Reassessment of the 56Co emission from SN 1991T

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Reassessment of the ^{56}Co emission from SN 1991T

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Abstract. The detection of ^{56}Co emission from SN 1991T has been previously reported at a level near the COMPTEL sensitivity threshold. The spectral analysis method, fitting the count spectrum to a background model plus a ^{56}Co emission template, is subject to possible systematic effects which had not been thoroughly studied at that time. To better evaluate the significance of that ~3.3σ detection, the same method has been applied to a grid of points with 5° spacing, out to 35° from the pointing direction, in each of 103 observing periods from phases 1 through 3. A dozen instances were found with a ^{56}Co signal as significant as that for either of the two observations of SN 1991T alone (~2σ). Nothing was found as significant as the combined observations of SN 1991T. The strongest instrumental background artifact in the vicinity of the two principal ^{56}Co lines, attributed to ^{27}Mg, falls between the ^{56}Co lines. It fills in the valley between those lines, and so will obscure real ^{56}Co emission rather than producing false ^{56}Co sources. Fortunately, this artifact was weak up to the time of the reboost during phase 3. Thus, it is very unlikely that the reported emission from SN 1991T was a statistical fluctuation or instrumental artifact. But, since the flux was so near the detection threshold, little can be said about the gamma-ray light curve of the supernova, the relative strengths of the ^{56}Co lines, or the line widths.

INTRODUCTION

The type Ia supernova SN 1991T was discovered on April 13, 1991, just 8 days after the launch of CGRO, in the spiral galaxy NGC 4527 on the edge of the Virgo cluster. The peak magnitude of SN 1991T was near V=11.5, about 0.5 magnitude brighter than a typical type Ia in the Virgo cluster. This, together with certain spectral peculiarities [1], suggested that an unusually large mass of ^{56}Ni (the short-lived progenitor of ^{56}Co) was produced, making SN 1991T intrinsically brighter than the typical type Ia in both the optical and γ-ray bands. Given its relative proximity, about 13.5 Mpc [2], SN 1991T was an obvious target for CGRO.

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It was observed by COMPTEL during two 14-day periods beginning 66 days (obs. 3) and 176 days (obs. 11) after the supernova explosion.

The initial analysis of the SN 1991T observations [3] employed background-subtracted count spectra, and maximum likelihood imaging for energy windows around each of the two principal ^{56}Co lines, at 847 keV and 1238 keV. Those efforts produced only upper limits on the line fluxes. The choice of an appropriate background spectrum is a difficult problem in a standard spectral analysis. The instrumental background changes with time, the spacecraft pointing direction and across the field of view, often confounding efforts to find the "right" background. A second difficulty is that the statistical fluctuations in background spectra contribute to the uncertainties in background-corrected spectra.

As an alternative, a new analysis method was developed which avoids selecting a measured background spectrum. Rather, this method fits the measured spectrum directly with model components, exploiting the accumulated knowledge of the instrumental background and models of the instrumental response. Evidence was found of ^{56}Co emission in both SN 1991T observations, though it was statistically significant ($> 3\sigma$) only for the combined observations [4]. A consistent detection ($\sim 3\sigma$) was obtained with maximum likelihood imaging by combining events in the two energy windows, as well as the two observations, for the analysis and utilizing an improved point-spread function.

Though these results were encouraging, an investigation of possible systematic errors in the spectral fitting was needed to provide confidence in the detection of ^{56}Co. This paper presents an assessment of such systematic effects.

THE SPECTRAL-FITTING METHOD

The function which is used to model the instrumental background is

$$f_B = a_0\left(1.- e^{-b(E-E_0)}\right) e^{-\alpha E} + a_K \exp\left[-0.5\left(\frac{E-E_K}{\sigma_K}\right)^2\right] + a_D \exp\left[-0.5\left(\frac{E-E_D}{\sigma_D}\right)^2\right] \quad (1)$$

The first term, with four free parameters, is a smooth underlying background with a threshold at E_0 and an exponential decline at high energies. The two remaining terms are Gaussians to model a feature near 1500 keV, due in part to the decay of ^{40}K in various spacecraft components, and the 2223-keV line from deuterium formation in the COMPTEL D1-detector liquid scintillator.

Figure 1 shows a typical but particularly pertinent example of a fit to this background model. The spectrum contains events in obs. 3 and 11 within 20° of SN 1991T. The spectrum is fit from threshold (~720 keV) to 2600 keV. Figure 1b shows the deviations from the fit. Significant deviations are apparent, particularly around 1500-1700 keV, but in the vicinity of the ^{56}Co lines the fit is quite good (χ^2 =10.9 for 14 points at 800-1500 keV).

When searching for ^{56}Co emission the fit is restricted to the energy range from threshold to 1800 keV. This eliminates the three free parameters for the deu-

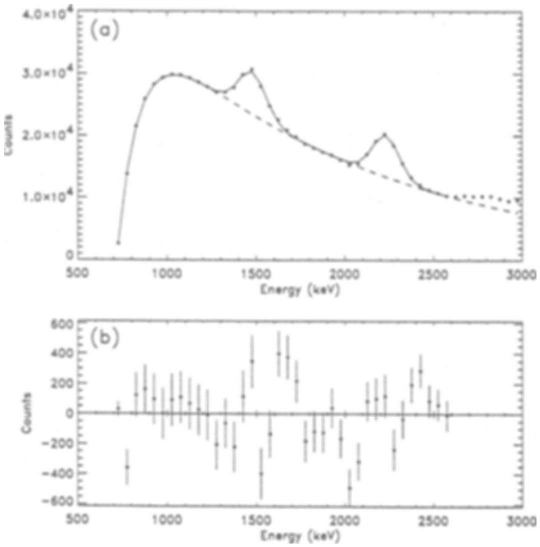

FIGURE 1. (a) Spectrum of events from obs. 3 and 11 combined, within 20° of SN 1991T. The solid line is the fit to the background approximation (1) with the dashed line showing the first term in (1) alone. (b) The residuals of the fitted spectrum.

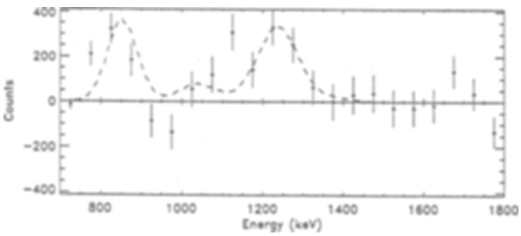

FIGURE 2. Deviations from the background model in a fit including the ^{56}Co template (dashed line) to events within 3° of SN 1991T.

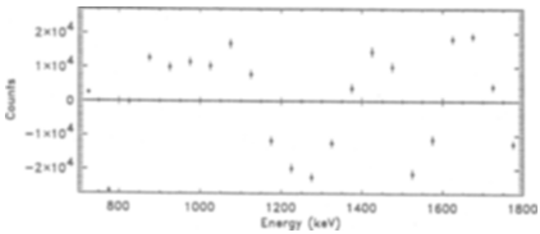

FIGURE 3. Deviations from the background model in a fit to all events within 20° of the pointing direction in observations through February 1997.

terium line and hopefully provides a better background fit in the vicinity of the ^{56}Co lines. After fitting to the background model alone, an emission template, derived from Monte Carlo simulations of the telescope response to the ^{56}Co lines, is included in the fit. If inclusion of the template significantly improves the goodness of the fit, as measured by the χ^2 statistic [5], the presence of ^{56}Co emission can be inferred. Figure 2 shows deviations from the background model for a fit with the ^{56}Co emission template to combined data from the two SN 1991T observations, within 3° of SN 1991T. The dashed line shows the fitted ^{56}Co template.

ASSESSMENT OF SYSTEMATIC ERRORS

Two approaches have been used to assess systematic errors in the spectral fitting analysis. Persistent deviations of the instrumental background from the model (1) have been sought by fitting spectra for large volumes of data. An empirical assessment of the significance of the ^{56}Co emission has been done by searching a large number of COMPTEL observations for ^{56}Co emission.

Figure 3 shows the residuals for a fit with the background model (1) to a spectrum of events within 20° of the pointing directions, summed over all observations through February 1997. There is an interval with positive residuals between the energies of the principal ^{56}Co lines. This feature is probably due to ^{27}Mg activation (^{27}Al(n,p)^{27}Mg) in passive materials near the D1 modules. The ^{27}Mg nuclei beta decay with a halflife of 9.5 min, emitting either an 844-keV or 1014-keV photon. Most ^{27}Mg background events result from the absorption of the decay photon in the D2 detector together with the scattering of a bremsstrahlung photon in the D1 detector, depositing at least 50 keV (the D1 energy threshold). Because the ^{27}Mg events fill the valley between the principal ^{56}Co lines, they obscure real ^{56}Co emission rather than producing false ^{56}Co sources. Fortunately the ^{27}Mg feature was weak before the spacecraft reboost in November 1993.

To search for ^{56}Co sources, software was developed to simultaneously accumulate spectra for many points in the field of view and to fit the spectra with the background model (1) plus an emission template. This in effect allows mapping of ^{56}Co emission. We produced 103 such maps on a 5°×5° grid with a field of 70°×70° and spectra accumulating events within 3° of each grid point. The maps cover all observations through phase 3 (to September 1994).

Local maxima in ^{56}Co flux more significant than that at SN 1991T in either one of the two individual observations (~2σ) were found at 12 positions in 11 maps. This is much smaller than the number that should be expected by chance. However, all those excesses were in the 79 maps for observations preceding the reboost and they were concentrated toward the center of the field of view: 5 of the 12 were within 10° of the center and 11 were within 20°. The dearth of ^{56}Co excesses in the later observations is probably due to increased ^{27}Mg activation. The distribution of ^{27}Mg background events across the field of view may well lead to the concentration of ^{56}Co excesses near the center. This question can be investigated through Monte Carlo simulations of ^{27}Mg events.

For a 10°-radius field of view and 79 maps about 1000 points were tested, with about 45 deviations $>2\sigma$ expected, half of them positive. However, the grid spacing was not so large that spectra at neighboring points are independent, so the discovery of only 5 local maxima exceeding 2σ may well be consistent with statistical expectations.

None of the excesses found in the ^{56}Co search was as significant as that at SN 1991T in the combined observations 3 and 11. No two of those excesses were found at the same point on the sky, so excesses in different observations cannot be combined to reveal a source more significant than SN 1991T.

OTHER CONFIDENCE TESTS FOR SN 1991T

Figure 4 is a spectral-analysis map of the ^{56}Co emission from SN 1991T on a 1°×1° grid, which can be compared directly with the maximum likelihood map in ref. 4. The two analysis methods produce very similar maps, with SN 1991T near the 1σ location contour, and the most likely source position about 1.5° to the northeast, away from the nearby bright continuum source 3C273. Independent imaging analysis with the 'software collimation' method [6], though less sensitive, also shows a 2σ excess at SN 1991T.

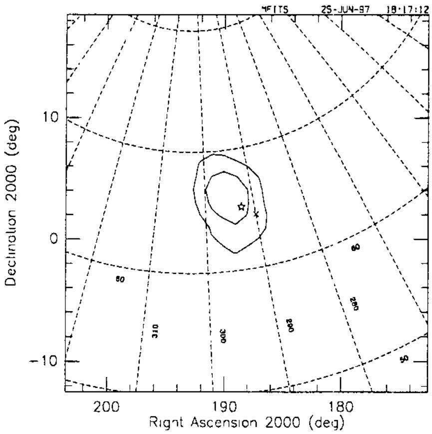

FIGURE 4. Map of the ^{56}Co emission in obs. 3 and 11 showing 1- and 2-σ source location contours. The positions of SN 1991T (star) and 3C273 (×) are indicated.

By varying the line weighting for the emission template, we have tested for absorption of the ^{56}Co γ-rays. The best fit is obtained with about a 20% reduction in the strength of the 847-keV line, relative to the 1238-keV line, corresponding to absorption in 10-20 $g\ cm^{-2}$ of Fe, but this fit is only marginally better than that for the production ratios (no absorption). Eliminating either of the principal lines entirely reduces the significance of the fit by about 1σ.

CONCLUSION

There is no evidence of systematic effects that mimic ^{56}Co emission in the spectral fitting analysis. Rather, the most persistent background feature in the vicinity of the principal ^{56}Co lines obscures ^{56}Co emission. A search for excesses of ^{56}Co flux found fewer than would be expected by chance, and none as significant as that at SN 1991T.

This empirical assessment of the significance of ^{56}Co emission shows that the formal statistical significance of 3.3σ does not overstate confidence in the source at SN 1991T. That confidence is bolstered by the coincidence of the emission in space and time with the expected source, the drop in significance if either of the principal lines is omitted from the emission template, and the good agreement between the spectral analysis and maximum likelihood mapping.

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