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OBSERVATION OF GAMMA RADIATION FROM THE CRAB NEBULA

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This Letter reports the detection of gamma radiation from the Crab Nebula with a balloon-borne instrument. Hard X-rays from this object have been previously observed by several groups (Clark 1965; Grader, Hill, Seward, and Toor 1966; Peterson, Jacobson, Pelling, and Schwartz 1967); the present experiment has in addition detected radiation up to 560 keV.

The gamma-ray detector (see Haymes and Craddock 1966) is a 4-inch-diameter by 2-inch-thick NaI(Tl) crystal viewed by an RCA 8054 phototube. Collimation is provided by a 10-inch-diameter by 12-inch-long NaI(Tl) well scintillator that surrounds the central crystal. It is viewed by six 8054 tubes. The summed output of the six tubes is connected in anticoincidence with the central photomultiplier output. Also connected in anticoincidence with the central phototube are three tubes that view a $\frac{1}{4}$-inch-thick plastic scintillator covering the aperture of the well; 4π anticoincidence shielding is thus provided for charged particles. The instrument is maintained at a constant $80^\circ \pm 1^\circ$ F temperature by thermostatically controlled heaters in order that the effects of temperature changes on the detector be minimized. The half-flux angle for a point gamma source is approximately 12° from the axis. The energy resolution of the detector is 9.2 per cent full width half-maximum at 511 keV.

A 128-channel balloon-borne pulse-height analyzer accepts gamma radiation between 35 keV and 560 keV, with all photons in excess of 560 keV counted in one integral channel. The output of the analyzer is digitally telemetered to receiving stations on the ground. Housekeeping data (battery voltages, high-voltage monitors, state-of-pressurization indicators, and heater status) are telemetered separately by the FM/FM system.

The gamma-ray detector is equatorially mounted with a geomagnetically oriented azimuth servo system. A clock drive-gear arrangement is used for tracking celestial sources in hour angle. Pointing-system accuracy has been checked by cameras mounted on the detector which periodically photograph the Sun's position. The system points to an accuracy of $\pm 1^\circ$.

The balloon was launched from Palestine, Texas, at 0615 C.D.T., June 4, 1967, and reached ceiling at approximately 0900 C.D.T. The pressure altitude, as indicated by a photobarograph, varied between 3.65 mb and 3.35 mb during the $7\frac{3}{4}$ hr that the balloon floated at ceiling. Termination occurred by radio command at 1643 C.D.T.

The method of the experiment was to drive the detector about the polar axis continuously at the sidereal rate, so that it would track the Crab in hour angle. In addition the polar axis was offset in azimuth by 180° every 10.5 min, after the servo system was turned on by radio command at 0913. The detector thus alternated between Crab and background measurements. Such a large offset angle was necessary for observing times near Crab transit. The Crab transits the meridian at only 10° from the zenith at a latitude of 32° N., so that a large azimuth variation is required to keep the nebula well outside the 12° half-flux angle of the telescope during the background measurement. During the background observations, no known discrete X-ray sources were in the field of view.

The 10-min-observation technique assures us of having reliable background segments for each source-observation period. It reduces the possibility of obtaining ambiguous data if the background flux suffers sudden, short-term variations and compensates for slow changes in the background, such as those caused by changes in the zenith angle and in the latitude.

At approximately 1400 C.D.T., 6 min prior to Crab transit, the azimuth pointing system failed. After this time, there was no control over the azimuth of the detector; it was free to follow balloon rotations.

On the day of the flight the separation between the Crab and the Sun was only $11\frac{1}{2}°$. Consequently, during the Crab-observation periods, the Sun was somewhat in the field of view. Since the Sun is known to be an emitter of soft X-rays, this factor must be considered in evaluating the data. It must first be noted that no X-rays in excess of 10 keV have, to date, been detected from the quiet Sun. There have been, however, several reports (Peterson and Winkler 1959; Chubb, Friedman, and Kreplin 1960) of high energy radiation (20 keV–500 keV) accompanying an Importance 2+ or Importance 3 solar flare.

No solar flare or geomagnetic activity was reported for the period of the flight either by the ESSA Space Disturbance Forecast Center (SDFC) at Boulder, Colorado, in its weekly summary issued on June 9, 1967, or by the Central Radio Propagation Laboratory (CRPL 1967). The planetary magnetic index, Kp, varied between 1− and 4− during the flight.

In addition, the ionizing-radiation background was independently monitored in flight by an ionization chamber kindly loaned to us by Professor H. V. Neher of the California Institute of Technology. The average rate of ionization observed while the balloon floated at ceiling was 147.3 ion pairs $\sec^{-1}$ cm^{-3} atm^{-1}; it corresponds quite closely to data taken by Neher (1967) in the 1965 period of the quiet Sun at these magnetic latitudes, and the ionization rate was constant from 0900 to 1320. We conclude that this result, taken along with the CRPL and SDFC data, indicates that the observation took place during an undisturbed time.

The most recent and comprehensive search for quiet-time solar gamma rays has been by Peterson, Schwartz, Pelling, and McKenzie (1966), in the energy range of 20 keV–10 MeV. No solar flux was detected. We have examined the spectrum that would have been detected by our instrument if indeed the Sun were steadily emitting at a rate equal to the upper limit set by Peterson *et al.* (1966). Since this curve lies at least an order of magnitude below our measurement for the Crab, we conclude that any solar flux is negligible, compared to the flux which we have detected from the Crab.

Figure 1 shows a time history of the flight. In the various energy intervals, the segments of data due to the Crab and due to the background observations are apparent from the changes in counting rate. The flux is considerably enhanced each time the detector swings around to view the Crab. At 1320 an increase is observed to commence in the background that is not correlated with any reported solar or geomagnetic activity. We have observed similar variations on other flights. The explanation for the variations is unknown, although Gregory and Kreplin (1967) have recently reported brief sporadic solar emissions of 1–10-keV X-radiation even when the Sun is otherwise quiet; the background variations may be connected with this phenomenon. A further analysis of the background fluctuations will appear in another publication. Data from an earlier flight had been analyzed by Haymes and Craddock (1966), using the assumption that the background radiation was time-independent. Figure 1 shows that this assumption is invalid. Finally, the increase observed at about 1510 is due to a balloon rotation that caused the Crab and Sun to pass once again into the field of view.

The radiation due to the Crab was found by averaging the background segments which were adjacent in time to a Crab-observation period and then subtracting this average from the data obtained while the Crab was in the field of view. Thus a residual was formed for each Crab-observation period. These residuals were then corrected for atmospheric absorption and for absorption due to the central photomultiplier, plastic scintillator, and mounting hardware; this latter absorption correction is experimentally determined for each detector to be flown by using various radioactive sources in our laboratory. The postflight calibrations agree with those obtained prior to the flight; there is no evidence for any changes in the system during the flight. All portions of the data that contained any noise were discarded.

The Crab spectrum obtained by carrying out this procedure is shown in Figure 2. No portions of data were used beyond 1320, so that the spectrum is based upon 87 min of Crab observation and 94 min of background data. Radiation is observed at all energies within the range of the experiment. The spectrum appears to be fit well by a power law. A least-squares fit to the data yields an expression of the form $dN/dE = (7.1 \pm 2.8)E^{-2.19\pm0.08}$ counts cm^{-2} sec^{-1} keV^{-1}. Therefore, the spectral index of the differential energy flux is 1.19 ± 0.08 over this range. The broad energy range covered in this experiment results in a very small standard deviation for the slope of the curve. The standard deviation is computed solely from the counting statistics; systematic errors could introduce a larger uncertainty.

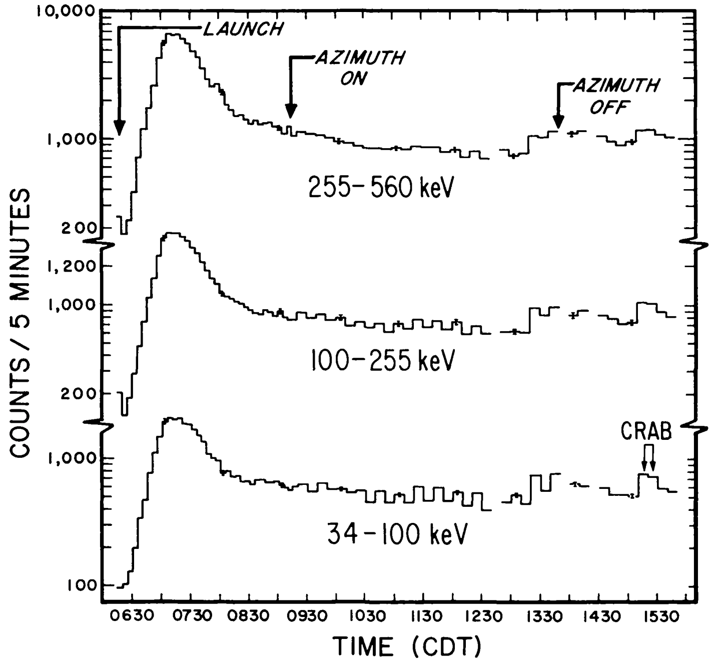

FIG. 1.—Partial time history of counting rates observed during balloon flight. The instrument was offset from the Crab every 10 min, to measure background. Increase in flux is apparent each time the detector points at the Crab. Background changed at about 1320 and a balloon rotation carried the Crab and Sun into the field of view at 1510.

In the least-squares analysis, each datum point was weighted in proportion to $1/\sigma^2$, where σ^2 is the variance of the point in question. If the data are not weighted, a spectral index of 1.37 results; this curve is shown as a dashed line in Figure 2. Subtraction of the upper limits for the Sun found by Peterson *et al.* (1966) from our measurement also yields a power law, but with an index of approximately −1.4. Corrections for the absolute detection efficiency and for the escape of iodine X-rays (Neiler and Bell 1965) would reduce the spectral slope by approximately 0.1.

Shown also in Figure 2 are the results of Peterson *et al.* (1967) which match our fluxes reasonably well in the region of overlap, although the spectrum we have found for the X-radiation and gamma radiation from the Crab is steeper than the spectrum that best fits the data points obtained by those investigators for the hard X-radiation alone. The dependence on energy found here seems to be in somewhat better agreement with the index of 1.3 ± 0.2 obtained by Grader *et al.* (1966) for the soft X-ray spectrum; the dependence also fits more smoothly to an extrapolation of the optical spectrum.

The pulse-height analyzer was arranged so that all photons with energies in excess of 560 keV were included in one integral channel. The upper limit on this "overflow" counting rate is 8.0×10^{-4} $\mathrm{cm^{-2}\ sec^{-1}}$, with a 95 per cent confidence. No statistically significant deviations from this power-law fit to the continuum spectrum were observed.

Since only a continuum was apparent, upper limits can be placed at the energies of the three strongest line emissions that were predicted for the Crab by Clayton and Craddock (1965), on the basis of the californium hypothesis. In addition to these, we have also placed an upper limit on the 511-keV line that might be expected from positron annihilation. These results, at the 95 per cent confidence level, are shown in Table 1, where we have assumed the absolute efficiency of the central crystal to be like that of a 3 × 3-

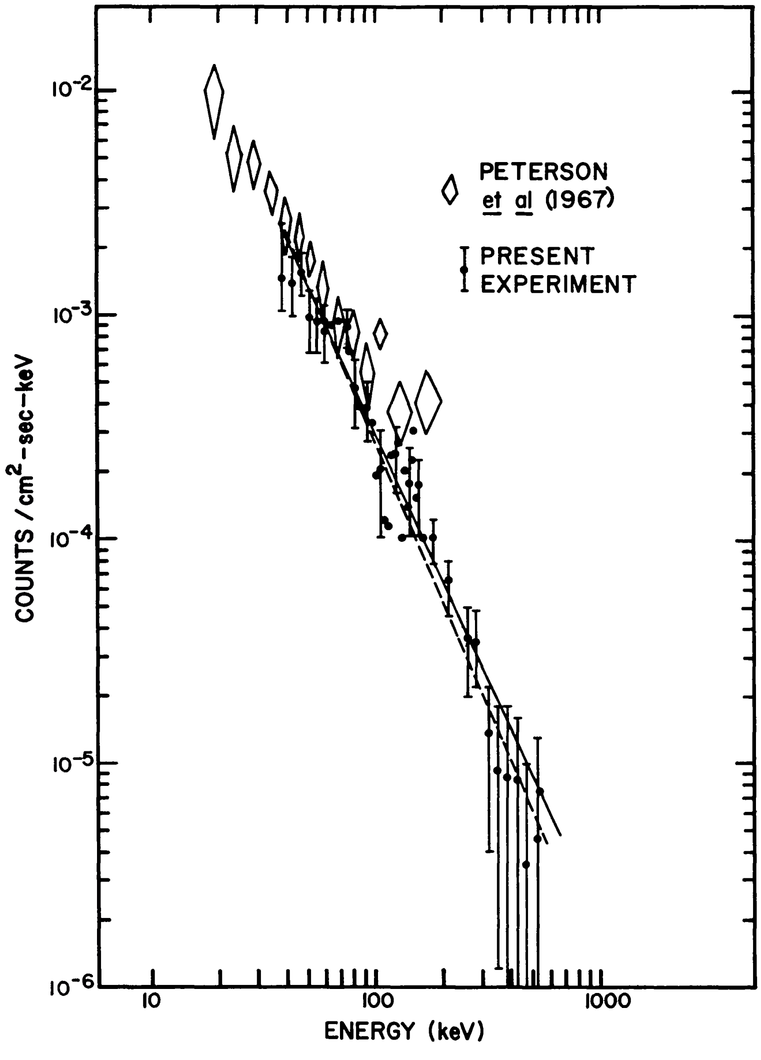

FIG. 2.—Gamma-ray spectrum of the Crab Nebula, at the top of the Earth's atmosphere. The solid line is the best power-law fit obtained when the data points are weighted inversely as their variances; spectral index is 2.19 ± 0.08. Dashed curve represents the spectrum that results when no weighting is done. Data of Peterson *et al.* (1967) are shown for purposes of comparison.

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inch detector (Neiler and Bell 1965). These upper limits are considerably below the fluxes calculated earlier by Savedoff (1959), who assumed that $10^{-2} M_{\odot}$ of Cf^{254} were formed during the explosion.

No time variations greater than about 46 per cent in the flux with characteristic times of $\sim 1\frac{1}{2}$ yr are apparent, at least up to energies of the order of 120 keV. This is the highest energy radiation previously detected from the Crab (Peterson *et al.* 1967) and therefore provides the highest energy data with which we may compare our results.

In Figure 3 we present a summary of data on the spectrum of electromagnetic radiation from the Crab Nebula. It appears that the gamma-ray spectrum matches well with the results of rocket-borne experiments of others (Grader *et al.* 1966) who have explored the soft X-ray spectrum down to energies of about 1 keV. Thus the whole X- and gamma-ray region may be characterized by the same spectral index.

TABLE 1

THE ESTIMATED AND THE UPPER LIMIT TO THE LINE INTENSITIES FROM THE CRAB NEBULA

Energy (keV)	Clayton and Craddock Estimate (cm^{-2} sec^{-1})	Upper Limit (cm^{-2} sec^{-1})
60........	5.7×10^{-5}	3.9×10^{-3}
180........	1.0×10^{-4}	1.5×10^{-3}
390........	9.7×10^{-5}	9.5×10^{-4}
511........	....	8.4×10^{-4}

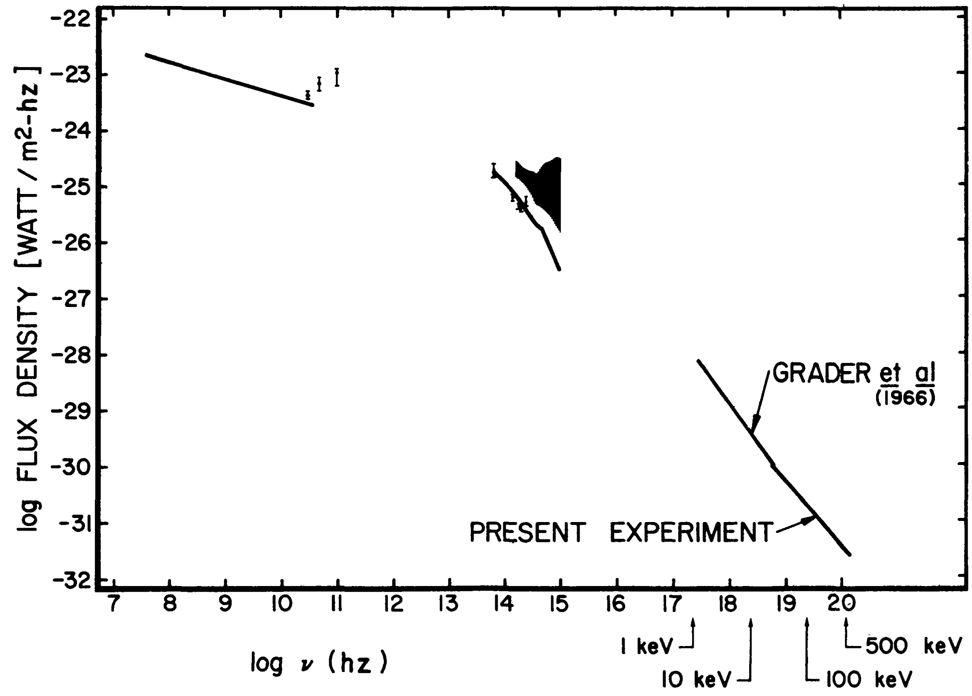

FIG. 3.—Electromagnetic radiation from the Crab, at wavelengths ranging down from the radio to 0.021 Å. Results of Grader *et al.* (1966) in the soft X-ray region are also shown for purposes of comparison. Radio data have been compiled by Howard and Maran (1965), and the three points in the millimeter range are from Tolbert (1965). The infrared points are taken from Moroz (1964). Shaded region represents the possible spectra in the optical if the absorption is between $1^{m}1$ and $3^{m}2$ (O'Dell 1962).

The most likely explanation for this radiation is the synchrotron process. Temperatures of the order of 5×10^9 ° K would be required to produce the observed 500-keV radiation by means of thermal bremsstrahlung.

The X- and gamma-ray spectrum can be smoothly joined to the optical data, if O'Dell's (1962) absorption correction of 1.6 mag in the visible is accepted. The ultraviolet region of the spectrum has not been observed, but the calculations of Williams (1967) show that the correct ionization conditions in the filaments are produced if the ultraviolet synchrotron radiation is taken to be an interpolation according to the power law between the optical and X-ray regions (assuming the distance to the Crab ~2 kpc).

Therefore the radiation from the Crab Nebula can be considered as a unified synchrotron spectrum that extends from about 10^8 to 10^{20} Hz. The spectral index is about 0.27 in the radio and about 1.2 over the frequency range $10^{14} \leq \nu \leq 10^{20}$ Hz.

Continuous injection of a power-law electron spectrum at a rate proportional to $(\tau - t)^{0.86}$, where $\tau \sim$ age of nebula, results in a spectrum of the type observed. From the observed frequency of the bend in the spectrum and the age of the nebula, we estimate the magnetic field to be $\sim 2 \times 10^{-4}$ gauss. It follows from this that the radiation at 560 keV is produced by electrons with energies ~320 ergs = 2×10^{14} eV; such electrons have gyro radii of 3×10^{15} cm (10^2 a.u.).

The total energy received from the Crab at the top of the Earth's atmosphere is 2×10^{-7} erg cm^{-2} sec^{-1}, integrated over the unified spectrum. If the distance to the Crab is taken to be ~2 kpc, then the power output is presently about 7×10^{37} ergs/sec, approximately 50 times the power input calculated to be available from radioactivity (Clayton and Craddock 1965). Integrating the electron spectrum out to 2×10^{14} eV, and using the radio-flux data, we find that the total energy injected into the nebula in the form of relativistic electrons is $\sim 5 \times 10^{49}$ ergs, or a factor of 20 or 30 greater than the previous estimates.

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