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Supplementary Materials for

^{44}Ti gamma-ray emission lines from SN1987A reveal an asymmetric explosion

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Supplementary Materials:

Materials and Methods

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Materials and Methods: We reduced the data from the two NuSTAR instruments, Focal Plane Modules (FPMs) A and B. The NuSTAR FPMs are cadmium-zinc-telluride pixel detectors with an energy resolution of 0.4 keV FWHM at 10 keV, and 0.90 keV FWHM at 68 keV. NuSTAR observes the energy band from 3 keV to 78.39 keV, which fully covers the expected emission from the ^{44}Ti 67.87-keV line, but cuts off the response to the 78.32-keV line. We processed the data with HEASOFT 6.16 and the NuSTAR Data Analysis Software (NuSTARDAS) v. 1.4.1 using CALBD version 20140414. We extracted source counts from circular regions with 30" radius centered on SN1987A from both NuSTAR FPMs (Fig. S1). We identified rectangular background regions excluding the source region on the same FPM detectors where the source locates. The spectra extracted from the source and background regions are shown in Fig. S2.

We used the XSPEC software package (v12.8.2) to fit the NuSTAR spectrum with a model consisting of an underlying power law continuum plus the ^{44}Ti lines. We first fit the 3-60 keV spectrum with the 'powerlaw' standard spectral model in XSPEC, including 'tbabs' absorption with a fixed the absorption $N_H = 2.35\times10^{21}$ cm^{-2}, and a Gaussian iron X-ray line. These best-fit parameters were fixed, and then the spectral range was extended to include the ^{44}Ti lines. This analysis was also performed replacing the 'powerlaw' model with the standard 'srcut' model. Detailed analysis of the full 3-79 keV continuum spectrum will be presented in a separate paper (34); however, given the good signal-to-noise in the lines, the results of this ^{44}Ti analysis are not sensitive to the details of the underlying continuum.

While the rest energy of the 78.32-keV line is near the 78.39-keV Pt absorption cutoff of the NuSTAR optics, our measured spectrum in Fig. 1 shows that this line is partially redshifted into the NuSTAR energy band. To account for this line we use three test cases, similar to those used in the NuSTAR Cas A analysis (25): (1) two Gaussian model components with the line widths, redshifts and normalizations tied together; (2) two independent Gaussian model components fit to data extending to 79 keV; and (3) a single Gaussian model fit to the 67.87-keV line, ignoring the counts above 72 keV. The results of these three cases are presented in Table S2. In all three cases the resulting ^{44}Ti yield, redshift and Doppler broadening of the ejecta are comparable. Given the significance of the 78.32-keV line, we take Case (1) as our baseline and focus on the combined 67.87-keV and 78.32-keV lines for quantitative analysis. The other two cases are evidence that analysis on the individual lines confirms the yield and redshift measurements inferred from the combined analysis.

The confidence contours for the 67.87-keV line flux for Case (1) compared to the measured redshift are shown in Fig. S3. The line centroid is redshifted by $0.23^{+0.09}_{-0.09}$ keV. For comparison the NuSTAR energy scale is calibrated to better than 0.040 keV (3σ), so the residual systematic uncertainty on the line centroid is negligible compared to the line shift (35). The line centroids correspond to an uncorrected Doppler redshift velocity of 1000^{+400}_{-400} km s^{-1}. There are two corrections required to get this redshift into the rest frame of SN1987A. First is the recession velocity of 286.7 km s^{-1} for SN1987A (36). Second, there is an expected redshift of the ^{44}Ti lines even for spherically symmetric ^{44}Ti distributions due to the 'look-back' effect (37). For a spherically expanding shell, the ^{44}Ti emission as seen by a distant observer would appear stronger from the far, redshifted side of the shell due to the light-travel time across the remnant and the finite lifetime of the ^{44}Ti decay. This redshift grows roughly linearly with time as the shell expands. Assuming a maximum expansion speed of $\leq$ 2,500 km s^{-1}, we estimate that for the current age of SN1987A this 'look-back' effect would produce a redshift of $\leq$ 50 km s^{-1}. Combining the recession velocity and the look-back effect, our estimate of the redshift velocity of the ^{44}Ti line in the rest frame of SN1987A becomes 700^{+400}_{-400} km s^{-1}. This corrected redshift is significant compared with the limits on the Doppler broadening, indicating large-scale asymmetry in the explosion.

Table S1. List of NuSTAR observations of SN1987A used in this analysis.

Observation ID	Start Date (Year:Day:UTC)	Exposure Time (ksec)
40001014023	2014:213:23:45:19	427.1
40001014020	2014:170:21:00:35	275.2
40001014018	2014:166:10:25:17	182.3
40001014016	2014:112:21:05:16	391.9
40001014015	2014:111:11:15:37	87.0
40001014013	2013:180:01:15:15	430.9
40001014010	2012:347:17:15:29	186.0
40001014007	2012:295:19:05:28	157.1
40001014006	2012:294:18:51:24	53.9
40001014004	2012:255:02:15:23	198.9
40001014003	2012:252:22:33:20	136.3
40001014002	2012:251:20:43:05	68.8

Fig. S1. NuSTAR images of the combined 3-80 keV SN1987A observations for FPMA (left) and FPMB (right). Extraction regions for the source (circle) and background (rectangle excluding source region) are shown.

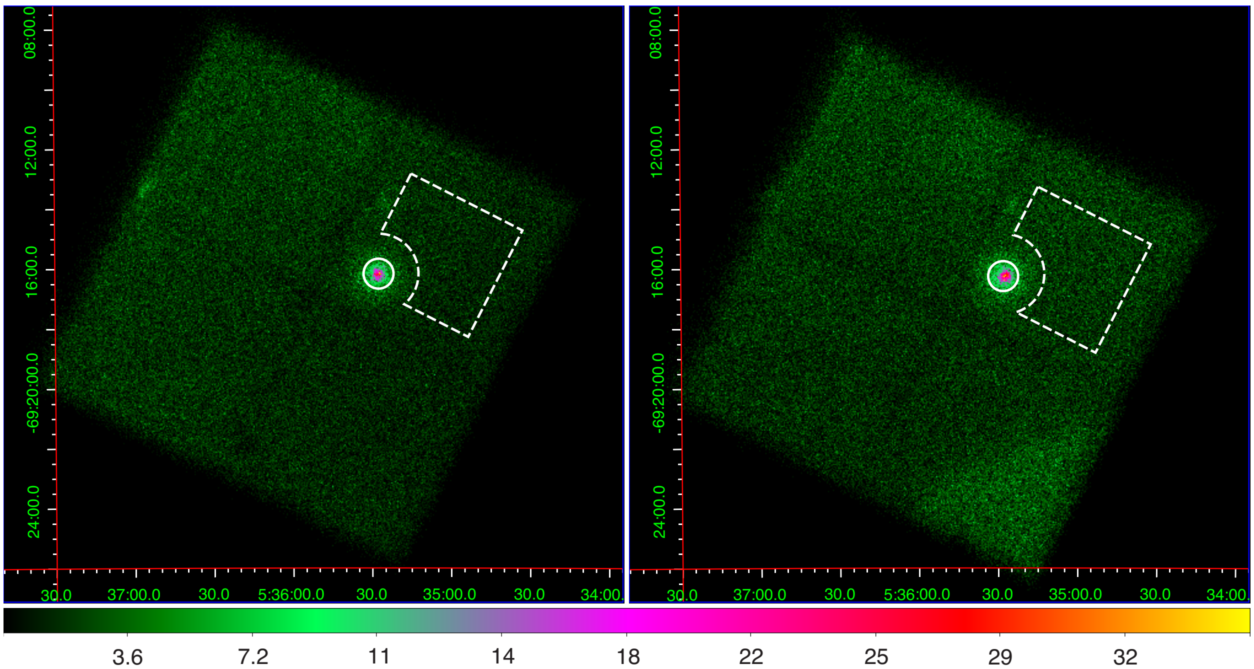

Fig. S2. NuSTAR spectra extracted from the source regions (black) and from the background region (red). NuSTAR has two co-aligned telescopes, but data from both telescopes are combined (for presentation only) and shown with 1σ error bars calculated from Poisson statistics. The NuSTAR background structures at 65, 67, and 75 keV are well constrained in these long observations, allowing direct background subtraction. The NuSTAR optics cut off above 78.39 keV, which is taken into account in the instrument response.

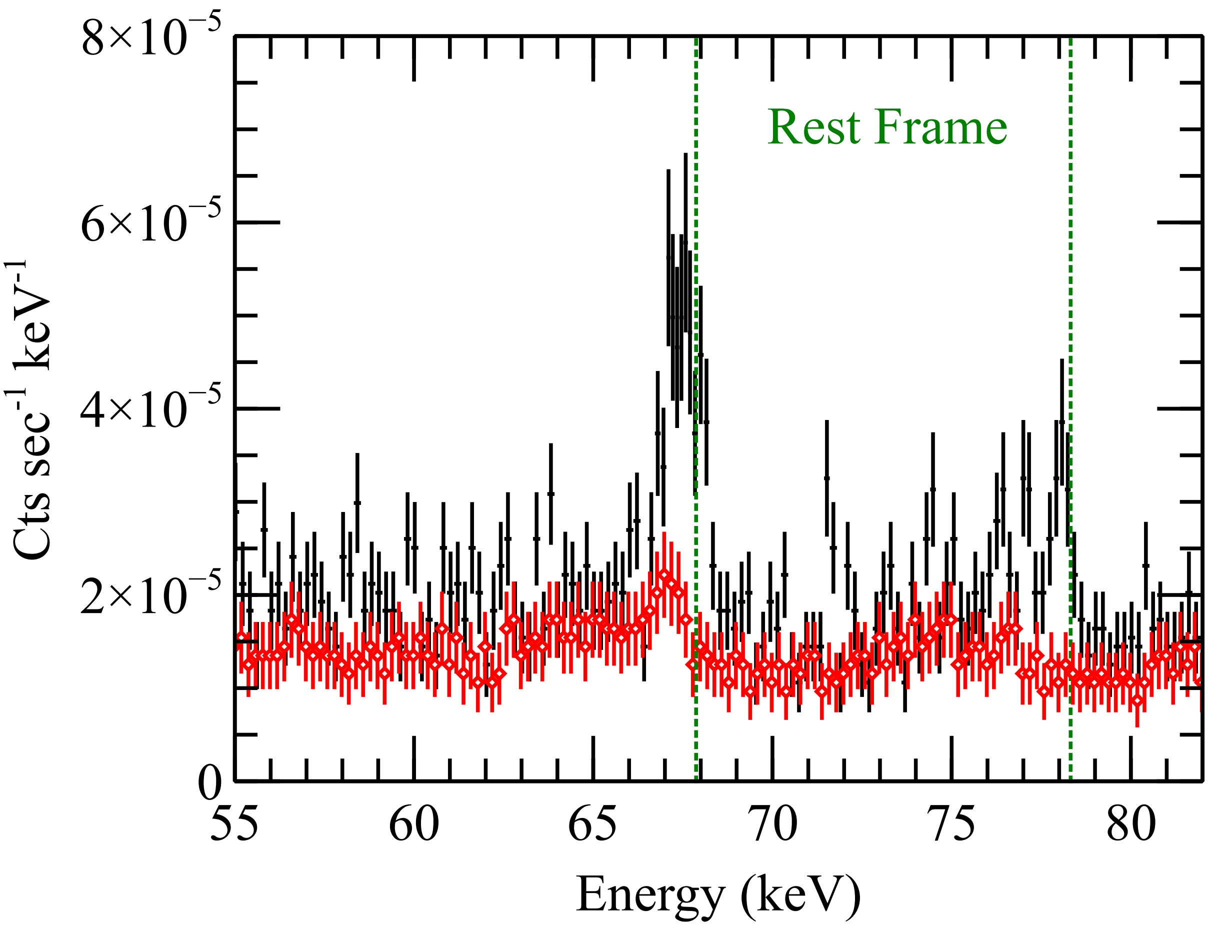

Fig. S3. Confidence contours for the measured 67.87-keV Gaussian line flux versus line centroid for Case (1). Contours are 68% (black), 90% (red), and 99% (green) confidence levels. The line is strongly redshifted from the 67.87-keV rest energy, and the flux well constrained.

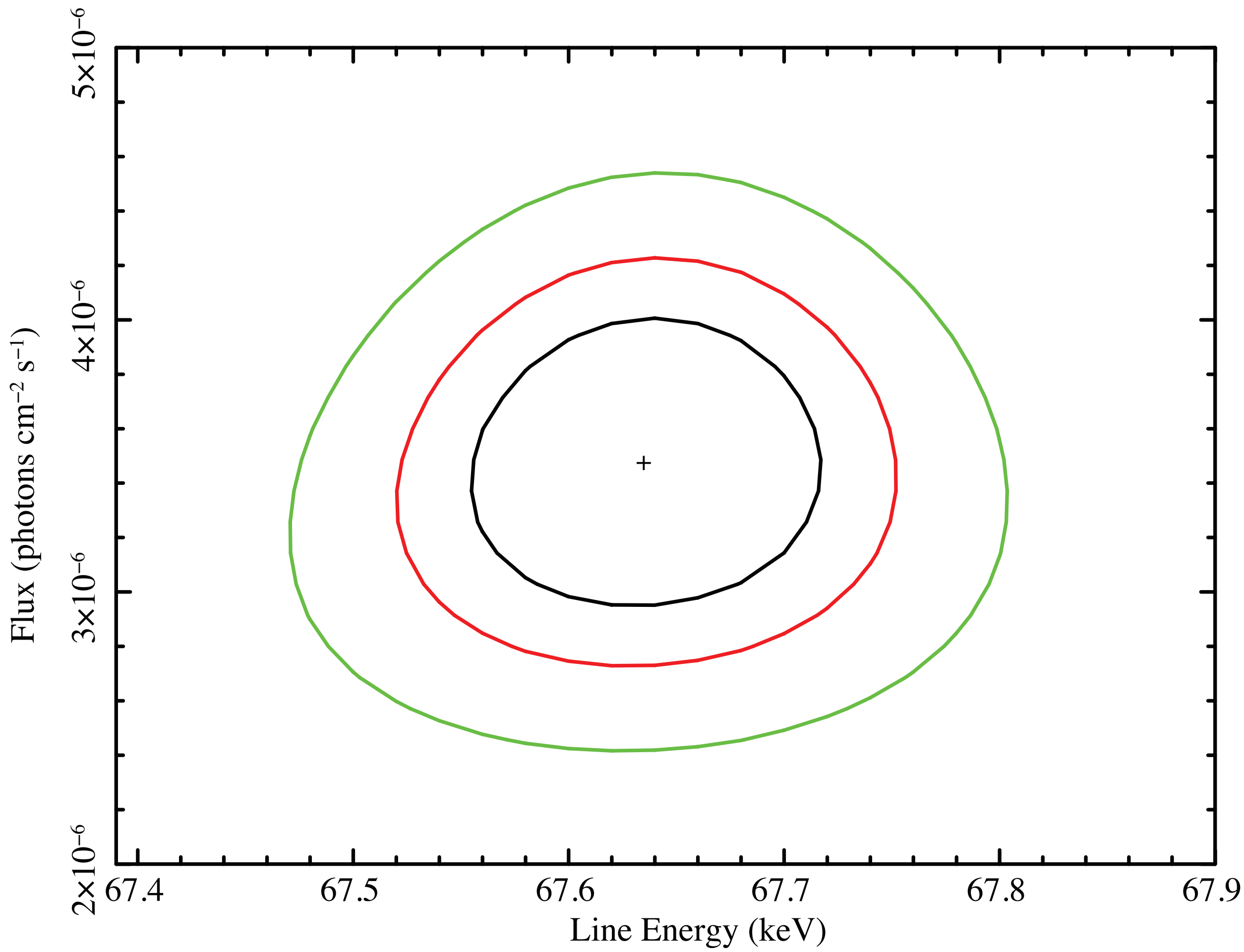

Table S2. Best-fit 67.87-keV and 78.32-keV line parameters.

Parameter	Case (1) 68/78 tied	Case (2) 68/78 independent	Case (3) 68 only
F_{68} (photons cm^{-2} s^{-1})	$3.5^{+0.7}_{-0.7} \times 10^{-6}$	$3.4^{+0.7}_{-0.7} \times 10^{-6}$	$3.4^{+0.7}_{-0.7} \times 10^{-6}$
E_{68} (keV)	$67.64^{+0.09}_{-0.09}$	$67.66^{+0.10}_{-0.12}$	$67.65^{+0.11}_{-0.11}$
z (redshift)	(0.0034)	(0.0031)	(0.0032)
σ_{68} (keV)	$0.24^{+0.13}_{-0.19}$	$0.27^{+0.12}_{-0.14}$	$0.27^{+0.12}_{-0.15}$
F_{78} (photons cm^{-2} s^{-1})	F_{68}*(96.4/93.0)	$3.7^{+1.3}_{-1.2} \times 10^{-6}$	-
E_{78} (keV)	E_{68}*(78.32/67.87)	$77.99^{+0.17}_{-0.11}$	-
z (redshift)		(0.0042)	-
σ_{78} (keV)	σ_{68}*(78.32/67.87)	$0.02^{+0.29}_{-0.02}$	-
χ^2/dof	1253.10/982	1250.54/979	1213.44/942
Reduced χ^2	1.276	1.277	1.288

Notes. Errors are 90% C.L. Line widths (σ_{68}, σ_{78}) correspond to source Doppler broadening, after accounting for the NuSTAR spectral resolution at these energies. Case (1), (2) fitting range 3-80 keV. Case (3) fitting range 3-72 keV.

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