[11]K. A. Anderson, J. Geophys. Res. 70, 4741 (1965).
[12]L. A. Frank, J. Geophys. Res. 70, 1593 (1965).
[13]Evidence for streaming of energetic electrons outward from the earthward direction and their spatial distribution is presented in J. R. Asbridge, S. J. Bame, H. E. Felthauser, R. A. Olson, and I. B. Strong, Trans. Am. Geophys. Union 46, 142 (1965).
[14]The second launch of twin Vela nuclear test detection satellites occurred on 17 July 1964. Details of the orbits and instrumental characteristics can be found in a series of abstracts in Trans. Am. Geophys. Union 45, 623 (1964).

SPECTRUM OF CRAB NEBULA X RAYS TO 120 keV

Laurence E. Peterson, Allan S. Jacobson, and R. M. Pelling
Physics Department, University of California, San Diego, La Jolla, California
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In this Letter, we wish to report a balloon determination of the Crab nebula x-ray spectrum over the range 16 to 120 keV. X rays from the Crab were first discovered from a rocket,[1] and were observed from a balloon to 60 keV by Clark.[2] In this work the spectrum has been extended and determined to a much higher precision.

The detector[3] consists of a NaI crystal 5 mm thick by 24-mm diameter. Collimation is provided by a cylindrical CsI scintillation cup 9.3 cm o.d. by 22.9 cm long with a 2-cm wall which surrounds the central detector and its phototube. This collimator, which is in anticoincidence with the central detector, also rejects background events produced by cosmic rays. The detector area is 9.4 cm^2, its geometry factor is 1.5 cm^2 sr, and its resolution, full width at half-maximum, 54%, at 30 keV. Postflight and preflight energy calibrations were identical. In-flight calibrations during a previous flight with the same apparatus showed no tendency for gain changes. Data were telemetered event by event in a digital format from a 128-channel pulse-height analyzer. The detector was mounted at a fixed elevation of 80°, and servo-controlled in azimuth to point true south. The reference was obtained from a magnetometer set to compensate for the average magnetic declination over Texas. The azimuth was independently verified to within about a degree by two additional crossed magnetometers.

The balloon was launched from Palestine, Texas, at 2234 CST, 23 September 1965, reached ceiling at 0050 CST, and floated level at 3.3 g/cm^2 until 0610 CST, when the instrument was inadvertently released by radio command. The Crab transit on this date, corrected for the drift in longitudes of the balloon, was 0545 CST.

Figure 1 shows the counting rates as a function of time for various energy ranges, averaged over 12-minute intervals. The peak on ascent is due to the cosmic-ray maximum. The rate increase at lower energies as the balloon approaches ceiling is apparently due to a diffuse component of cosmic photons. This flux, when corrected to zero depth, seems

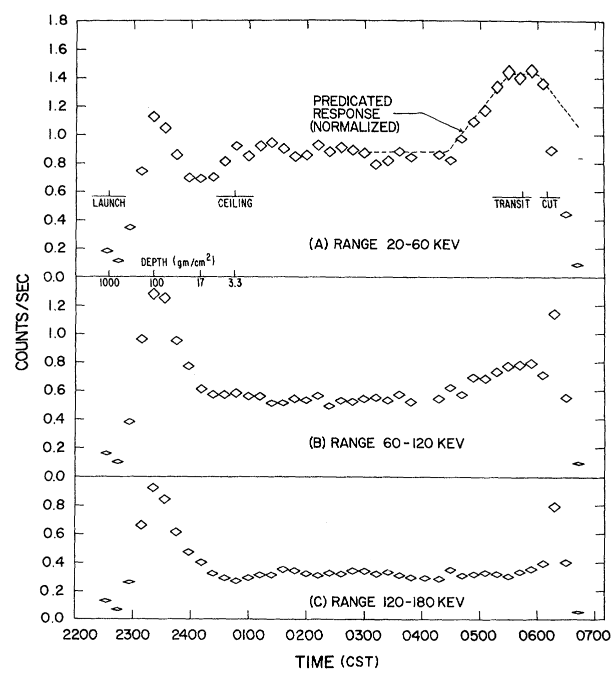

FIG. 1. The counting rates at various energy ranges as a function of time. Background data were obtained at ceiling before the meridian transit of the x-ray source. The dashed line shows the expected transit profile for a point source at the position of the Crab nebula.

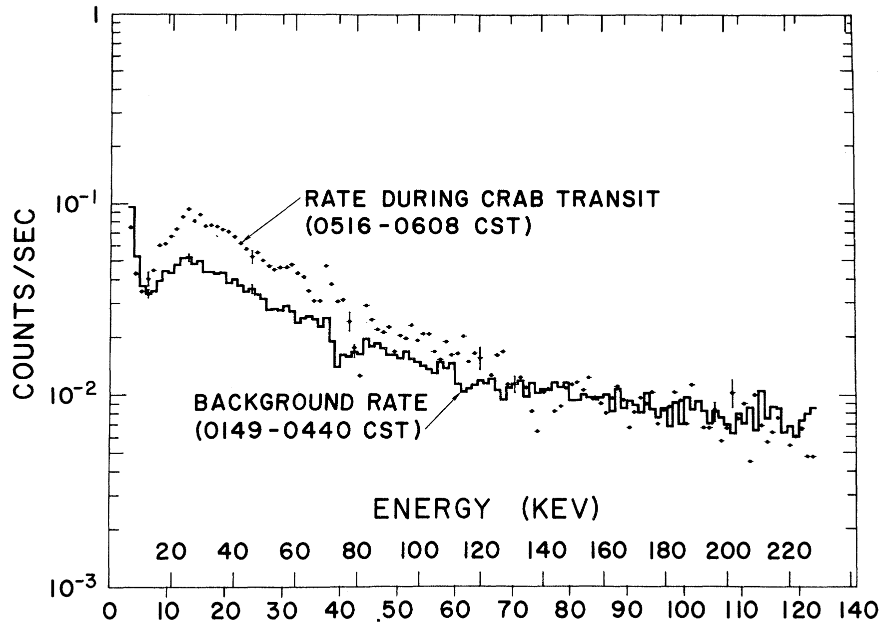

FIG. 2. The pulse-height distributions obtained during the background interval, and during the transit of the Crab. No significant difference is apparent above 120 keV.

in general agreement with the results reported previously.[4,5] This component contributes about half of the measured background in the 20- to 50-keV range. About one-half is due to cosmic-ray production in the overlying atmosphere and only about 5 or 10% is true detector background.

The increase near the end of the flight is attributed to the meridian passage of an x-ray source. The dashed line in Fig. 1(a) shows the expected time-dependent response for a point object of the observed peak intensity at the position of the Crab. The observed source must be within about $\pm 2°$ in right ascension and $\pm 4°$ in declination of the Crab nebula.

Figure 2 shows the pulse-height distribution of the background, and of the Crab during its transit. The incident flux is obtained by subtracting these spectra and correcting for atmospheric absorption, efficiency, deadtime, channel width, and geometry factor. The spectrum obtained by carrying out this procedure is shown in Fig. 3, averaged over suitable channel groupings. No statistically significant fluxes above background were found above 120 keV. Atmospheric absorption removes x rays below 16 keV. A least-squares fit to the spectrum gives a power-law exponent of 1.91 ± 0.10. Therefore α, the index of the differential energy flux, is 0.91 ± 0.10 over this range.

Clark[2] quotes a spectral index $\alpha = 2$ with an upper limit at 60 keV, as shown in Fig. 3. Our flux seems significantly above his upper limit. His observations were made through a considerably higher background and with less energy resolution. Inspection of his results reveals that an α of 1 is also consistent with his data, if the upper limit at 60 keV is excluded. There may possibly be secular variations in the Crab nebula. Also shown in Fig. 3 are the rocket observations reported by the Naval Research Laboratory group[6] and the upper limits obtained during a search for solar γ rays.[7]

Various mechanisms for the production of x rays in astronomical sources have been described by Gould and Burbidge.[8] Thermal bremsstrahlung from a hot gas produces an exponential spectrum. A model temperature and density distribution to reproduce the power law observed here requires a temperature on the order of 10^9 °K. Bremsstrahlung from nonthermal electrons gives a $1/E$ number spectrum. A distribution of slow electrons which will give the observed photon spectrum seems somewhat artificial, and would be quickly cooled by collision loss. The synchrotron mechanism, with an appropriate time-dependent source of 10^4-BeV electrons in a 10^{-4}-G field, can

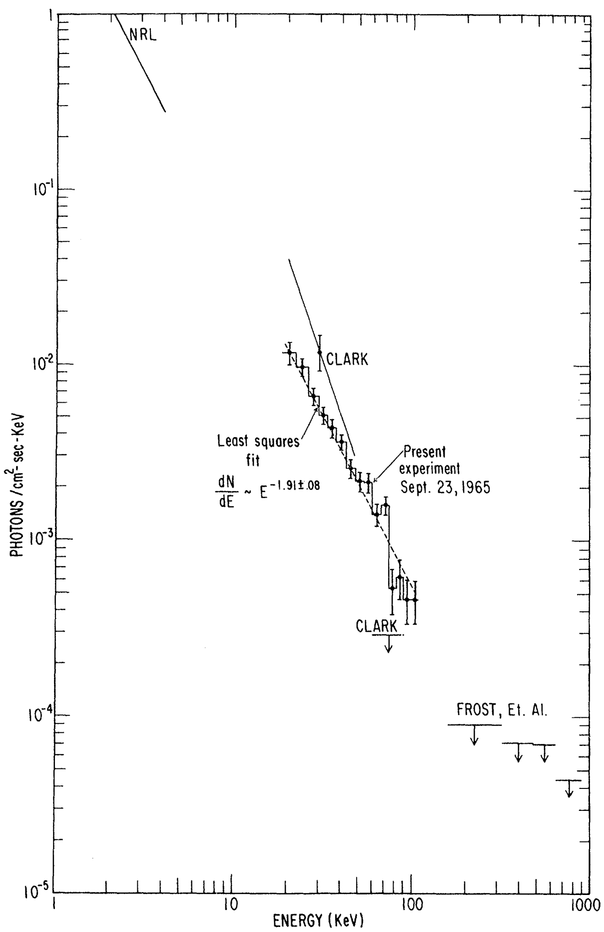

FIG. 3. Observations of the spectrum of the Crab nebula in the x-ray range. The previous measurements of Clark were made with a detector of higher background and may not be inconsistent with this determination.

produce the observed photon spectrum.[9]

Clayton and Craddock[10] have estimated γ-ray line emission from the Crab nebula on the basis of heavy-element production by the r process in supernova explosions. They predict a line at 60 keV due to Am^{241} decays with an intensity about 5.7×10^{-5} photons cm^2 sec. Our upper limit on this line is about 1.1×10^{-2} photons cm^2 sec.

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[1]R. Giacconi, H. Gursky, F. R. Paolini, and B. R. Rossi, Phys. Rev. Letters 9, 439 (1962).

[2]G. W. Clark, Phys. Rev. Letters 14, 91 (1965).

[3]D. B. Hicks, L. Ried, Jr., and L. E. Peterson, IEEE NS 12, 54 (1965).

[4]R. Rothenflug, R. Rocchia, and L. Koch, in Proceedings of the Ninth International Conference on Cosmic Rays (unpublished).

[5]A. E. Metzger, E. C. Anderson, M. A. Van Dilla, and J. R. Arnold, Nature 204, 766 (1964).

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

[7]K. J. Frost, E. D. Rothe, and L. E. Peterson, to be published.

[8]R. J. Gould and G. R. Burbidge, Ann. Astrophys. 28, 171 (1965); Handbuch der Physik (to be published), Vol. 46, Pt. 2.

[9]W. H. Tucker, private communication.

[10]D. D. Clayton and W. L. Craddock, Astrophys. J. 142, 189 (1965).