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BALLOON OBSERVATION OF THE X-RAY SPECTRUM OF THE CRAB NEBULA ABOVE 15 keV*

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A concentrated source of cosmic x rays with energies above 15 keV has been observed in a balloon flight conducted on 21 July 1964. The sky was scanned with a directional x-ray detector rotating about a vertical axis, and a peak in the counting rate occurred when the Crab Nebula was within the field of view of the detector. Since the Crab Nebula is known to emit x rays near 4 keV,[1] it is probable that the higher energy x rays observed in this experiment came from the same object. Assuming this to be the case, the data yield an approximate determination of the x-ray spectrum of the Crab Nebula in the energy range from 15 to 60 keV.

The x-ray detector was a scintillation counter employing a NaI(Tl) crystal 97 cm^2 in area and 1 mm thick. A collimator of brass slats gave a field of view $\pm 16°$ wide in one direction and $\pm 55°$ wide in the other. A Mumetal shield and a layer of $\frac{1}{16}$-inch lead sheet covered the sides and back of the photomultiplier. The pulses were fed to a five-channel differential pulse-height analyzer and scaler. The indicator lights from the scalers were photographed on a moving film together with the indicator lights of a scaler driven by a crystal-controlled oscillator which provided the time base of the experiment. The apparatus was suspended so that the detector axis was inclined at 35° to the vertical, and the $\pm 16°$ direction of the field of view was horizontal. The payload was rotated by a line twister which had a period of 9.3 minutes. The azimuth of the detector axis was determined every 20 seconds from a magnetometer reading, and intermediate values were obtained by interpolation.

The detector was calibrated with 25- and 65-keV x rays. At both energies the distributions in height of pulses going into the five-channel analyzer had half-widths at half-maximum of 37%. Using the centers of these pulse-height distributions as calibration standards we adjusted the discriminators to record pulses of the average size produced by 9- to 15-keV x rays in channel I, 15-28 keV in channel II, 28-42 keV in channel III, 42-62 keV in channel IV, and greater than 62 keV in channel V. The energy loss of a minimum-ionizing particle traversing the crystal was greater than 600 keV so that most pulses produced by charged cosmic rays were recorded in the fifth channel only.

The balloon was launched at dawn from Palestine, Texas. It reached a maximum pressure altitude of 2.9 mbar about 3 hours before the meridian transit of the Crab Nebula, and then gradually descended, passing below 5 mbar near the time of transit.

In order to search for x-ray emission from a specific object with maximum sensitivity, it was necessary to combine the data from many rotations, taking into account the diurnal motion of the object. This was done by tabulating separately the number of counts and the exposure time for each interval of relative azimuth measured from the object, and then dividing the total counts by the total exposure time to find the average counting rate in each of the intervals of relative azimuth. When this procedure was applied for the case of the Crab Nebula to the data obtained at pressure altitudes above 3.9 mbar, it gave the results summarized in Fig. 1. During this 80-minute period of observation the zenith angle of the Crab Nebula decreased from 35° to 18°, and its azimuth increased from 96° to 118° from geographic north. Distinct peaks in the counting rates are seen in channels II, III, and IV at a relative azimuth about 10° greater than that which would be expected for a peak due to the Crab Nebula if the error in determining the magnetic azimuth were negligible. Inspection of the payload and calibration of the magnetometer indicated the presence of systematic errors in the magnetic azimuth determination that are large enough to account for the discrepancy.

The shape of a peak due to a concentrated source was measured in the laboratory by suspending the payload as in flight and rotating it uniformly past the direction of an artificial 25-keV x-ray source mounted above it. The expected peak shapes for a source at a zenith angle of 30° are indicated in Fig. 1. Also indicated for each peak is the number of standard deviations by which the combined counting rate in the central three intervals exceeds the grand average around the entire circle. The probability of these peaks occurring by statistical fluctuation is negligible, and it seems necessary to conclude that they are caused by a source of x rays in a direction near and, most likely, coincident with the Crab Nebula.

Information concerning the spectrum of the observed x rays can be obtained from the data, provided that proper allowance is made for absorption in the atmosphere. Assuming that the source is the Crab Nebula one can calculate the thickness of the atmosphere along the line of sight. When a given object crosses the center line of the rectangular field of view, the expected counting rate of pulses with sizes in the interval from H_1 to H_2 can be expressed by the formula

$$R = A(\theta)\int_{H_1}^{H_2} dH \int_0^\infty j(E)\exp[-\mu_{\text{air}}(E)x] \times\{1-\exp[-\mu_{\text{NaI}}(E)t]\}[1/\sigma(2\pi)^{1/2}] \times\exp[-(E-H)^2/2\sigma^2]dE, \quad (1)$$

in which $A(\theta)$ is the projected area of the detector in a direction lying on the center line at an angle θ from the detector axis, $j(E)dE$ is the intensity of x-ray photons with energy E in dE, $\mu_{\text{air}}(E)$ and $\mu_{\text{NaI}}(E)$ are the mass absorption coefficients at energy E of air and

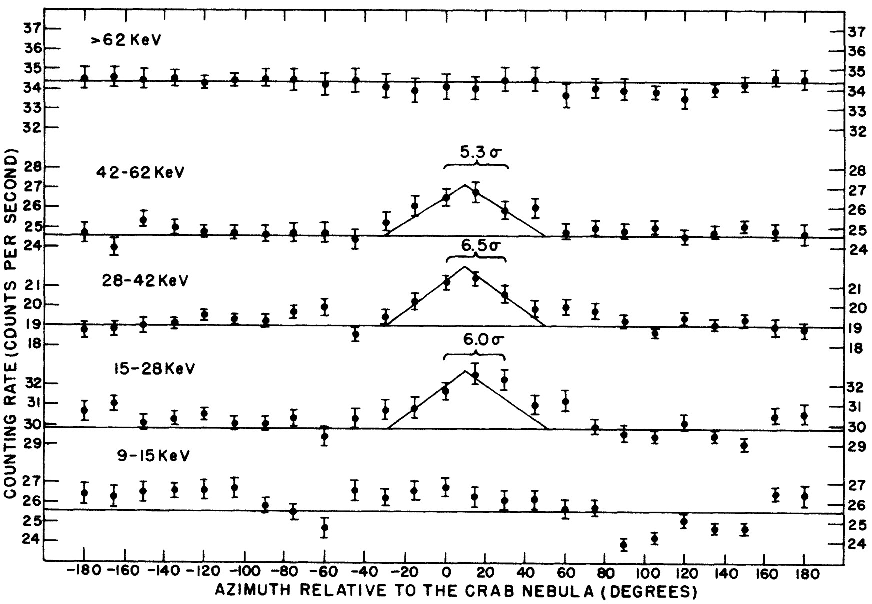

FIG. 1. Average counting rates in the five pulse-height channels versus the magnetically determined azimuth relative to that of the Crab Nebula. The peak near 0° in channels II, III, and IV is attributed to the x-ray source in the Crab Nebula. The cause of the variations in channel I is not known, and may be instrumental.

sodium iodide, respectively, x is the thickness of the atmosphere along the line of sight, and t the thickness of the sodium-iodide crystal. In this expression the energy resolution of the detector is represented by a Gaussian response function with a standard deviation σ.

The differences between the average background counting rates and the average peak rates observed as the source crossed the field of view were determined for each of the five pulse-height channels during the portion of the flight when the atmospheric thickness along the direction to the Crab Nebula was between 3.5 and 4.0 g cm^{-2}. These differences, which are the counting rates attributable to the Crab Nebula, are shown in Fig. 2. The lines join the expected values calculated for three assumed incident differential number spectra given by the formula

$$j(E)=j_0(E/E_0)^{-\alpha-1}, \qquad (2)$$

with $\alpha = 1$, 2, and 3, and normalized to the observed value in channel III. The best fit for channels II, III, and IV is obtained with $\alpha = 2$. No peaks were observed in channels I and V, for which only upper limits are indicated in the Figure. It is evident that the spectral index above 60 keV is greater than 2.

The flux density $I(\nu)$, which is the energy incident per unit area, per unit time, and per unit frequency interval, is related to the number spectrum by the formula

$$I(\nu)=Ej(E)h, \qquad (3)$$

where $h=dE/d\nu$ is Planck's constant. Taking $\alpha = 2$ and adjusting the constants j_0 and E_0 to fit the rates observed in channel III, one finds for the flux density the expression

$$I(\nu)=I_0(\nu/\nu_0)^{-2}, \qquad (4)$$

where

$$I_0=(2.4\pm0.6)\times10^{-27}\text{ erg cm}^{-2}\text{ sec}^{-1}\text{ (cps)}^{-1}$$

and

$$\nu_0=7.2\times10^{18}\text{ cps}$$

over the range from 5.0×10^{18} to about 1.0×10^{19} cps, corresponding to the energy range from 20 to 40 keV. This result is plotted in Fig. 3, together with an upper limit of 1.2×10^{-28} erg cm^{-2} sec^{-1} $(cps)^{-1}$ at $\nu=2\times10^{19}$ cps (~80 keV) derived from the negative result in channel V. Also shown is a summary of the previous data on the electromagnetic spectrum of the Crab Nebula. The spectrum in the radio and optical regions was taken from the recent review of Moroz.[2] The optical portion is subject to considerable uncertainties due to poorly known corrections for interstellar absorption. The spectrum from 3×10^{17} to 10^{18} cps was computed from data of the Naval Research Laboratory group.[3]

The results of this experiment are new evidence against the idea that the x rays from the Crab Nebula are the blackbody emission from the surface of a neutron star. Previously, the

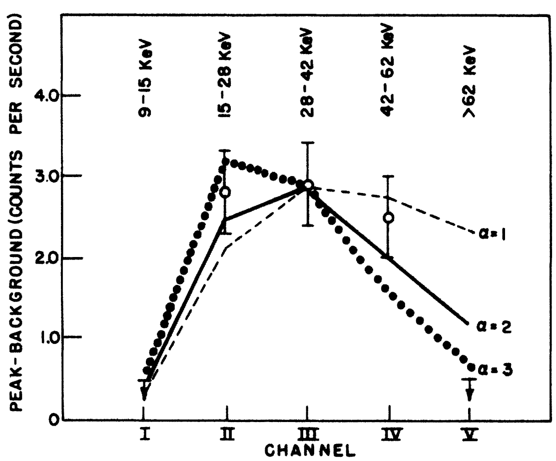

FIG. 2. Peak minus background counting rates from the observed source for the five pulse-height channels. Upper limits only are indicated for channels I and V. The dashed, solid, and dotted lines represent the expected variation in counting rates for incident spectra in the form of power laws with spectral indices of 1, 2, and 3, respectively, and normalized to the observed rate in channel III.

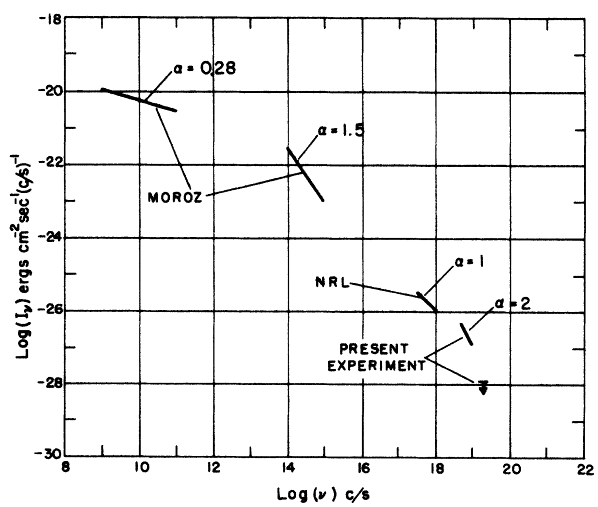

FIG. 3. Summary of data on the spectrum of electromagnetic radiation from the Crab Nebula.

observation of a gradual lunar occultation by Bowyer et al.[4] indicated that the source was not an unresolvable point as expected for any star, but rather an extended object with an angular diameter of about 1′. Now, in addition, in order to explain the x-ray intensity above 15 keV observed in this experiment, it would be necessary to assume a surface temperature of more than 6×10^7 °K, which is considerably greater than the theoretical limit of 1.6×10^7 °K derived by Morton from an analysis of the effect of neutrino processes in the core on the rate of cooling.[5] On the other hand, the data above 15 keV can be reasonably well fitted to an incident spectrum of radiation emitted in free-free transitions in a hot gas near 2×10^8 °K.

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[1]S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman, Nature 201, 1307 (1964).

[2]V. I. Moroz, Astron. J. 7, 755 (1964).

[3]H. Friedman, private communication.

[4]S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman, Science 146, 912 (1964).

[5]D. C. Morton, Astrophys. J. 140, 460 (1964).

MECHANICAL PROCESS OF PARTICLE ACCELERATION INVOLVING THE SLOW TRANSVERSE WAVE IN AN ELECTRON BEAM

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Veksler[1] has suggested two mechanisms for the coherent acceleration of heavy particles, the second of which entails the coherent transfer of momentum between a large number of light particles and a negligibly small number of heavy particles; this could ultimately result in an effective transfer of velocity and thus in very high energies for the accelerated particles. The intent of this note is to establish the plausibility of a mechanism related to this one, the light particles being electrons in a beam and the heavy ones a number of positive ions small enough that their mass and charge per unit length of beam can be neglected compared with those of the electrons. The electron beam is supposed sufficiently relativistic that the space-charge repulsive force is small and, consequently, that only a few positive charges are needed to keep the beam from expanding. These positive charges are then tightly bound to the beam, rather like balls contained but rolling freely within a pipe. If it is supposed that the pipe makes an angle θ with the positive direction and has an acceleration f in this direction, then the component of acceleration at right angles to the pipe is $f\sin\theta$, and the total acceleration of the contained balls in the positive direction is $f\sin^2\theta$. Because this is an even function of θ, the acceleration is effective even if the pipe is not straight but has a sinusoidal or other configuration. For the same reason the accelerated balls are not in general locked in phase with such a transverse wave; phase slippage over wave crests does not impair the effectiveness of this mechanism. The accelerated particles must of course acquire a substantial component of transverse velocity and will therefore generally have a smaller forward velocity than the pipe.

To pursue this analogy, suppose that the electron beam has transverse motion only in the y direction and that at a given instant it has the configuration $y_1(z,t)$. The force $\vec{F}$ on the positive particle with coordinates (z,y) is taken to have the following characteristics:
(1) The tangential component (along the beam) is zero; (2) the normal component is $-Kd_n(1-\beta v_0\cos\alpha/c)\cos\alpha$, where d_n is the normal