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IMAGING OBSERVATIONS OF SN1987A AT GAMMA-RAY ENERGIES

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ABSTRACT

The Caltech imaging γ-ray telescope was launched by balloon from Alice Springs, NT, Australia for observations of SN1987A during the period 18.60-18.87 November 1987 UT. The preliminary results presented here are derived from 8200 seconds of instrument livetime on the supernova and 2500 seconds on the Crab Nebula and pulsar at a float altitude of 37 km. We have obtained the first images of the SN1987A region at γ-ray energies confirming that the bulk of the γ-ray emission comes from the supernova and not from LMC X-1. A count excess is detected between 300 and 1300 keV from the direction of the supernova, one third of which comes from energy bands of width 80 and 92 keV centered on 847 and 1238 keV, respectively. The excess can be interpreted as a line photon flux plus scattered photon continuum from the radioactive decay of ^{56}Co synthesized in the supernova explosion. We compare our data to recent predictions and find it to be consistent with models invoking moderate mixing of core material into the envelope.

INTRODUCTION

The observations reported here were performed with the Caltech Gamma-Ray Imaging Payload (GRIP), a balloon-borne coded-aperture telescope sensitive to radiation in the energy range from 30 keV to 10 MeV[1]. The instrument in its current configuration employs a rotating hexagonal-celled uniformly redundant array (URA) and a 5 cm thick by 41 cm diameter position sensitive NaI scintillation detector to image a 14° diameter field of view with 1.1° angular resolution. The mask cell size in the November flight was 4.8 cm and the separation of the mask and detector was 2.5 m. The instrument has flown twice previously[2] including a flight in May 1987 from Australia to observe SN1987A. No γ-ray or hard X-ray emission was detected in this initial observation of SN1987A and preliminary upper limits have been reported elsewhere[3]

IMAGES

Images of the Crab and SN1987A regions from the flight on 18 November 1987 are shown in Fig. 1 and 2. The Crab region image is the sum of 4 different observation periods. The source peak is clearly evident, as is the ring structure which results from use of a rotating mask having multiple repetitions of the basic URA pattern[4]. The ring can be removed in later analysis. The locations of the image peaks (each greater than 8σ) from individual Crab observations varied over a range of ±0.25° in the azimuthal direction and ±0.1° in the elevation direction. We attribute the larger azimuthal variations to incomplete correction for deviations between the actual and the assumed magnetic field direction used as a pointing reference during flight. The image of Fig. 1 was obtained by aligning the centroids of the peaks from the individual Crab observations.

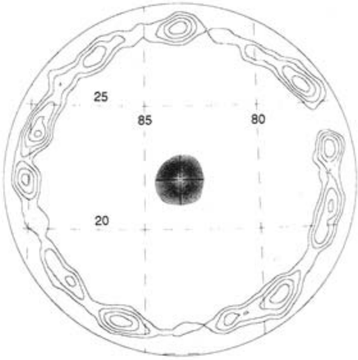

Fig. 1 Image of the Crab region from 30 to 2700 keV covering a 14° field of view. Right ascension (vertical lines) and declination (horizontal lines) are indicated. The contours indicate the number of excess counts in a given direction calibrated in units of the statistical significance of the excess, with contours beginning at the 2σ level and spaced by 1σ intervals.

Fig. 2 Image of the SN1987A region from 40 to 1300 keV. Parameters as in Fig. 1 except for the contour spacing which is 0.5σ. The large cross indicates the expected position of SN1987A. The small cross indicates the expected position of LMC X-1.

Figure 2 shows an image of the supernova region for energies between 40 and 1300 keV. The image is a composite of data from 4 individual observation periods with the individual fields aligned by using the pointing corrections determined from the Crab observations. Flux is detected at a nominal 4.9σ level from within 0.28° of the expected position of SN1987A. The 1σ statistical error in the peak location is estimated to be 0.16° in both azimuth and elevation directions. The residual deviation is in the azimuthal direction and may be due to incomplete magnetic field offset correction. In the elevation direction, which is approximately aligned with the declination axis in these observations, the peak centroid is consistent with the position of the supernova. This indicates that the observed flux above 40 keV does not have a strong contribution from LMC X-1 which is 0.47° away in declination.

SPECTRA

Measurements of the γ-ray flux from SN1987A for selected energy intervals are listed in Table I. The differential flux measurements were derived from the number of excess counts in the image at the position of the supernova determined from the data of Fig. 2. Because many of the factors that determine photon detection efficiency are energy dependent, a calculation of the expected excess counts was made by integrating a power-law differential continuum flux, $F = K(E/100keV)^{-\alpha}$, folded with the estimated photon detection efficiency. The predicted and measured image counts were compared, iteratively adjusting the factors K and α in the power law until a consistent result was obtained. This analysis for the Crab yielded a flux of 4.4 x 10^{-4} (E/100 keV)$^{-2}$ (cm^2 s keV)$^{-1}$ between 40 and 500 keV.

Table I			
Energy Interval (keV)	Weighted Mean Energy (keV)	SN1987A Flux Measurement	Statistical Significance
		Differential Flux (cm^2 s keV)$^{-1}$	
40-303	152	1.95±0.48 x 10^{-5}	4.1σ
303-1286	625	0.56±0.22 x 10^{-5}	2.5σ
1608-3752	2471	< 3.71 x 10^{-6}	3.0σ
		Integral Flux (cm^2 s)$^{-1}$	
807-887	847	1.08±0.53 x 10^{-3}	2.0σ
1192-1284	1238	1.07±0.64 x 10^{-3}	1.7σ
807-887 + 1192-1284		2.15±0.83 x 10^{-3}	2.6σ

The first two differential flux estimates in the table were obtained using a power law spectral index, $\alpha = -0.9$, and flux normalization, K = 2.8 x 10^{-5} (cm^2 s keV)$^{-1}$. The second energy interval was chosen to include possible 1238 keV emission, and the gap between 1286 and 1608 keV was chosen to eliminate the strong 1460 keV background line contribution.

It is of interest to estimate the flux near the energies of the prominent γ-ray lines expected from ^{56}Co decay. Table I gives integral flux values for intervals centered on 847 keV and 1238 keV and a sum for the combined intervals. The widths of the intervals are chosen to be approximately 1.2 times the FWHM instrumental resolution. Because the energy dependence of the detection efficiency is not strong in these narrow intervals, no spectral index assumption was required.

We stress that the results reported here are of a preliminary nature. The present analysis incorporates only the preliminary calibration data for the new coded-aperture mask and low-energy collimator used in the 18 November flight. Further, we have recently obtained more detailed magnetic field data which will be used in later analyses and which may remove the pointing uncertainties mentioned above. We estimate the possible systematic errors in the absolute flux measurements to be less than 50 percent. Systematic errors in the relative flux measurements should be smaller and generally negligible compared to the statistical errors in Table I. Most conceivable systematic errors, in particular pointing uncertainties, will tend to yield an absolute measured flux lower than the true flux. We note that the estimate of the Crab spectrum given above is ~20-40% below other measurements at 100 keV[5] and may indicate an overall systematic underestimate of the flux.

DISCUSSION

The results given in Table I should be considered in the context of other measurements of the hard X-ray and γ-ray flux made during the period of August through November 1987. These include results using the Mir-Kvant observatory[6], the Ginga satellite [7], and the Solar Maximum Mission (SMM) [8]. Our continuum flux measurement on 18 November at 152 keV is consistent with the flux of approximately 1.5 x 10^{-5} $(cm^2\ s\ keV)^{-1}$ at 150 keV measured by the Mir-Kvant observatory during the period 10-21 August 1987, although a factor of two increase in flux is marginally acceptable, differing by approximately 2σ from the measured value. Our finite flux detection in the 303 to 1286 keV range lies just above the 3σ upper limit reported from the Mir-Kvant Pulsar X-1 instrument for the 10-21 August period, indicating a probable increase in flux at γ-ray energies near 1 MeV. While our integral fluxes measured in the region of 847 keV and 1238 keV should be interpreted as continuum plus line emission, the values given in Table I are consistent with the γ-ray line fluxes reported by the SMM instrument for the August through October period: 1.0$\pm$0.25 x 10^{-3} cm^{-2} s^{-1} at 847 keV and 6$\pm$2 x 10^{-4} cm^{-2} s^{-1} at 1238 keV. Our measurements should also be compared to the results obtained from three other balloon-borne instruments. These include the sensitive hard X-ray measurements of the NASA Marshall Space Flight Center group on 29-30 October [9] which cover the energy range 45 to 200 keV, and the high-resolution γ-ray line measurements of the Lockheed [10] and NASA Jet Propulsion Laboratory[11] groups on 29-30 October and 6 December respectively.

A likely origin of the observed hard X-ray and γ-ray flux is the decay of ^{56}Co which is a product of the decay of ^{56}Ni synthesized in the supernova explosion [12-14]. The ^{56}Co decays are expected to yield both line emission (in particular at 847 and 1238 keV) and a continuum of Compton degraded photons. Approximately 0.075 solar mass of ^{56}Ni was synthesized in the initial explosion as is well determined from the late time decay of the bolometric luminosity of the supernova [15]. The results given in Table I are compared with recent theoretical predictions in Fig. 3. The continuous histogram is based on a Monte Carlo calculation of the expected photon flux on day 250, taken from Pinto and Woosley[16]. Similar calculations have been carried out by other authors [17-21]; the calculation in Fig. 3 is a recent example of models which incorporate mixing to explain the early turn-on of X-rays and γ-rays seen by the Mir-Kvant, Ginga, and SMM instruments. The model assumes a 6 solar mass He core, a 10 solar mass hydrogen envelope, 1.3 x 10^{51} erg explosion kinetic energy, and a moderate degree of mixing of ^{56}Co out into the helium envelope.

In general, our differential flux measurements shown in Fig. 3 are consistent with the calculations. To compare the measured and calculated values more directly in the 40 to 303 keV interval where energy dependent efficiency factors change rapidly, we have folded the Monte Carlo spectrum in Fig. 3 with the estimated photon detection efficiency. We find that the Monte Carlo calculation predicts an excess of 3480 photons in the image compared to the measured value of 2251$\pm$559. This is a nominal 2.2σ discrepancy, but given the range of possible systematic errors discussed above, we do not view the difference as serious at this time. A 30% underestimate of the absolute flux would reduce the difference to less than 1σ.

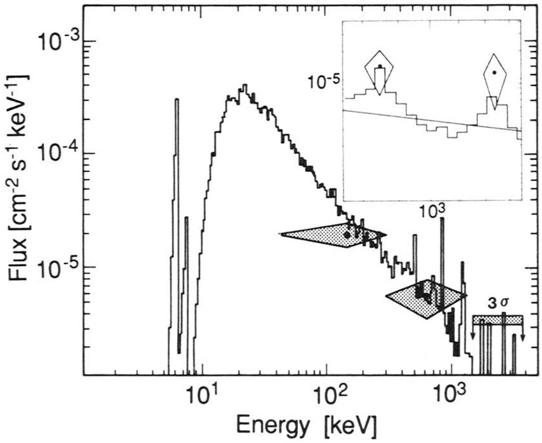

Fig. 3 Flux measurements and calculations for SN1987A. The continuous histogram is a Monte Carlo calculation of the expected flux on day 250 of the supernova from Pinto and Woosley[16] convolved with a gaussian representation of the instrumental energy resolution. The measurements are indicated by diamonds with centers plotted at the weighted mean energy and the width indicating the energy interval of the measurement. The inset shows an expanded view of the 750 to 1350 keV interval. The straight line shown in the inset indicates a power law continuum flux with spectral index α = -0.9

The insert in Fig. 3 is an expanded view of the energy region between 750 and 1350 keV and includes our integral flux measurements for the 847 and 1238 keV regions plotted as differential fluxes by dividing by the width of the energy intervals. Our results are consistent with the Monte Carlo calculations which have been convolved with the instrumental energy resolution. In particular, when taken together with our continuum flux estimate at 625 keV, the results are consistent with a flux excess in the region of the expected γ-ray lines from ^{56}Co decay. The chance probability for obtaining excesses as large as those observed at 847 and 1238 keV is 1% assuming a power law continuum flux with spectral index $\alpha = -0.9$ and using a flux normalization (with errors) determined from the measured flux of $0.56 \pm 0.22 \times 10^{-5}$ (cm^2 s kev)$^{-1}$ at 625 keV. An excess in the region of the 847 and 1238 keV lines will include both line photons and a contribution from forward scattered Compton photons. To estimate the unscattered line photon intensity it is thus necessary to subtract off the forward scattered contribution assuming a specific model for the depth distribution of ^{56}Co in the supernova remnant.

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