitting with a full detector model and assuming several continuum models, including the Band ‘GRB’ function.

5. BATSE Results

The addition of the Spectroscopy Detectors (SDs) to the BATSE instrument was motivated by the line results from the Konus instruments. There are eight SDs, each a 12.7 cm diameter by 7.6 cm thick NaI crystal. The BATSE team expected to easily find numerous lines in GRBs. Our first approach was to manually examine selected spectra from bright GRBs, scanning for possible features. Spectra with possible features were fit with continuum models and continuum-plus-line models to evaluate the statistical significance of the feature. No significant features were found by this technique (Palmer et al. 1994, Band et al. 1996).

BATSE has several advantages for detecting lines:

- Excellent resolution for NaI detectors,
- Advanced electronics to handle large pulses and high counting rates,
- Excellent temporal resolution to enable detection of lines on many timescales,
- The Large Area Detectors provide locations to aid analysis of the spectral data from the Spectroscopy Detectors,
- Multiple detectors to increase the chance of observing a line and to allow consistency tests.

Simulations show that BATSE should be able to detect lines like the 40 keV lines seen by Konus and Ginga with comparable sensitivity to Ginga (Band et al. 1995, Freeman et al. 1993). Ground and space-based tests demonstrate that the detectors are working as expected (Paciesas et al. 1996).

Our failure to find lines was surprising. To make sure that the manual search was not at fault, a comprehensive, automatic computer search procedure was developed (Briggs et al. 1996). The goal of the automatic search is to thoroughly search the spectra collected from bright bursts so that no line could be accidentally missed. Because we do not know a priori when in a burst a line will occur or for how long it will last, we search essentially all available timescales. The individual high-temporal resolution spectra from the SDs (the SHERB data) are all searched, as are all consecutive pairs, triples, groups of five, etc., up to the entire duration of the SHERB data. The search is limited
by choice to finding lines below 100 keV. Since we also do not know a priori at what energies lines will occur, we fit a continuum model to each spectrum, then continuum-plus-line models with line centroids closely spaced over the available data up to 100 keV. Because the well-calibrated data typically begins at 20 keV, the search is insensitive to lines with centroids of 20 keV.

At this time 117 bright GRBs that were observed before 1996 May 31 have been examined. An average of 2.1 Spectroscopy Detectors observed each burst, producing a total of 10,942 SHERB records. These records were combined into 120,700 spectra, many of which overlap or have low signal-to-noise ratios (SNR). We estimate the number of independent spectra with sufficient SNR to enable the detection of a Ginga-like line as a few hundred to a several thousand.

From the results of the automatic search, 17 candidates with $\chi^2$ changes from adding a line above $\Delta \chi^2 = 20$ were identified. Manual fitting of the data leaves 11 candidates with $\Delta \chi^2$ values ranging from the threshold of 20 to 50.8. Since we assumed lines with narrow intrinsic widths compared to the detector resolution, the line fits involve only two parameters, centroid and amplitude. There are about 5 independent energy resolution elements between the detector threshold and 100 keV. This implies that the candidates have fluctuations probabilities in a single spectrum of $2 \times 10^{-4}$ (for $\Delta \chi^2 = 20$) to $5 \times 10^{-11}$ (for $\Delta \chi^2 = 50.8$). With at most several thousand bright, independent spectra, the ensemble probability of the most significant event is $\sim 10^{-7}$.

The candidate spectral feature in GRB 940703 (BATSE trigger 3057) (Briggs et al. 1996) has the following properties: 1) the significance is high, $\Delta \chi^2 = 31.3$, corresponding to a fluctuation probability in a single spectrum of $8 \times 10^{-7}$, 2) the interval in which the line is most significant is close to the entire flux of the GRB, 3) the feature is an emission line, 4) the centroid is 44 keV. The appearance of the feature is shown in Fig. 6. While there are exceptions, these properties are quite typical of the other candidate features.

The final stage of the analysis is the comparison of the observations collected with all of the BATSE Spectroscopy Detectors. In the case of GRB 940703, this analysis cannot be done because none of the other SDs have useful data: either the detector gains were inappropriate or the burst was viewed at too large of an angle. Most of the other candidates have useful data from more than one SD. The comparison analysis is complex because we are not comparing the data from one detector to a known model, but rather comparing the data of two or more detectors, not knowing the photon flux that created the data. For example, it is quite possible to have line flux values obtained from different detectors that disagree because of upward and downward fluctuations. The consistency or inconsistency of differing fit results can only be determined with simulations.

Our procedure has been to jointly fit the data from all the SDs with good angles and gains, and to assume that the photon model parameters so obtained are a good representation of reality. We then use this photon model and the detector models to create simulated count data incorporating Poisson fluctuations. Many simulations are created and fit in order to determine the range of results expected. The actual data are compared to expected range of results to determine whether the data from all of the detectors is consistent with a common origin. Because the data of at least one detector indicate a statistically significant line, if the data from all of the detectors are consistent with the
common photon spectrum, then there is strong evidence for a spectral feature. Conversely, if the data from two or more detectors is inconsistent, the interpretation becomes uncertain—at least one of the detectors is suspect, either because of hardware problems or an inadequate detector model.

The best case is that of GRB 941017 (trigger 3245). Good data is available from both SD 0 and SD 5; a feature was found by the automatic search in the data of SD 0 and the data of SD 5 appear consistent (Briggs et al. 1998).

However, there are other cases in which the consistency is poor. In GRB 930916 (trigger 2533), the data of SD 2 (Fig. 7) contain a highly significant line feature (Briggs et al. 1999). Useful data is also available from SD 7 (Fig. 8), but this data contains no indication of a line. Furthermore, adding a line with the centroid and strength obtained from the fit to the data of SD 2 actually increases the $\chi^2$ of the fit to the data of SD 7. The consistency between these two datasets has been analyzed via simulations (Briggs et al. 1999): assuming the model parameters obtained from a joint fit to the data of SD 2 and 7, simulated datasets are created for both detectors. These simulated datasets are then fit to determine the expected range of line strengths. In only 9% of the simulations of SD 2 is a $\Delta \chi^2$ value above 23.1 obtained, indicating that the observed line signal is somewhat stronger than expected. Conversely, in the simulations of SD 7 a $\Delta \chi^2$ value below 0.1 is obtained in only 2% of the cases, indicating that observed line signal is weaker than expected. These two results are at best marginally consistent.

Figure 6. Two fits to the data of GRB 940703 from SD 5 for a 38 s interval. Left figure: continuum-only fit using the Band ‘GRB’ function, Right figure: continuum-plus-line fit adding a narrow Gaussian line. The data and model are shown as energy loss or count rate spectra; the corresponding deconvolved spectra are shown in Fig. 5. The data are shown as points with the vertical error bars showing the uncertainties due to Poisson fluctuations and the background model. The histograms depict the model: the solid line is the total model, while the dashed line show the continuum-only contribution. The feature is assumed to be narrow—the width in count space originates from the spectral resolution of the detector.
Figure 7. Data from SD 2 for a 61 s interval of GRB 930916. Left panel: a continuum-only fit using the Band GRB function. There is an obvious cluster of data points above the model from 41 to 51 keV. Right panel: A narrow Gaussian line is added to the model. The emission line with a centroid of 45 keV reduces $\chi^2$ by 23.1, corresponding to a chance probability of $5 \times 10^{-5}$.

If GRB 930916 were the only such case, the agreement might be considered acceptable. Unfortunately, this level of disagreement occurs for several other candidates. The poor agreement between the detectors leaves us uncertain of which to believe: the data which seems to indicate the existence of a line of strength $S$, or the data which seems to show the absence of a line of strength $S$. Until this discrepancy is resolved, the meaning of the BATSE results will remain unclear.

6. Other Recent Results

There are two GRB instruments on the WIND spacecraft, which has a low and stable background because of its location in interplanetary space. Konus-W consists of two oppositely oriented NaI detectors which are very similar to the BATSE SDs (Aptekar et al. 1998). Since November 1994 at least 20 GRBs have been identified as containing possible line candidates. Golentskii et al. (1998) show energy loss spectra and deconvolved photon spectra for three possible absorption features and one possible emission feature. Final statistical analysis is in progress.

The WIND spacecraft also has a gamma-ray burst detector using a cooled germanium crystal, the Transient Gamma-Ray Spectrometer (TGRS). This detector is characterized by a better spectral resolution than scintillators but a rather small effective area, 36 cm². Comparing to the BATSE Spectroscopy Detectors, the better resolution but lesser area of TGRS causes TGRS to be more sensitive to lines narrower than the resolution of the BATSE detectors but less sensitive to lines of width comparable to the resolution of the BATSE detectors (Kurczynski et al. 1999). A search of 36 bright events, not all of which
are GRBs, found no significant lines with centroids from about 40 keV to a few hundred keV (Kurczynski et al. 1999).

In the 1980’s there were many papers on the physics of line formation via cyclotron resonant scattering on nearby highly magnetized neutron stars. With the evidence for a cosmological distance scale for most or all GRBs, the picture of the physical conditions has changed: the outflow must be highly relativistic. Several recent papers treat the subject of line formation in relativistic outflows, either in sources in the galactic halo, a possible origin for some GRBs (Isenberg et al. 1998), or in a cosmological fireball (Hailey, Harrison & Mori 1999). The later paper attempts to explain Ginga-like lines as complex ionization spectra emitted by high density material entrained in a relativistic fireball at cosmological distances, observationally smeared by the spectral resolution of the detectors. Much more work could be done on the possibility of line formation in cosmological sources; one fundamental problem is that a range of Lorentz factors should preclude the formation of any narrow feature.

7. Conclusions

The observational status of GRB lines is mixed: in the 1980’s several instruments reported low-energy absorption lines to be present in a large fraction of all GRBs, while there has been a dearth of recent detections. The BATSE database contains ~10 highly significant line features, but these are low-energy emission features. More disturbingly, in several cases the data from the several BATSE detectors that viewed an event appear inconsistent. In hindsight, it appears that insufficient attention was paid to possible systematics, such as the correct continuum model, detector performance and detector modeling. Com-
parisons between the data of the BATSE Spectroscopy Detectors are a start on testing these problems. Further progress will be made by comparing data from several instruments, e.g., BATSE and Konus-W, and by observations with future instruments.

In the 1980’s GRBs lines were seen as important or even conclusive evidence that GRBs originate from nearby (100 pc scale) highly-magnetized neutron stars. The BATSE evidence of the combination of isotropy with a deficiency of bright bursts (inhomogeneity) cast strong doubt on this picture. With the measurement of redshifts in some GRB afterglows, the paradigm has shifted to that of GRBs originating at cosmological distances. This has created an excessive biases against GRBs lines—we should consider the spectral observations on their own merit and remember the possibilities that there might exist a galactic subclass of GRBs or that lines might form in cosmological GRBs via some as yet unthought of process.

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