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A SEARCH FOR GAMMA-RAY LINES FROM NOVA CYGNI 1975, NOVA SERPENTIS 1970, AND THE CRAB NEBULA*

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ABSTRACT

A balloon-borne γ-ray telescope employing a large-volume lithium-drifted-germanium detector as the central element was flown in an attempt to detect γ-ray lines from two recent nova explosions and from the Crab Nebula. The energy range covered was 100 keV to 5 MeV. No lines were detected from the novae, even though a sensitivity relevant to current theories of explosive nucleosynthesis was achieved. The Crab continuum was detected between 100 keV and 1 MeV. Evidence for a line feature from the Crab Nebula at 400 ± 1 keV is presented. Such a line may be produced by positron annihilation at the surface of the Crab neutron star.

Subject headings: gamma rays: general — nebulae: Crab Nebula — stars: neutron — stars: novae

I. INTRODUCTION

In late 1973, a joint Bell Laboratories–Sandia Laboratories group was organized for the purpose of doing nuclear γ-ray line astronomy from a balloon platform, employing a large-volume lithium-drifted-germanium [Ge(Li)] crystal as the primary detector. The original scientific motivation for the project came from theoretical calculations concerning explosive nucleosynthesis in supernova and nova detonations (Schramm and Arnett 1973) and also from the galactic center observations of Johnson and Haymes (1973) and Haymes *et al.* (1975), using NaI detectors.

During the latter part of the 1960s and early 1970s, very large and fast computers became available for general use. This made it possible to follow the complex nuclear reaction matrix that takes place when a highly evolved star explodes and hydrodynamically expands. A remarkable result of these calculations was that many of the low- and intermediate-mass elements were produced in the correct cosmic abundance. This lent great credence to the idea that these elements are made explosively. Our primary goal was to provide some observational basis for this theory. The calculations indicated that many of the stable species should be produced first as unstable radioactive elements that decay, often with the emission of characteristic γ-ray lines (Clayton and Hoyle 1974). The unequivocal detection of even a single γ-ray line from explosively produced radioactive matter would represent a substantial breakthrough in this area. To this end, in the experiment to be described, we searched for γ-ray lines between 100 keV and 5 MeV from Nova Serpentis 1970 and Nova Cygni 1975 with an energy resolution better than 5 keV. No lines were detected from either nova, even though a sensitivity relevant to current theories of explosive nucleosynthesis was achieved.

In addition, we successfully observed the γ-ray continuum from the Crab Nebula between 100 keV and 1 MeV. A possible line feature at 400 keV was detected superposed on this continuum. It is suggested that this result, if verified, may be due to positron annihilation at the surface of the Crab neutron star.

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II. THE INSTRUMENT

The γ-ray telescope was designed around the largest single Ge(Li) crystal that Ortec, Inc., could provide. The limit of Ortec's capability at that time turned out to be a cylinder about 6.3 cm in height and about 4.7 cm in diameter with an active volume of about 92 cm^3. In the design of the physical telescope and the electronics associated with the germanium detector, we worked closely with Ball Brothers, Inc. Figure 1 is a schematic diagram of the telescope.

The procedure in designing the cryostat was to adhere as closely as possible to commercial design, using only high-vacuum materials and liquid-nitrogen-cooled molecular sieve material to provide the vacuum. Our detector operated for many months without showing any signs of performance degradation. The Ge(Li) temperature is typically 85 K. The liquid-nitrogen Dewar is a 30 liter Minnesota Valley Engineering Company commercial Dewar modified for additional mechanical strength. The hold time for the flight system is about four days.

Surrounding the central detector assembly are 184 kg of active NaI provided in three sections by Harshaw, Inc. These shield crystals are operated in

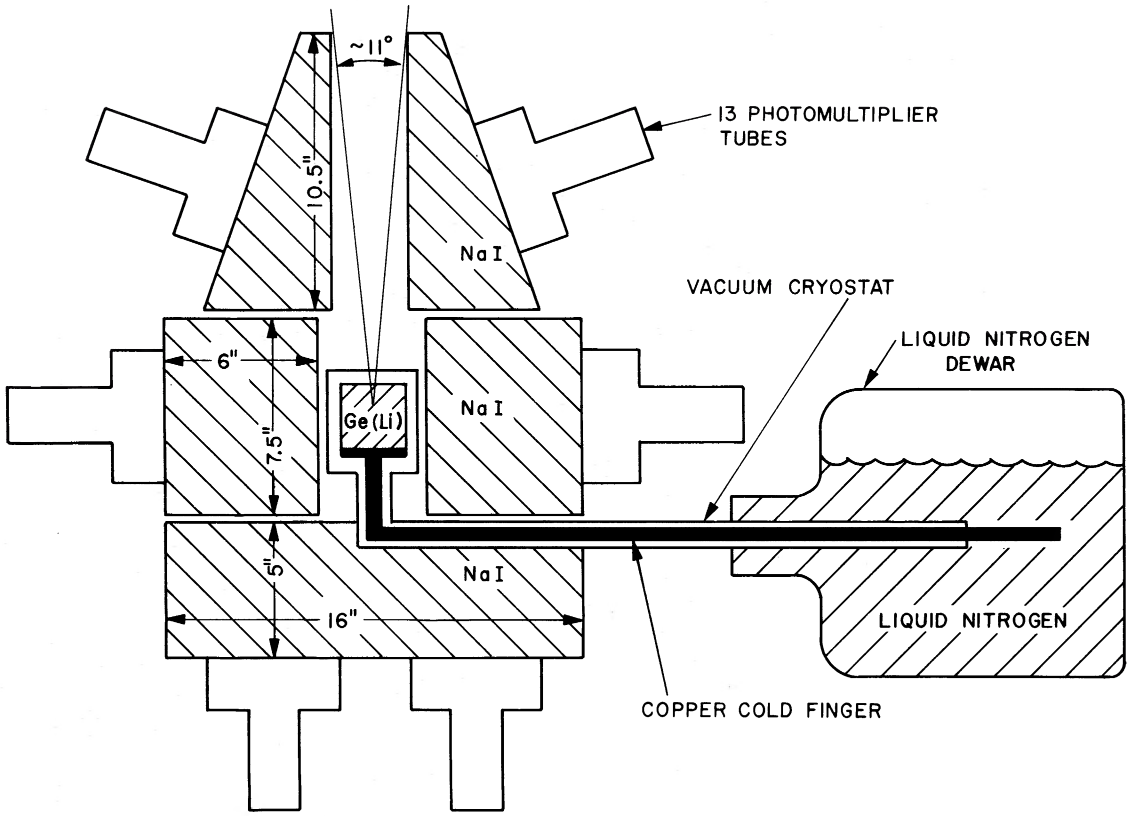

FIG. 1.—Schematic diagram of the apparatus

anticoincidence with the Ge(Li) detector and perform three separate functions. First, by detecting any Compton scattered γ-rays, the shield ensures that only full-energy events in the Ge(Li) are analyzed. Second, the opening in the NaI shield defines the field of view, i.e., it acts as a collimator. The effective entrance aperture of the collimator increases slowly with energy from 11° full width at half-maximum (FWHM) at 50 keV to 13° FWHM at 1.33 MeV. Third, the NaI shields the Ge(Li) detector from the large atmospheric γ-ray background. The energy resolution of the individual sections of the shield was about 20% at 0.662 MeV.

Ge(Li) pulses not vetoed by a coincident shield pulse pass through a preamplifier and a shaping amplifier, and are finally analyzed and stored in the memory of a 4096-channel pulse-height analyzer. The design of this circuitry was provided by Ball Brothers, Inc., and is described in the literature (Smeins and Juergens 1974). The energy resolution of the system below 2 MeV was 3.4 keV FWHM.

Figure 2 is a simplified block diagram of the circuitry. The upper-level discriminator trigger was set at 4.8 MeV; its gate width was 38.6 μs. The lower-level discriminator trigger level was set at 86 keV; its gate width was 4.6 μs. These trigger levels were adjustable in flight and were set so that each contributed a dead time of roughly 10% to the counting circuitry.

The engineering design and construction of the alt-azimuth pointing system, gondola, power system, and telemetry system were done at Sandia Laboratories. A more detailed description of these systems is given in the Appendix. Pointing accuracy was about 1°, much better than the telescope aperture. This was verified in flight by commanding a light-sensing element with field of view about 1° to point at the Sun.

III. SYSTEM TESTING AND FLIGHT CHARACTERISTICS

The system was extensively characterized in the laboratory with a series of 14 radioactive sources obtained from the National Bureau of Standards that spanned the energy range 0.059–1.836 MeV. Monte Carlo calculations of the full energy peak crystal efficiency at these energies agreed with experimental results after multiplication by a constant factor 0.90 ± 0.02; the code was then used to calculate efficiencies at other energies. A wealth of experimental information was accumulated concerning such properties as γ-ray detection efficiency, energy resolution, angular resolution, stability, effectiveness of the shield in removing the Compton tail from the Ge(Li) spectra, and dead-time corrections. In addition, the system underwent a substantial amount of testing in environmental chambers both at Sandia Laboratories and at Holloman Air Force Base. The temperature

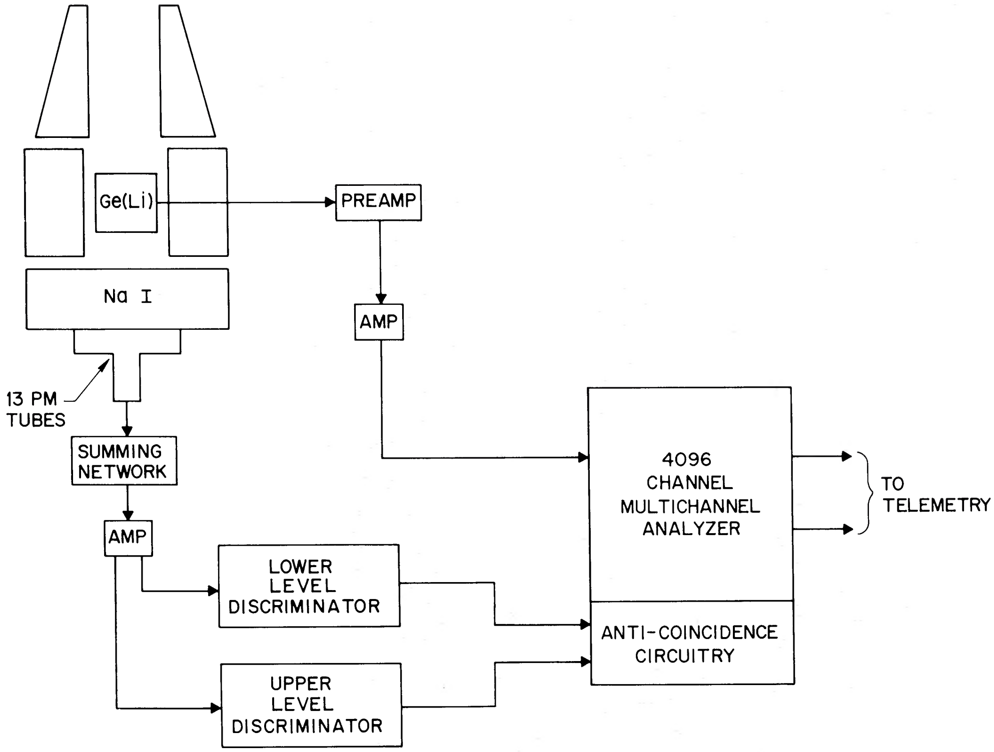

FIG. 2.—Simplified block diagram of the counting circuitry

and the vacuum properties of the upper atmosphere were simulated and the total system performance was studied under these conditions. Several problems were revealed by these tests and were subsequently corrected.

A preliminary flight of the complete γ-ray telescope assembly was made 1975 October 9. The general engineering viability of the entire system was established during this flight. However, two serious failures forced its termination about 10 hours after launch: (1) damage to telemetry antennae at launch resulted in erratic communication with the balloon; and (2) the azimuth drive system failed. It was also observed that the anticoincidence shield was not functioning properly. The months after the preliminary flight were used to correct these failures and to upgrade the entire system in several ways indicated by its observed performance characteristics. A second flight, during which real astrophysical data were accumulated, occurred 1976 May 10–11. The second flight was reasonably successful. About 20 hours of useful astronomical data were accumulated before the flight was terminated because of proximity to the Mexican border. The system was recovered near Rock Springs, Texas.

Both flights were made with the assistance of the Air Force Geophysics Laboratory Balloon Group and utilized 26 million cubic feet (7.4×10^5 m^3) Winzen balloons to carry the payload and ballast to altitudes varying between 36 and 39 km. Both flights were launched at dawn from Holloman Air Force Base in Alamogordo, New Mexico, at about the time of the upper atmosphere wind turnaround. Sufficient ballast and batteries were carried each time to allow for a flight of several days. The command and data-acquisition facilities were mounted in a mobile telemetry van, which followed the balloon on the ground when necessary to keep it within telemetry range ($\sim$650 km). An Air Force plane was also used each time to provide continuous and precise position information.

The count rate in the upper-level shield discriminator during the second flight was about 3 kHz; in the lower-level discriminator it was about 17 kHz. In the Ge(Li) detector the count rate for events above about 90 keV was about 300 Hz; net rate for unvetoed events, however, was only about 3 Hz. Aside from a period of approximately 3 hours when the telemetry signal was erratic, no serious system failures were encountered. The erratic signal has since been identified as a hardware problem. Data were obtained from Nova Cygni 1976, Nova Serpentis 1970, and the Crab Nebula. These data are discussed below.

IV. EXPERIMENTAL RESULTS

a) *The Crab Nebula*

Data were accumulated in alternate 20 minute target-background segments, with the telescope rotated in azimuth by 180° but maintained at the same zenith angle for the background measurements. Seven

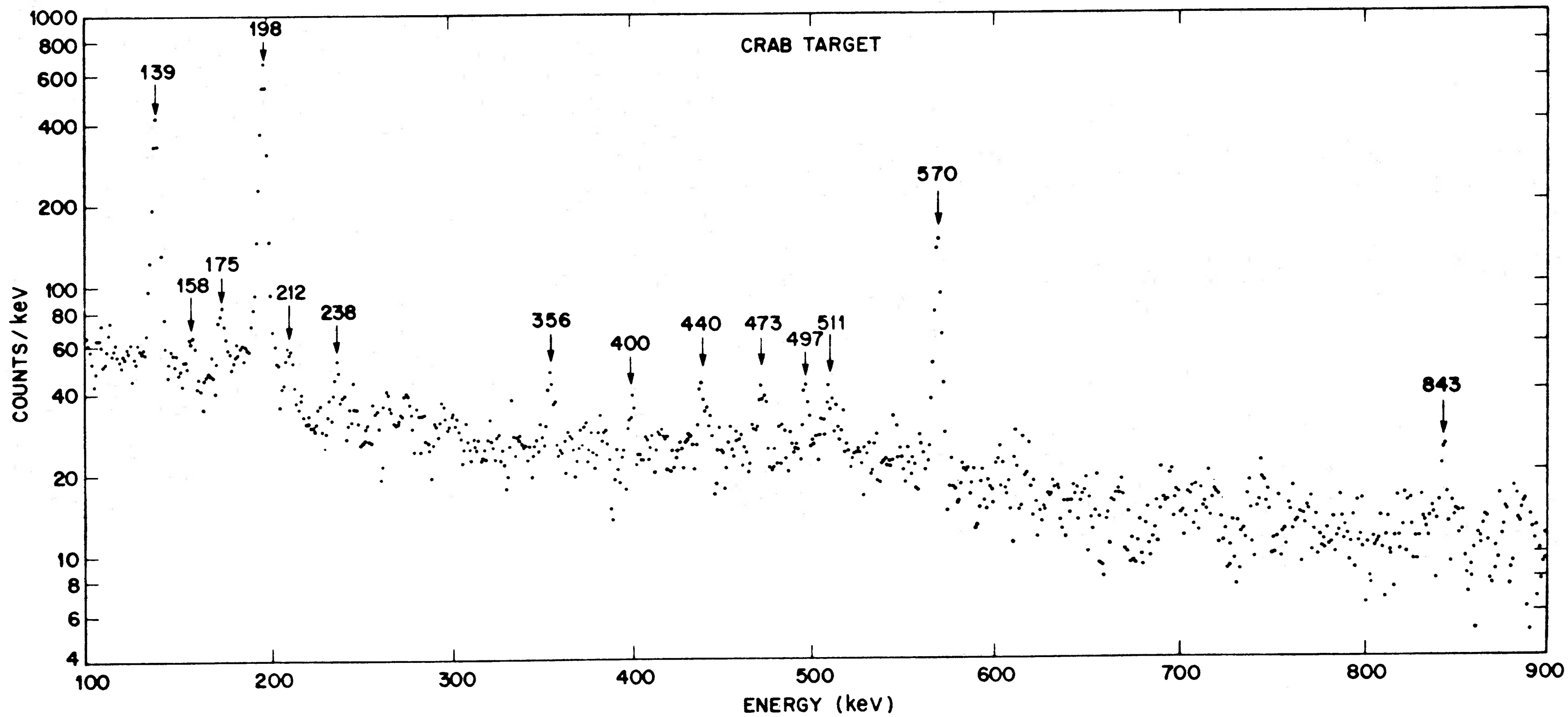

FIG. 3*a*.—Energy spectrum between 100 and 900 keV for the sum of all Crab target runs. Raw data corrected only for drifts in energy calibration (see text). Each dot represents a 1 keV energy bin. A real line should contain at least five dots above background.

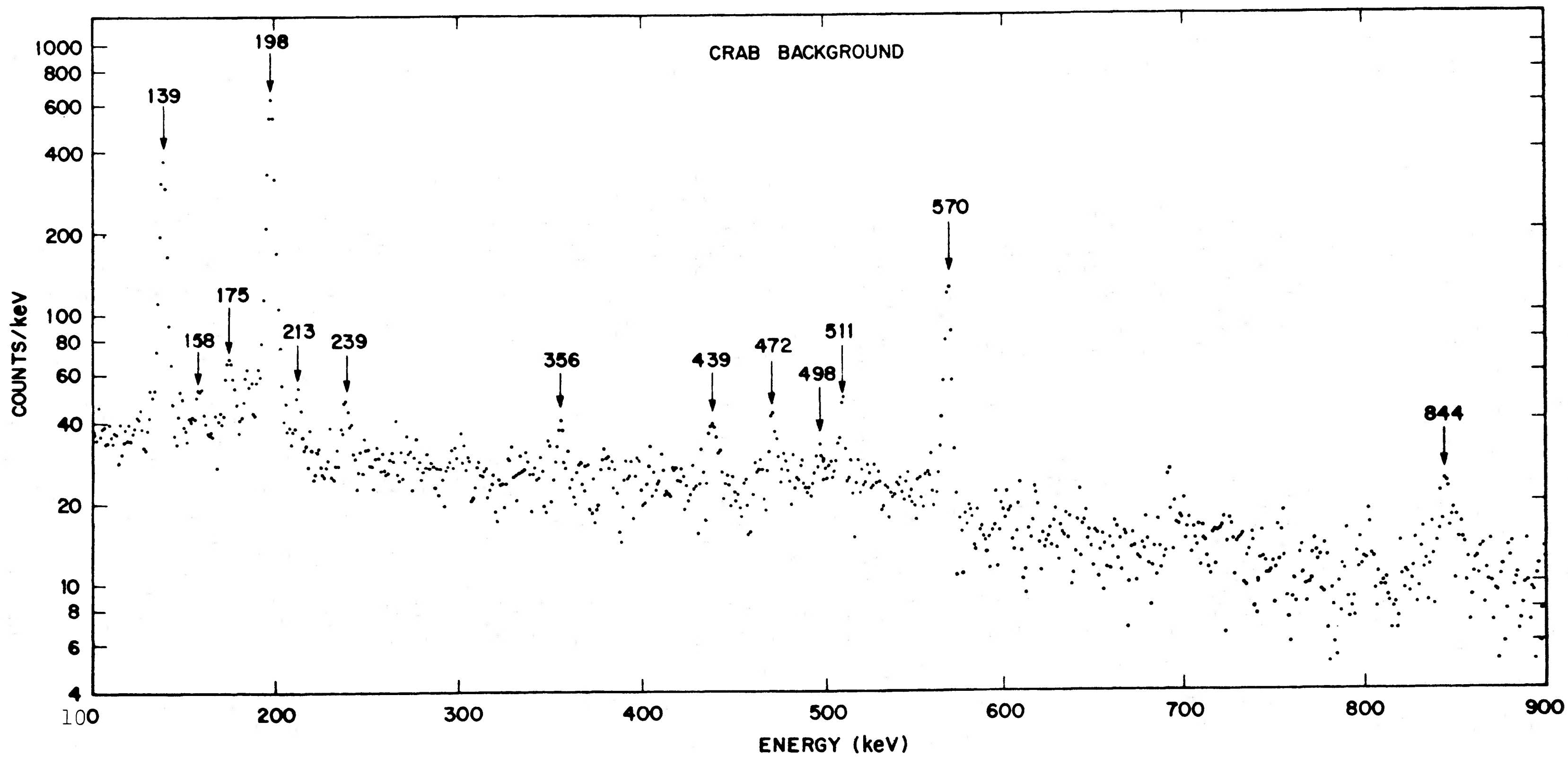

FIG. 3b.—Energy spectrum between 100 and 900 keV for the sum of all Crab background runs. See Fig. 3a legend.

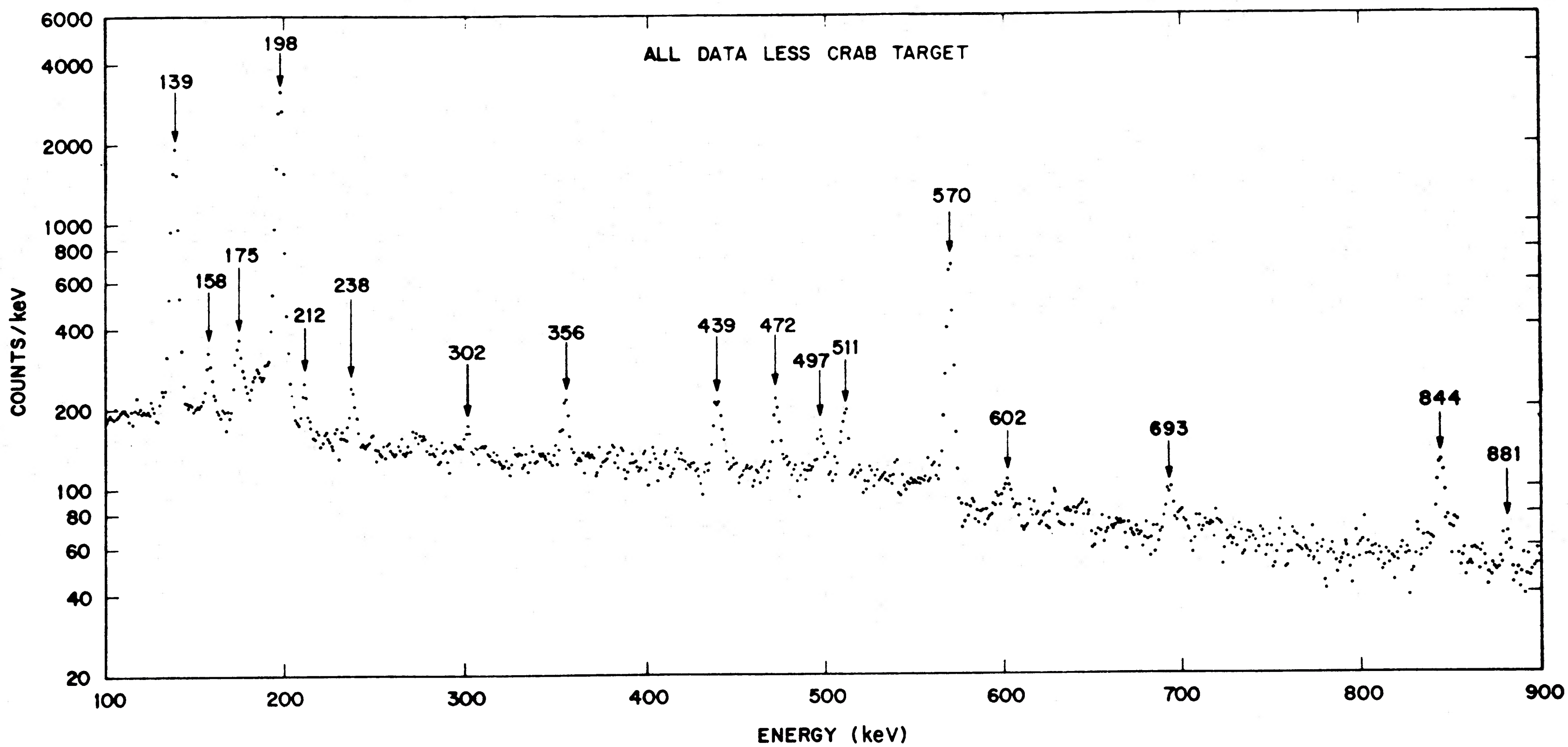

FIG. 3c.—Energy spectrum between 100 and 900 keV for the sum of all experimental runs other than Crab target runs. See Fig. 3a legend.

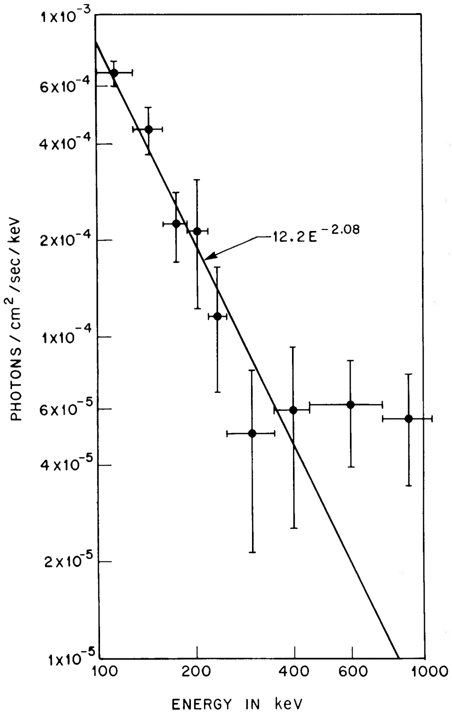

FIG. 4.—Energy spectrum of the Crab Nebula's total emission at the top of the atmosphere. *Solid line*, power law that best fits the experimental data. Raw data corrected for atmospheric attenuation, detector efficiency, system dead time, statistical averaging, and drifts in energy calibration (see text). Error bars are statistical.

complete and one shortened Crab target and Crab background segment pairs were obtained.

In Figures 3*a*, 3*b*, and 3*c* we show energy spectra for the sum of all the Crab target runs, the sum of all the Crab background runs, and the sum of all runs other than Crab target runs accumulated during the flight. Comparison of Figures 3*a* and 3*b* shows the detection of continuum radiation from the Crab Nebula at the low-energy end of the record.

In Figure 4, the Crab Nebula target-background difference spectrum extrapolated to the top of the atmosphere is plotted between 100 keV and 1 MeV. The data have been lumped here into 30, 100, and 300 keV bins to reduce statistical scatter. Beyond 1 MeV, the quality of the continuum data has degenerated to the point that the spectrum becomes consistent with zero net counts from the Crab. This spectrum is the sum of both the pulsed and the continuous radiation from the Crab, which our experiment was unable to separate. Although there is a hint of an "excess" near 1 MeV which has been the subject of recent controversy (Baker *et al.* 1972; Schonfelder, Lichti, and Moyano 1974; Gruber 1975; Walraven *et al.* 1975; Carpenter, Coe, and Engel 1976), the data are statistically compatible with the best-fit power law, which is also shown. (The chi-squared value for this fit is 11.4 with eight degrees of freedom; the probability of exceeding this value by chance is 18%.) The power-law fit falls just within the error bound of recent measurements by Walraven *et al.* (1975) and Carpenter, Coe, and Engel (1976). In making comparisons between experiments performed at different times, however, one should bear in mind the large temporal variations recently reported in much higher energy radiation from the Crab by Greisen *et al.* (1975) and Grindlay, Helmken, and Weekes (1976). The high-energy γ-ray source $\gamma(193, +3)$ is about 12° away from the Crab. Given the measured angular response and pointing accuracy of the telescope, our sensitivity to this source could have been only a few percent relative to the Crab.

In obtaining the spectrum we have made corrections to the raw data to account for the effects of atmospheric attenuation, detector efficiency, system dead time, statistical averaging, and drifts in the calibration of the energy axis during the course of the flight. Atmospheric attenuation corrections were based on altitude measurements provided by the Air Force Geophysics Laboratory Balloon Group, using a mean standard atmospheric model confirmed by Air Force rocket measurements performed on flight day. Photopeak detector efficiency as a function of energy was obtained from Monte Carlo calculations confirmed by laboratory measurements at 14 discrete energies. The coupled photon-electron transport code used takes into account photoelectric absorption shell by shell, Compton scattering, pair production, bremsstrahlung, fluorescence, positron annihilation, electron scattering and range straggling, Auger processes, and K shell ionization by electrons, in a complex multimedia geometry. The high effectiveness of the anticoincidence shield in suppressing the Compton tail plus the steepness of the energy spectrum justified the neglect of down-scattered photons, hence the use of simple efficiency factors rather than an elaborate matrix inversion. Dead-time corrections based on laboratory measurements were generally of the order of 20%, primarily because of veto counts in the NaI shield. Flux uncertainties from all these causes totaled less than 5%. They are not included in the much larger error bars shown in Figure 4, which are purely statistical. In the statistical averaging of different runs, target-background counting rate differences for each energy bin were corrected for atmospheric attenuation appropriate to that run pair and energy bin, and were weighted in inverse proportion to their associated variances. To correct for system drift in transforming from pulse-height-analyzer channel spectra to energy spectra, we first determined, in each record, the peak channels corresponding to five lines at known energies. These lines appeared clearly in all records. The energies were 1769.7, 1063.4, and 569.4 keV resulting from leakage through the shield of γ-rays from a ^{207}Bi calibration source mounted on the payload frame, plus 198 and 139 keV resulting from (n, γ) reactions within the Ge detector. Energies corresponding to other channels were then determined by linear interpolation or extrapolation.

The data were searched for sharp-line features superposed upon the continuum from the Crab

Nebula. An automated computer program searched both the target and background data for 5 keV wide bins containing greater than a 3 σ excess number of counts over what would be expected from the two adjacent 10 keV wide bins. The data were also plotted and scanned visually. Twelve lines which appear in both the Crab target and the Crab background data were detected. These are included in Table 1 along with tentative identifications. Table 1 lists all lines found at a 3 σ level of significance in a search of all data recorded ($\sim$15 hours of data). Aside from the ^{207}Bi calibration lines, most of the remaining lines can be understood in terms of cosmic-ray–induced nuclear transitions in the telescope structure. Many of these have been seen by other investigators. Chapman *et al.* (1972) list six background lines, Womack and Overbeck (1970) list 13, Jacobson *et al.* (1975) list 17, and we list 20 besides the three calibration lines. Although there is a high degree of overlap, each list (except for Chapman *et al.*'s) contains lines which are contained in no other list. Some of these are unidentified. The lists are not expected to be identical, since the detector efficiency and energy range, as well as the amount and location of material in the telescope structure, vary from experiment to experiment.

In addition to the 12 lines detected in both the Crab target and the Crab background data, one potential line feature has been detected at 400 $\pm$ 1 keV in the Crab target data but not in any of the background data. The Crab target and Crab background spectra in the vicinity of 400 keV, along with a spectrum that consists of a sum of all our data except for the Crab target segments, are shown in Figures 5*a*, 5*b*, and 5*c*. These spectra are raw data, corrected only for drifts in the energy calibration with time. It is believed that the telescope continuum at this energy is dominated by leakage of the atmospheric γ-ray background through the NaI shield together with neutron-induced interactions in the shield and detector. The fact that the feature appears in only the Crab target spectrum is taken as strong evidence that it is not a telescope artifact. It is also important that the line is evident in most of the individual target segments. The feature represents a 4.0 σ deviation above telescope continuum as determined from the 387.5 to 397.5 keV energy bins and the 402.5 to 412.5 keV energy bins of the target spectrum. When the Crab target spectrum is extrapolated to the top of the atmosphere, the feature represents a 3.5 σ deviation above the telescope continuum. A 4.0 σ deviation occurs once in 32,000 tries, and a 3.5 σ deviation occurs once in 4300 tries. Here, in effect, we have made of the order of 1000 independent tries to find a line; therefore the probability that the feature is a statistical accident is small but not negligible. This matter can be settled only by further experimentation. After being corrected for atmospheric attenuation and dead time,

TABLE 1

LINES OBSERVED IN THE TARGET AND BACKGROUND SPECTRA*

Energy (keV) ± 1	Rate (c/s)	Tentative Identification
139†.........	$(1.31 \pm 0.02) \times 10^{-1}$	^{74}Ge(n, γ)^{75}Ge
158........	$(8.49 \pm 0.86) \times 10^{-3}$	^{76}Ge(n, γ)^{77}Ge
175†.......	$(1.12 \pm 0.09) \times 10^{-2}$	^{70}Ge(n, γ)^{71}Ge
198†.......	$(2.29 \pm 0.02) \times 10^{-1}$	^{70}Ge(n, γ)^{71}Ge
213........	$(4.89 \pm 0.83) \times 10^{-3}$	?
239†‡......	$(6.46 \pm 0.74) \times 10^{-3}$	?
301........	$(2.24 \pm 0.65) \times 10^{-3}$	^{73}Ge(n, n')^{73}Ge
355†‡......	$(6.69 \pm 0.70) \times 10^{-3}$	^{56}Fe(n, γ)^{57}Fe (?)
439†.......	$(8.21 \pm 0.71) \times 10^{-3}$	^{23}Na(n, n')^{23}Na
473†.......	$(7.62 \pm 0.69) \times 10^{-3}$	^{23}Na(n, γ)^{24}Na and/or ^{76}Ge(n, γ)^{77}Ge
497†.......	$(3.62 \pm 0.64) \times 10^{-3}$	?
511‡.......	$(6.28 \pm 0.67) \times 10^{-3}$	$e^+ + e^-$
570†.......	$(4.41 \pm 0.11) \times 10^{-2}$	^{207}Bi(EC)§ ^{207}Pb
601........	$(2.27 \pm 0.52) \times 10^{-3}$	^{74}Ge(n, n')^{74}Ge
693........	$(2.53 \pm 0.49) \times 10^{-3}$	^{72}Ge(n, n')^{72}Ge and/or ^{56}Fe(n, γ)^{57}Fe
844†.......	$(5.25 \pm 0.53) \times 10^{-3}$	^{27}Al(n, n')^{27}Al and/or ^{56}Fe(n, n')^{56}Fe
881........	$(1.41 \pm 0.41) \times 10^{-3}$	^{23}Na(n, γ)^{24}Na
1014........	$(1.70 \pm 0.41) \times 10^{-3}$	^{27}Al(n, n')^{27}Al
1063†.......	$(6.78 \pm 0.12) \times 10^{-2}$	^{207}Bi(EC)§ ^{207}Pb
1117‡.......	$(1.55 \pm 0.31) \times 10^{-3}$	^{65}Cu(n, n')^{65}Cu (?)
1460‡.......	$(1.87 \pm 0.27) \times 10^{-3}$	^{40}K(β^+)^{40}Ar
1770†.......	$(7.38 \pm 0.43) \times 10^{-3}$	^{207}Bi(EC)§ ^{207}Pb
2122........	$(7.10 \pm 0.17) \times 10^{-4}$	?

* Quoted count rates were determined by searching all data recorded (approximately 15 hours).

† Lines marked with a dagger were seen at a 3 σ level in the Crab target data and in the Crab background data.

‡ Lines marked with a double dagger were seen on the ground before the flight, as were lines at 911 and 1763 keV.

§ EC is electron capture.

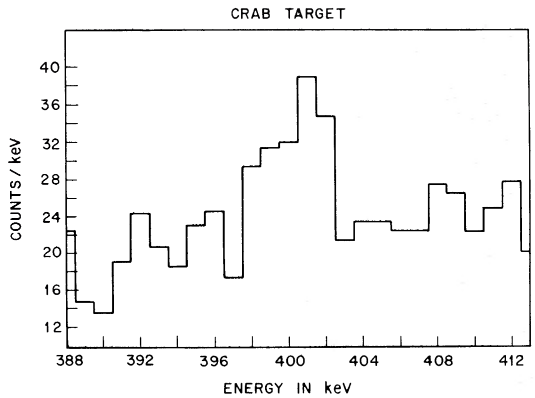

FIG. 5*a*.—The Crab target energy spectrum in the vicinity of 400 keV. Raw data corrected only for drifts in energy calibration (see text).

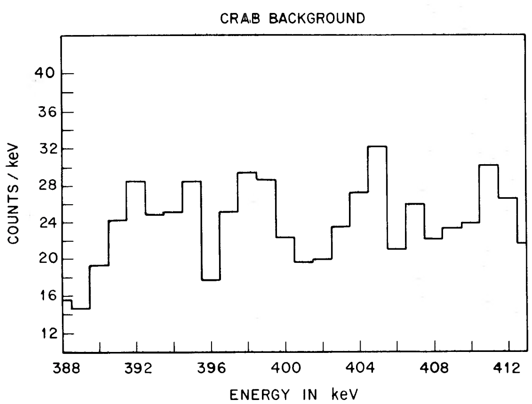

FIG. 5*b*.—The Crab background energy spectrum in the vicinity of 400 keV. Raw data corrected only for drifts in energy calibration (see text).

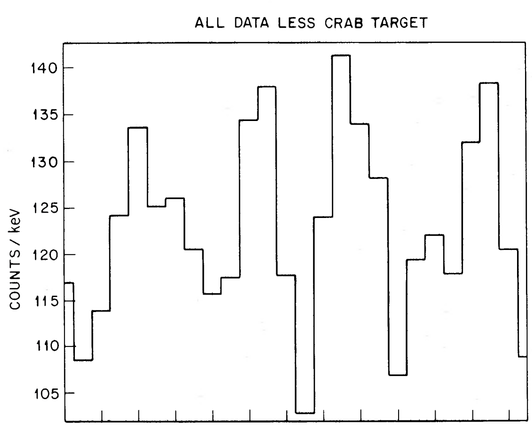

FIG. 5*c*.—Energy spectrum in the vicinity of 400 keV, including all data taken except for Crab target segments. Raw data corrected only for drifts in energy calibration (see text).

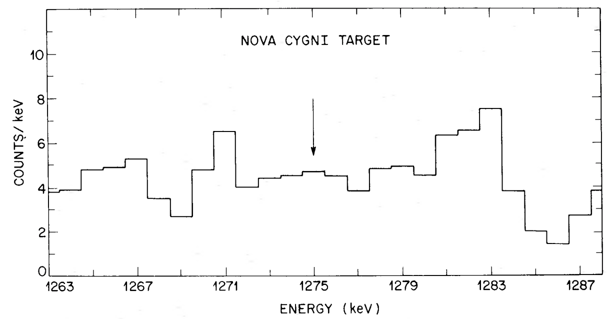

FIG. 6.—Nova Cygni target energy spectrum in the vicinity of 1275 keV. Raw data corrected only for drifts in energy calibration (see text).

the feature in Figure 3*a* corresponds to a line flux of $(2.24 \pm 0.65) \times 10^{-3}$ photons cm^{-2} s^{-1} incident upon the Earth with a width not more than 3 keV. Such a line flux could have produced a noticeable feature in the previously most sensitive searches for lines from the Crab Nebula (Walraven *et al.* 1975; Jacobson and Ling 1976). The absence of a clear indication of it in these earlier data signals a note of caution about accepting the reality of the present result.

b) *Nova Cygni 1975*

Nine target and nine background segments were obtained from this nova. No evidence for γ-ray emission of any kind from the nova is apparent in these data. The current theory of explosive nucleosynthesis in nova explosions (Clayton and Hoyle 1974; Truran 1975) predicts that the most intense γ-ray line occurring several months or more after the explosion will be the 1275 keV line that follows the decay of ^{22}Na to ^{22}Ne. Figures 6 and 7 show our measured energy spectra in the neighborhood of 1275 keV for the sum of all Nova Cygni target runs and for the sum of all Nova Cygni background runs.

Our data may be used to set a 2 σ flux limit on this line of not more than 1.0×10^{-3} photons cm^{-2} s^{-1} at the top of the atmosphere on 1976 May 10. The procedure used in obtaining this numerical value was to take the difference between the 5 keV bin centered

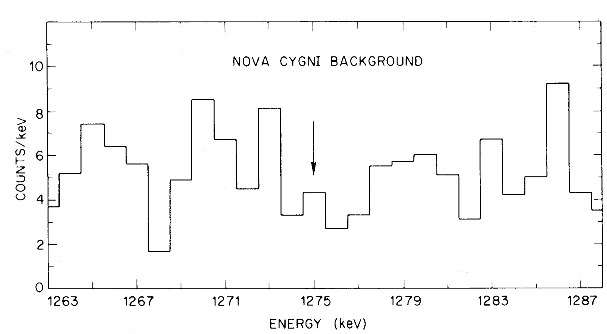

FIG. 7.—Nova Cygni background energy spectrum in the vicinity of 1275 keV. Raw data corrected only for drifts in energy calibration (see text).

on 1275 keV and one-fourth the sum of the two 10 keV bins on either side, to average this quantity with the appropriate statistical weights over all target runs, and to extrapolate to the top of the atmosphere as described above for the Crab continuum data. The same procedure was followed for an average over all runs *other* than Nova Cygni target runs. Neither procedure showed statistical evidence of a line. The variances of the two results were added to define the standard deviation, σ, quoted above.

c) Nova Serpentis 1970

Five target segments without corresponding background segments were obtained from this nova. Again, no evidence for γ-ray emission can be seen in the data. That part of our measured energy spectrum in the neighborhood of 1275 keV for the sum of all Nova Serpentis target runs is shown in Figure 8. The ^{22}Na 2σ flux limit is not more than 1.1×10^{-3} photons cm^{-2} s^{-1}, obtained as described above for Nova Cygni.

V. DISCUSSION AND CONCLUSION

Evidence has been presented for the existence of a γ-ray line at 400 ± 1 keV superposed upon the continuum radiation from the Crab Nebula. Counting statistics are clearly not sufficiently conclusive to rule out the possibility that the apparent line is merely a statistical accident. However, since the energy in question can be given an intriguing physical significance, we present the evidence and our tentative identification of the line in hopes of stimulating other experimenters to repeat the observation with more sensitive detectors of high-energy resolution.

Several mechanisms exist for generating positrons at or above the surface of the Crab neutron star (Ramaty, Borner, and Cohen 1973; Ruderman 1972). Positron annihilation in dense gases and solids usually results in the emission of 511 keV photons. Should this occur near the stellar surface, the photons would appear to us to be gravitationally redshifted. This measurement then determines $Z_{\text{Crab}} = 0.28$. Recent neutron star models can then be used to determine the mass of the Crab, yielding $\sim 1.4\, M_{\odot}$, which is not unreasonable (Borner and Cohen 1973; Ramaty, Borner, and Cohen 1973). For this hypothesis to be correct, $\sim 10^{41}$ positrons per second must be annihilating into 511 keV photons near the neutron star surface (assuming isotropic radiation), and the photons must then reach the Earth without significant Compton scattering. Varma (1977) has speculated that stimulated emission of annihilation photons may occur along magnetic field lines. Such a mechanism would reduce the required number of annihilations to $\sim 10^{40}$ positrons per second and would lead to the emission of a narrow line such as we observe.

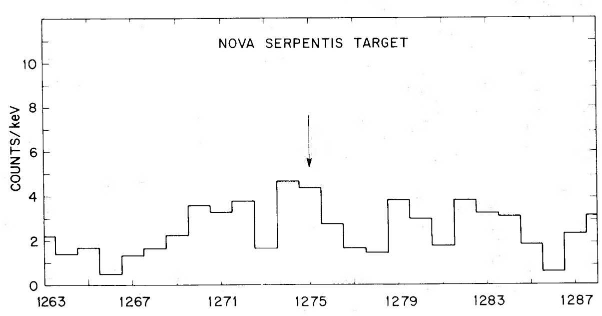

FIG. 8.—Nova Serpentis target energy spectrum in the vicinity of 1275 keV. Raw data corrected only for drifts in energy calibration (see text).

Before our first flight and before the explosion of Nova Cygni 1975, Truran (1975) provided the following prediction for the flux at the Earth in the 1275 keV ^{22}Na line produced by a nova event:

$$\Phi = \frac{8 \times 10^{-3} \exp(-t/3.8)}{R^2} \text{ photons cm}^{-2}\text{ s}^{-1},$$

where R is the distance to the nova in kiloparsecs and t is the time since the nova in years. The multiplicative coefficient above is proportional to the product of two poorly known factors. The first is the total amount of mass ejected from the star in the nova explosion. Observational values for this quantity generally fall in the range from 10^{-5} to 10^{-3} solar masses; the value used to obtain the numerical coefficient above was 10^{-4} solar masses. The second and even more uncertain factor is the enhancement of mass-22 nuclei in the ejected material relative to solar system abundance. Very large values for this quantity result from theoretical hydrodynamic calculations of nova events; the value used to obtain the numerical coefficient above was 10^2, which was considered at that time to be conservative. Taking the distance to Nova Cygni 1975 as 1.5 kpc (Gallagher and Ney 1976), we determine a predicted flux in 1976 May of 3×10^{-3} photons cm^{-2} s^{-1}. Our 2σ experimental upper limit for the flux in the energy bin 1275 ± 2.5 keV is only 1.0×10^{-3} photons cm^{-2} s^{-1}. Since the value used above for the total mass ejected in the Nova Cygni event is now believed to be fairly accurate (Gallagher and Ney 1976), we conclude that the enhancement factor is probably at least half an order of magnitude less than 10^2. This is consistent with the results of more recent hydrodynamic modeling of nova explosions (Starrfield 1976).

Using a distance to Nova Serpentis 1970 of 0.9 kpc, we determine a predicted flux in 1976 May of 2×10^{-3} photons cm^{-2} s^{-1}. Our 2σ experimental upper limit is 1.1×10^{-3} photons cm^{-2} s^{-1}. The constraint on the theoretical parameters is again significant, especially as the true distance may be somewhat less than we assumed.

Table 2 lists the 2σ line flux limits established by our experiment at a distributed set of energies for each of our three targets. Most of the numerical values were determined in the manner already described for Nova Cygni 1975 at 1275 keV. In those cases (marked with an asterisk) where line structure occurred near

TABLE 2

GAMMA-RAY LINE FLUX LIMITS: VARIOUS SOURCES AND ENERGIES

ENERGY (keV)	2 σ UPPER LIMIT (photons cm^{-2} s^{-1}) Nova Cygni 1975	Nova Serpentis 1970	CRAB NEBULA
120	0.9×10^{-3}	1.3×10^{-3}	1.2×10^{-3}
180*	1.2×10^{-3}	...	1.5×10^{-3}
270	0.8×10^{-3}	1.3×10^{-3}	1.1×10^{-3}
390	1.0×10^{-3}	1.5×10^{-3}	1.5×10^{-3}*
511*	1.8×10^{-3}	...	2.4×10^{-3}
535	1.2×10^{-3}	1.8×10^{-3}	1.5×10^{-3}
650	1.0×10^{-3}	1.6×10^{-3}	1.3×10^{-3}
820	1.1×10^{-3}	1.6×10^{-3}	1.4×10^{-3}
847*	1.7×10^{-3}	...	2.2×10^{-3}
1040	1.2×10^{-3}	1.7×10^{-3}	1.6×10^{-3}
1275	1.0×10^{-3}	1.1×10^{-3}	1.1×10^{-3}
1330	0.8×10^{-3}	1.3×10^{-3}	1.0×10^{-3}
1630	0.8×10^{-3}	1.1×10^{-3}	1.1×10^{-3}
2000	0.8×10^{-3}	1.0×10^{-3}	0.9×10^{-3}
2500	0.8×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
3000	1.0×10^{-3}	1.2×10^{-3}	1.2×10^{-3}
3500	0.9×10^{-3}	1.4×10^{-3}	1.2×10^{-3}
4000	1.1×10^{-3}	1.5×10^{-3}	1.4×10^{-3}
4440	1.2×10^{-3}	1.6×10^{-3}	1.7×10^{-3}

* Energies marked with an asterisk lie near line structure. Flux limits for these energies were established by comparing individual target and background runs. (This was not possible for Nova Serpentis, for which background runs were not made.) Other flux limits were determined by comparison with the sum of all runs other than the target in question (see text).

the energy in question, however, the standard deviation was determined by comparing target runs individually with corresponding background runs only. This was necessary because the line structure, where it existed, was observed to be sometimes time-dependent. The standard deviation in these cases is correspondingly higher. The upper limits for the nova targets must be reckoned with by any future theory of explosive nucleosynthesis that may predict other γ-ray line emissions from nova explosions. In the case of the Crab, 2 σ line flux upper limits have also been established by other experimenters. Ling *et al.* (1977) report a value at 511 keV twice as large as the value we report. Walraven *et al.* (1975) report values at eight energies between 180 keV and 6130 keV that vary between half as large and twice as large as the values we report.

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APPENDIX

The collection, storage, and transmission of γ-ray spectra by the payload depend upon information transmission and processing through two radiofrequency links: the up-link, or command, system, and the down-link, or telemetry, system. These interactions are controlled by the operators through the ground-station computer.

The command link consists of a 100 watt FM transmitter currently operating at 416.6 MHz and a receiver mounted in the payload. The encoder and decoder are commercially purchased units which use PCM/PSK modulation of an 1800 Hz carrier to transmit either 16 bit digital data or one of 48 momentary relay latching commands. The digital capability of the system is used to transfer 12 bit words to one of 16 registers in the payload. The command system will operate reliably to the radio horizon which, at 40 km altitude, is approximately 700 km.

The telemetry link consists of two 3 watt FM transmitters on the payload at frequencies of 230.4 and 248.6 MHz. The transmitter in use is modulated by a PCM encoder at 64,000 bits per second. The ground station includes antennae with selectable gains of 8 or 16 dB and two telemetry receivers. The range of the telemetry system also extends to the radio horizon. The PCM format—which includes four subframes—contains state-of-health data, from scalers that monitor the Ge(Li) and shield rates, command-link duplex data, and data from the payload memory.

The γ-ray events detected by the telescope are analyzed by a 12 bit analog-to-digital (A-to-D) converter and accumulated in a 10 bit by 4096-word random access memory. This memory was specifically designed for this application and uses p-MOS dynamic memory elements. The A-to-D converter and memory form a 4096-channel pulse-height analyzer. The mode of the analyzer (standby, reset, accumulate, or readout) is controlled by the command system. In the readout mode the memory data are transmitted sequentially by the telemetry system. A period of approximately 11 s is required for a complete cycle through the memory.

The γ-ray telescope is mounted on an azimuth/elevation mount. Power is applied to the elevation drive system only when the pointing angle is updated. The remainder of the time the elevation angle is fixed with respect to the payload, which therefore must be leveled and balanced before flight. The orientation of the payload with respect to the gravity vector is sensed during flight by inclinometers. The azimuth of the telescope is actively controlled by using a servo loop and a single-axis magnetometer as a sensor. Restoration torque is provided by a direct-drive DC motor, which torques against the outer frame of the gondola. Inertial damping is provided by a single-axis rate gyro. The azimuth angle is changed by rotating the magnetometer with respect to the telescope. Power is applied to the magnetometer rotation servo only when the azimuth angle is updated. When tracking a celestial target, the telescope mount must be updated periodically because of the diurnal rotation of the Earth and the movement of the balloon.

The output of the ground-station telemetry receivers is conditioned and converted to bi-phase PCM by a bit synchronizer and recorded on magnetic tape. Time code, voice annotation, and the command encoder output are also recorded. The playback output of the recorder is applied to a PCM synchronizer, which is interfaced with the ground-station computer. The computer checks and displays state-of-health data and displays the counting rates in the Ge(Li) detector and shield. Upon command, the computer accepts data from the payload memory, checks parity, and stores the data in core. Up to four spectra from the payload memory may be stored in core. The computer will also, upon command, perform algebraic manipulations on the stored data and generate a plot of selected spectra. The computer periodically updates the payload pointing system by using payload position and the right ascension and declination of the source. These data must be input initially by the operator. The required commands to the payload are transmitted by the computer and checked as they are returned in the telemetry data.

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