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PROBLEMS IN THE ANALYSIS OF GAMMA-RAY BURST SPECTRA

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ABSTRACT

Spectral measurements by the Solar Maximum Mission have been used to confirm the cyclotron lines in gamma-ray bursts reported from the Konus experiment. We present ISEE-3 data for the same burst (GB800419) during the same period of time which show no line. We discuss various problems in the analysis of scintillator spectra and point out that unfolded spectra are not necessarily unique and that the position of a data point in a deconvolved spectrum may vary depending on the assumed overall shape of the spectrum. As a result, if the analysis assumes a soft spectrum (such as optically thin thermal bremsstrahlung) an absorption feature might appear, whereas a harder spectrum (such as a Comptonized blackbody) would not require the feature. Since the continuum shape probably changes during the duration of a typical burst, the nonuniqueness of the spectral unfolding, combined with the assumption that the continuum is optically thin thermal bremsstrahlung, could give rise to spurious "absorption" features which vary on a time scale of seconds. Despite these problems, there is still some evidence for narrow spectral lines in the range 45 to 65 keV but not for the broad lines reported from the Konus experiment. Unfortunately, the range 45 to 65 keV is the most difficult spectral region to unfold.

The Konus experiment has provided three major observational results for gamma-ray burst spectra: the continuum can often be fit by optically thin thermal bremsstrahlung, there are low energy absorption features (identified as cyclotron lines), and high energy emission features (identified as red-shifted annihilation lines) [1]. However, OTIE and cyclotron lines are probably mutually exclusive due to the vastly different sizes they imply for the emitting region [2]. Indeed, other continuum processes have now been suggested: Comptonized blackbody [3] and thermal cyclotron [4]. The cyclotron lines have also been somewhat controversial. In a previous paper, we have compared spectra observed by the Berkeley/Los Alamos gamma ray spectrometer on ISEE-3 with the Konus results and found that the continua disagreed. If that disagreement was due to an incorrect calibration of the gain of the Konus instrument, then use of that incorrect gain could result in producing spurious absorption features in the range of 25 to 50 keV [4]. There are also problems in the physical interpretation of the absorption dips as cyclotron lines; one would expect higher harmonics, which are not observed.

because of the physical significance of the cyclotron lines, observational confirmation would be very important. It has been suggested that the 1980 April 19 gamma-ray burst could only provide confirmation [5]. Although GB800419 was at first thought to be a solar event, a rough position based on the time-of-arrival method shows it to be about 18° away from the sun [6]. The Goddard Hard X-ray Burst Spectrometer on the Solar Maximum Mission (SMM) observed the burst with good temporal and energy resolution. An OTIE fit to the SMM data shows a clear deficiency of counts below 80 keV (see Figs. 3 and 4 of Ref. [5]). This line the significant temporal variations in shape and size, which could have important implications for gamma-ray burst models [5,7]. However, the SMM data could also be fit by an exponential shape [5], which is a much harder spectrum. The purpose of this paper is to compare the SMM spectrum for GB800419 with that measured by the Berkeley/Los Alamos ISEE-3 instrument and to investigate problems associated with spectral unfolding. Since Los Alamos performed the Monte Carlo calculations to determine the response functions of both instruments, we are in an excellent position to intercompare the spectra with identical analysis techniques. We conclude that the spectral unfolding can have a key influence on the physical interpretation of the continuum. As a result, GB800419 may not necessarily confirm cyclotron lines.

Figure 1 presents the SMM data and the ISEE-3 data for GB800419 using a variety of assumptions in the unfolding analysis. Plotted is spectral flux (photons $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$) as a function of energy (keV). The SMM data are from effectively the whole burst (4.992 s) and

Fig. 1. Spectra for GRB00419: a) OTTB fit from SSM [5], b) OTTB fit from JPLA (squares and dashed line) shown with fit from 1a, c) exponential fit from SSM [5], d) figures 1a and 1c combined, and e) exponential fit with small change in the 1st dead layer.

the ISEE-3 data is from a nearly identical 5.0 s interval. Figure 1a is the best fit OTTB continuum to the SMC data and is effectively the same as Fig. 3 of Ref. [5]. However, it was produced by the Los Alamos analysis codes. Note that it agrees with the Goddard analysis which concluded that there was a large absorption dip at energies less than 60 keV [5]. The shape and strength of the line is similar to that observed in other bursts by the Konus experiment, in particular, GB790412, GB790610, GB790731, GB791036 and GB791101 [1]. Figure

1b overlays the ISEE-3 result on the SMC spectrum of 1a. The dashed line and squares are the best fit to an OTTB continuum for the ISEE-3 data and does not show the absorption dip below 60 keV reported in the SMC data.

Fig. 2. a) counts predicted from a trial spectrum (triangles) compared to the data (circles); b) counts mapped onto the best fit trial spectrum.

Methods based on direct deconvolution, Fourier methods or matrix inversion are often numerically unstable in the presence of noise, especially when the instrument response functions are complex as in the present burst detectors. Thus, an analysis method similar to the one described above is often required. However, the method has two potentially serious problems. First, the unfolded spectrum may not be unique; two different trial shapes may result in effectively the same distribution of predicted counts. Second, the position of a point in the photon keV^{-1} spectrum is arbitrary since it depends on the mapping process from counts to photon keV^{-1} , which in turn depends on how well the trial spectrum matches the observations over the full energy range. Thus, the position of each data point is related to the positions of other data points by the complex instrument response functions.

One can demonstrate the above two problems. As pointed out in Ref. [1], a very simple spectral shape can also fit the data. Figure 3 shows the same OTTB data as used in Figs. 1a and 1b, but fit with an 100 keV exponential. Although the lowest three points do not fit exactly, one does not have the strong features of a line as one did in Fig. 1a. The fit for Fig. 3 has a χ^2 of 21 with 16 degrees of freedom. Note that the data points in Fig. 1a seem to fall along a straight line at the low energy end of the energy range, whereas they seem to appear to be curved in Fig. 3a. Figure 4d is a comparison of Figs. 1a and 3a. The two problems discussed above have combined to cause the data points to follow a different path. A single energy point has moved two standard deviations (three times the fitting statistical error). The differences can even cause confusion as to whether the spectrum is increasing or decreasing with photon energy. Note that in Fig. 1a the first data point is at a higher energy than the second point, whereas the opposite is true in Fig. 3a. The points between 10 and 20 keV have moved slightly, but always in a direction to agree with the trial spectral shape. In this sense, the points might be characterized as "floating" in that they will tend to agree to agree with whatever the person analyzing the data has assumed.

¹Please note that the differences between OTTB and the exponential fit to Fig. 1a are less than a factor of 2 than shown at the conference. This paper was a late contribution to the suggestion of the session chair. It was prepared from material forty-four hours before the conference. Moreover, the OTTB fit was taken from a plot of Ref. [5] which did not utilize the response function from the Monte Carlo calculations. So, it is not clear whether confusion might have been prevented.

The perception of a strong line in Fig. 1a is due to the large deficiency of counts relative to the OTTB continuum. For the exponential spectrum (which can be harder than the OTTB), no strong line is perceived because there is not a large deficiency of counts relative to an exponential shape (Fig. 1c). From this type of behavior, one can envision a scenario where a line shape can appear to vary on a short time scale when, in fact, the line is a spurious artifact of the analysis. Suppose the spectrum of the gamma-ray burst is initially quite hard but the analysis rigorously assumes only OTTB. As a result, the unfolded spectrum would be soft at high energy (in accordance with the assumed continuum shape) and there will be a deficiency of counts at lower energy which might be interpreted as an absorption line. Later (e.g. 4 s), the true spectrum may have softened to the extent that it is possible for OTTB to fit the entire energy range without a deficiency of counts at low energy. The "line" would have appeared to come and go on a short time scale giving the false impression that it was not an instrumental effect.

The exponential fit to the SMM data (Fig. 1c) still seems to show some structure in the continuum below 100 keV; there might be a shallow, narrow absorption line near 65 keV. The point at 65 keV is below the general level of the other points by about 5σ. However, the error bars are difficult to interpret since they do not reflect the fact that the points can move. If the Konus spectra that had broad absorption lines were fit with spectral shapes harder than OTTB, they too might have shallow narrow lines at 45 to 65 keV (e.g. GB79 412, GB790610, GB791006, and GB791101). However, the small dips are in a range where it is most difficult to unfold the spectrum. We have found it necessary to model accurately the detector with a Monte Carlo calculation and have that calculation supported by calibrations. In addition, an accurate onboard gain calibration is required. For NaI, one must take into account the nonlinearity of the light output as a function of energy deposited. For CsI, one must take into account the dead layer. Even small changes in the assumed detector geometry can cause a different physical interpretation, particularly in the 30 to 100 keV range. For example, in Fig. 1c, it was assumed that the CsI dead layer was 0.0025 inches, whereas a recent reanalysis of the calibration data indicates a thickness of 0.005 inches [5]. Figure 1c shows the resulting SMM spectrum which appears to have a strong emission feature at 45 keV. In this case, the dead layer doubled its efficiency for stopping 65 keV photons (to ~17%) and roughly 40% of those events contributed a fluorescence photon to the detector. As a result, the relative height of the escape peak changed from 0.22 to 0.39. This demonstrates that the range 45 to 65 keV is very sensitive to the calibration of the instrument, especially in thin detectors where the escape peak is relatively more important. Either uncertainties in the gain [2] or uncertainties in the response curves can cause a narrow spectral feature between 45 and 65 keV to appear due to the problems associated with unfolding a spectrum near an absorption edge.

In summary, there exist spectral shapes (e.g., exponential) which fit the SMM data for GB790619 without requiring a broad absorption feature. The reported broad feature [1] and those reported from the Konus experiment [4] are probably the result of restricting the trial spectrum to OTTB. The use of harder spectra (such as a computerized blackbody [6]) could provide a fit with monotonic spectra. However, in both the SMM spectra and the Konus spectra which show broad absorption features, the use of a harder spectrum might still require a narrow absorption feature near 50 keV. These narrow lines probably cannot be considered confirmed since the ISEE-3 spectral fit for GB790419 is completely inconsistent with the SMM continuum below 100 keV and because all of the instruments used so far are very susceptible to errors in the range 45 to 65 keV due to small changes in the gain and the response function.

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