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The Earth's ALBEDO

More than 90% of the primary cosmic rays incident on the earth's atmosphere are hydrogen nuclei, or protons. In their interaction with the atmospheric constituents, these particles produce a variety of secondary particles that participate in further interactions. As a result of this complex sequence, there exists in the upper atmosphere an equilibrium flux of neutrons, some of which have the energy and direction to escape the earth's atmosphere. These "albedo" neutrons may be an important source of the protons and electrons in the inner Van Allen zone. This is because the free neutron is unstable (it decays, with a half-life of about 1000 sec, into a proton, electron, and neutrino), and, being neutral, it can enter the trapping region free of the influence of the earth's magnetic field.

Both theoretical calculations and direct experimental measurements have been made of the magnitude, spectrum, and spatial distribution of the albedo neutron flux. One of the experimental measurements was obtained from a neutron detector designed and built at APL and launched aboard the TRAAC satellite 1961$\alpha\eta$2.[1] This article presents a description of the TRAAC experiment and a discussion of the results obtained.

Experimental Method

Description and Discussion—Pertinent details of the neutron detector flown aboard the Navy research and attitude control satellite 1961$\alpha\eta$2 are shown in Fig. 1. The complete assembly consists

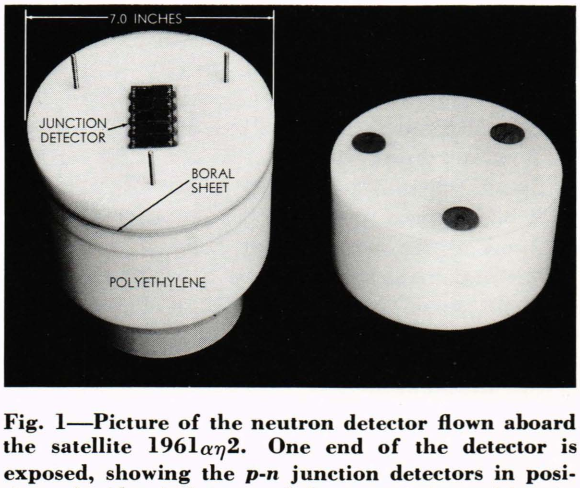

Fig. 1—Picture of the neutron detector flown aboard the satellite 1961$\alpha\eta$2. One end of the detector is exposed, showing the *p-n* junction detectors in position. An identical array of detectors is in position on the other side of the boral plate and look out the opposite end of the package.

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[1] R. E. Fischell, "The TRAAC Satellite," *APL Technical Digest*, 1, Jan.-Feb. 1962, 2–9.

An important source of the particles that constitute the inner radiation zone is the albedo neutron flux that leaks out from the earth's atmosphere. Presented here is a description of a neutron detector that was designed and constructed by the Laboratory and was placed aboard the TRAAC satellite to measure the flux of leakage neutrons. Summaries of data telemetered from the neutron detector are compared with findings of other researchers.

NEUTRON FLUX

of twenty *p-n* junction solid-state detectors, each 1 cm square, imbedded in a 15-lb cylinder of polyethylene. This cylinder, in turn, is enclosed in a thin aluminum can to support it within the satellite structure.[2]

It was intended to orient the payload gravitationally, and to measure separately the neutron flux both toward and away from the earth. The polyethylene cylinder was thus to be aligned along the orientation axis, with the expectation that one group of ten detectors would always face the earth and the remaining group of ten detectors would face away from the earth. A boral plate was inserted between these two groups of detectors to attenuate the thermal neutron flux across the center of the package by a factor of $\approx 10^3$. The 4.8 in. of polyethylene in front of the detectors is sufficient to thermalize ≈ 2 Mev neutrons.

Eight of the ten detectors on each side of the package were coated with a 1-mg/cm^2-layer of B^{10}. Neutrons were detected by observing, with the solid-state detector, the alpha particles released in the $[B^{10}\ (n, \alpha) Li^7]$ reaction. The remaining two detectors were uncoated and served as background monitors. The background detectors were included to monitor the ambient charged particle flux.

The neutron detector package is shown in Fig. 1, with one section of polyethylene removed in order to display the detectors. The detectors were biased to have a nominal depletion depth of $\approx 50\ \mu$. Due to this depletion depth, all detectors were sensitive to a narrow energy range (≈ 110 to 110.5 Mev) of protons incident normal to the top or bottom of the package. In addition, protons of $E > 70$ Mev could penetrate the side of the package and trigger the detectors.

On each end of the package the eight neutron-sensitive units were divided into two equal groups. The outputs of the four units in a group were fed in parallel to a charge-sensitive preamplifier, following which were two stages of amplification and a discriminator. The paralleling of four detectors, and the consequent high-input capacitance presented to the preamplifier, led to a noise level of ≈ 150 kev. To remain well above this noise the discriminator levels were in all cases set at 500 kev. The two discriminator outputs, corresponding to two groups of four detectors each, were then fed in parallel to a shift register and subsequently read out on a telemetry channel. Likewise the outputs of the two background detectors on each side were

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[2] This section is based on the following paper by the authors: "Albedo Neutrons in Space," *J. Geophys. Res.*, **69**, 1964, 377–391.

fed in parallel to a charge-sensitive preamplifier and subsequent electronics.

Two events took place that precluded full attainment of the objectives of the experiment. First, the intended gravity orientation failed because of a failure in the boom-erecting mechanism. Thus, the bi-directional feature of the experiment could not be realized. However, an even more serious failure occurred a few days after launch, when one or more of the neutron-sensitive detectors on the side that was planned to look away from the earth became noisy. This rendered useless the set of eight neutron detectors on that side of the package. Thus, the effective neutron package consisted of eight neutron-sensitive detectors and two background groups of two detectors each.

CALIBRATION—Flight detectors were selected on the basis of equal depletion depths at the given bias voltage and of equal relative sensitivity to neutrons. The depletion depth measurements were carried out at the University of Maryland Van de Graaff accelerator by using protons obtained from the $[D(He^3, p)\alpha]$ reaction. The relative neutron sensitivity measurements were obtained by placing each detector in a fixed geometry with a Ra-Be source and counting for a fixed time.

The absolute efficiency of the complete experiment was obtained from a series of runs on the Van de Graaff accelerators at the University of Maryland and the Naval Research Laboratory. By using various reactions, monoenergetic neutron beams from 0.5 to 1.8 Mev were available at the University of Maryland and up to 4.25 Mev at the Naval Research Laboratory. The resulting absolute efficiency is shown in Fig. 2. The error bars represent the uncertainty in the knowledge of the absolute neutron flux obtained in the above calibration runs. The line drawn through the points represents the efficiency curve used in converting observed count rates into a neutron flux.

The low observed efficiency, low neutron flux, and high background meant that data-accumulation times had to be quite long to obtain statistically meaningful results. The neutron counting rate (neutrons/sec) averaged over a 10-min pass proved to be worthless. Consequently, the neutron count rate was obtained by constructing daily, weekly, bi-weekly, and monthly averages. Finally, an average over the life history of the satellite 1961$\alpha\eta$2 was obtained. These results will be presented and discussed in this paper.

To correct for variations among detectors, such as slight irregularities in depletion depths, detector areas, and discriminator levels, the following in-

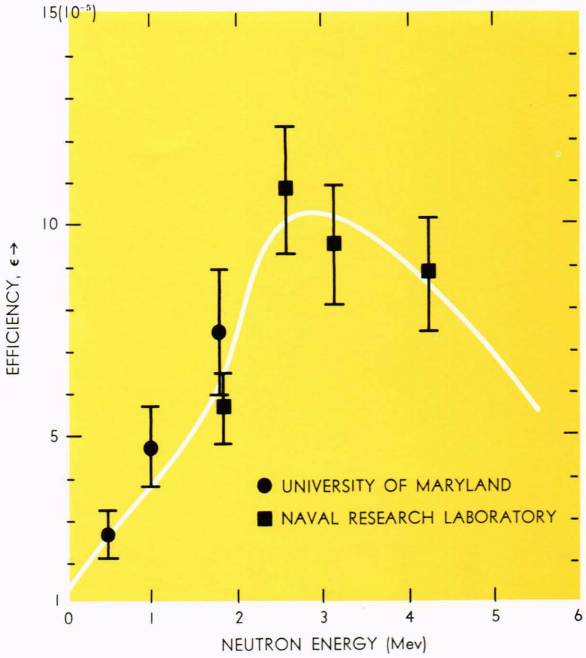

Fig. 2—Absolute efficiency of the neutron detector as a function of neutron energy. All points were obtained with monoenergetic neutron beams.

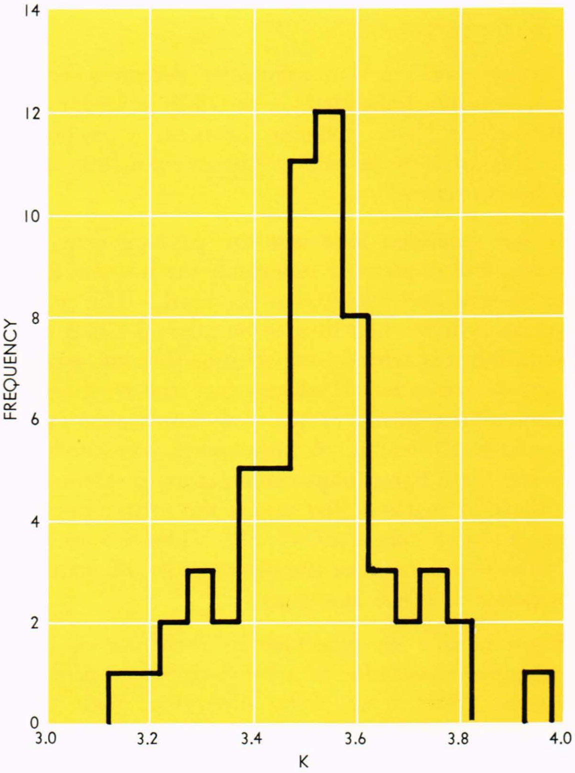

Fig. 3—Histogram of the value of *K* versus frequency of determination. Sixty-seven passes were used for the data, and a mean value of 3.54 ± 0.20 was obtained.

flight calibration procedure was used. Many passes were recorded by stations in South Africa and Hawaii, in which the satellite is either just entering or just leaving the inner radiation zone. In these passes the count rate in all neutron channels is seen to increase (or decrease) monotonically until the counters begin to overflow. It proved to be quite simple to track the count rates through several counter turnovers as long as the initial (or final) count rates were at a suitably low level and were reached in a continuous manner. Also, the behavior of the other charged-particle detectors

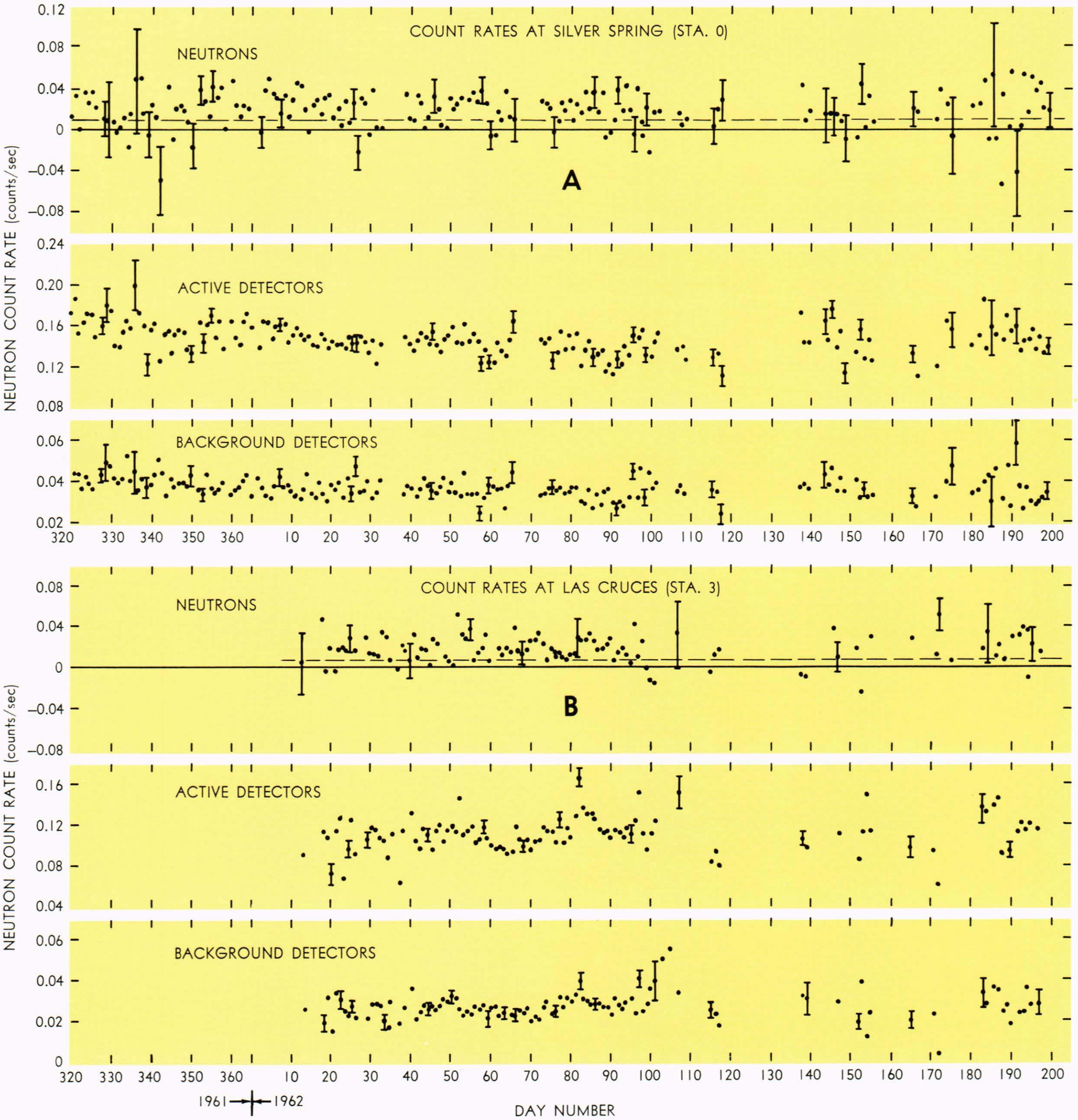

Fig. 4—(A) Station 0 and (B) Station 3 daily-average count rates versus day number. Count rates are shown for active and background detectors separately. The top curve, in both (A) and (B), shows the resulting neutron count rate, and the dashed line in each of these plots is the expected count rate from HCL. On these same plots the expected count rate from Lingenfelter would be 0.0014 count/sec in (A) and 0.0011 count/sec in (B).

aboard the satellite aided considerably in the determination of the behavior of the neutron detectors.

The assumption made in the analysis was that all detectors were responding essentially only to the charged particle flux and that any neutron contamination was very negligible. The count rates observed at these times increased to well over 100 counts/sec. The average count rate for the duration of the pass was obtained for the background and for the active detectors. The following ratio was thus obtained:

$$K = \frac{n_A}{n_B} = \frac{\textit{active detector count rate}}{\textit{background detector count rate}};$$

K was determined individually in 67 separate passes into the radiation zone. The average statistical accuracy of each individual determination of K was 1%. Figure 3 is a histogram showing the value of K versus its frequency of determination. The value of K determined by this process is 3.54 ± 0.20. Therefore, the neutron count rate that applies when the satellite is not in the radiation zone is given by

$$\textit{neutrons/sec} = n_A - 3.54\, n_B.$$

This expression has been used in all the subsequent data reduction.

Results

All data used to compute neutron counting rates were obtained from two receiving stations, Stations 0 at Silver Spring, Maryland, and 3 at Las Cruces, New Mexico. Approximately 1050 passes of useful data were received by these stations throughout the life of the satellite. The average count rates were determined as already noted, and an average over the life of $1961\alpha\eta 2$ was taken. The results for each station are shown in Figs. 4, 5, and 6. The bars indicate the probable error of the neutron count rate due to all causes, including the uncertainties mentioned above and the uncertainty in the value of K.

Since conversion from neutron count rate to an observed neutron flux is spectrum-dependent, all results are presented as observed count rates. These results, Figs. 4 through 7, have not been corrected for local neutron production in the payload. This problem will be discussed later.

Comparisons of the TRAAC results are made with predictions based on the theoretical works of Hess, Canfield, and Lingenfelter[3] (hereafter abbreviated HCL) and Lingenfelter.[4] These calculations will be discussed further in a later section of the article.

The main feature of interest in Fig. 4 is the wide scatter of points, indicating the necessity of long-term averages in order to obtain statistically meaningful results. However, even in these daily averages there is a definite trend toward a count rate above that predicted by HCL. This trend is even more pronounced when compared to the value predicted by Lingenfelter. Note that these data and Figs. 5 and 6 present observed count

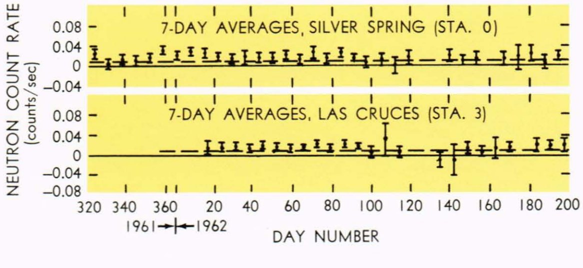

Fig. 5—Station 0 and Station 3 neutron count rates versus day number. Dashed lines indicate expected count rates from HCL. Expected count rates from Lingenfelter for Stations 0 and 3 are 0.0014 count/sec and 0.0011 count/sec, respectively.

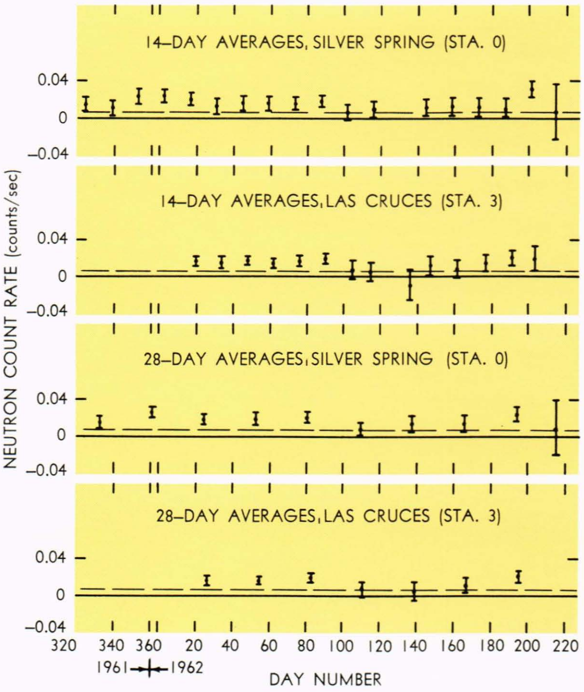

Fig. 6—Station 0 and Station 3 neutron count rates versus day number. Dashed lines indicate expected count rates from HCL. Expected count rates from Lingenfelter for Stations 0 and 3 are 0.0014 count/sec and 0.0011 count/sec, respectively.

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[3] W. N. Hess, E. H. Canfield, and R. E. Lingenfelter, "Cosmic-Ray Neutron Demography," *J. Geophys. Res.*, **66**, 1961, 665–677.

[4] R. E. Lingenfelter, "The Cosmic-Ray Neutron Leakage Flux," *J. Geophys. Res.*, **68**, 1963, 5633–5639.

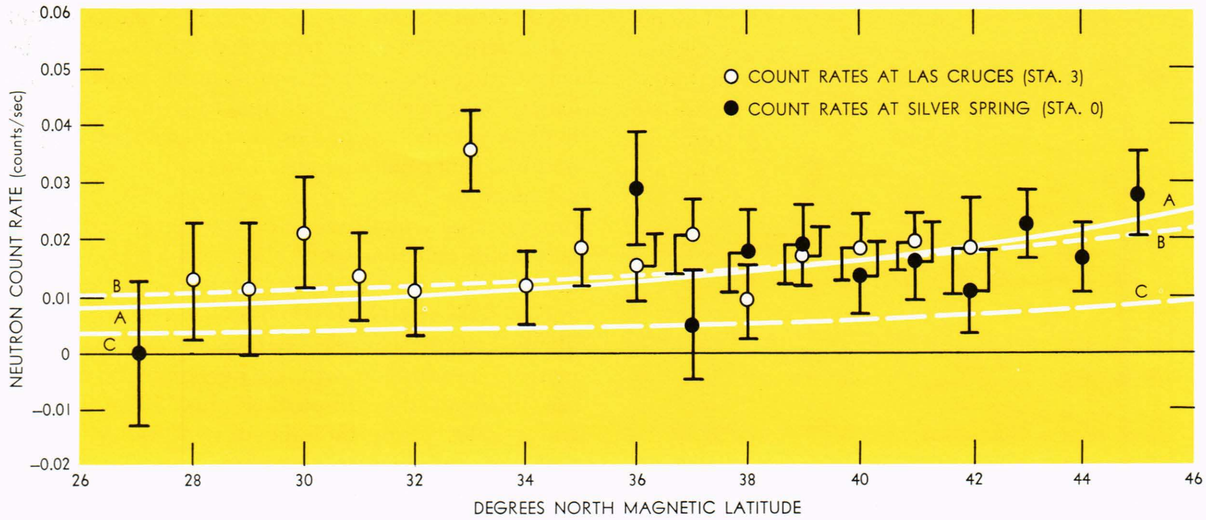

Fig. 7—Observed latitude variation of the neutron count rates obtained in this experiment. Curves A and B are, respectively, the latitude variation obtained by Lingenfelter and that measured by Simpson; they are normalized to our data at 40° north magnetic latitude. Curve C is the same as B but normalized to the results of HCL.

rates over a period of 240 days, commencing at day 320, 1961.

The 7-day, 14-day, and 28-day averages shown in Figs. 5 and 6 bear out the trend of higher-than-expected count rates seen in Fig. 4. An additional interesting feature of Figs. 5 and 6 is the apparent decrease in the observed neutron flux around day 95 (April 5, 1962), with a recovery to almost the previous rates taking place in the vicinity of day 180 (June 29, 1962). Computation shows that the neutron count rates in this period have an average value of ≈ 0.51 ± 0.38 of the pre-day-95 rates and an average of ≈ 0.43 ± 0.30 of the post-day-180 rates. No explanation for this decrease has yet been found.

Figure 7 presents the observed latitude variation, together with curves derived from theory. Curves A and B represent the latitude variation as predicted by Lingenfelter and measured by Simpson,[5] respectively. These curves have been normalized to the data at 40° north magnetic latitude. Curve C presents the same variation as curve B but is normalized to the results of HCL. We see from Fig. 7 that over this latitude range the present data cannot distinguish between the two latitude variations shown. From the combined data of Stations 0 and 3, no statistically significant longitude effect can be seen for neutrons. Simpson obtained from his atmospheric measurements at 312 grams/cm^2 and 448 grams/cm^2, neutron intensity decreases of 1.5% per degree and 1% per degree, respectively, in going from east to west. These results were obtained in the region of 95° to 110° west geographic longitude and at 41° north magnetic latitude. From these data a decrease of some 20% or more might be expected in going from Station 0 to Station 3. As the data in Fig. 7 show no such trend, it is concluded that the neutron longitude effect is smaller at 1000 km than previously reported from atmospheric measurements.

On the other hand, the count rates of the active and background detectors, taken separately, do show a longitude effect. Figure 8 presents the active and background detector count rates for overlapping latitudes from both receiving stations. Averaging over latitudes and both sets of detectors, a decrease in the charged-particle count rate of ≈ 17% is obtained in going from Station 0 to Station 3. Data obtained by Biehl and Neher,[6] with an ionization chamber on the same flights as Simpson, would indicate an expected effect of about 7%.

As is seen from the figures, the observed count rates are two to three times as high as those predicted by HCL, and better than ten times as high as those predicted by Lingenfelter. These values are undoubtedly increased by local neutron production because of the incident cosmic-ray flux.

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[5] J. A. Simpson, "Neutrons Produced in the Atmosphere by the Cosmic Radiations," *Phys. Rev.*, **81**, 1951, 1175–1188.

[6] A. T. Biehl and H. V. Neher, "The Latitude and Longitude Effects in Cosmic Rays Over the United States and Canada at 30,000 Feet," *Phys. Rev.*, **78**, 1950, p. 172.

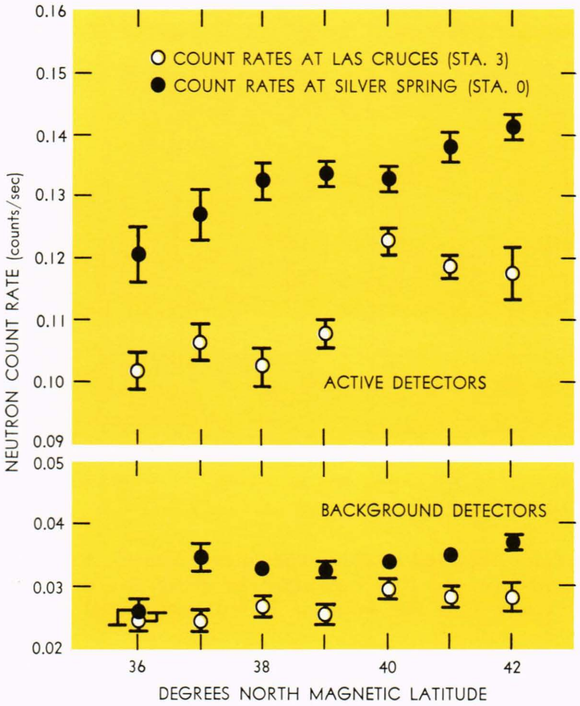

Fig. 8—Plot of active and background detector count rates for Stations 0 and 3 at overlapping latitudes of observation. These curves show the longitude effect of the incident cosmic rays at 1000 km.

Using the cosmic-ray flux as measured by Albert, Gilbert, and Hess,[7] we have calculated an expected count rate of 0.0052 count/sec from this source. This represents ≈ 30% of the observed count rate. Thus, multiplying our observed values by 0.7 yields a measured neutron rate corrected for local neutron production by incident cosmic rays. Of this local production, 67% is due to production in the payload and 33% to production in the polyethylene moderator.

At an altitude of 1000 km, the possibility exists for local neutron production by stray protons from the inner radiation zone. Effects such as this have been previously observed.[8] In the present experiment this effect was looked for during the in-flight calibration procedure and was not observed. Therefore, even if present, it is too small to affect the data.

The above result may at first sight appear contradictory, i.e., local neutron production in the belt is insignificant in the in-flight calibration procedure, whereas local neutron production caused by incident cosmic rays yields a 30% effect. That these results can be reconciled can be seen by considering the average number of neutrons released (the neutron multiplicity) in a proton-nucleus interaction at cosmic-ray energies and at nominal inner-belt energies. Interactions at cosmic-ray energies yield, on the average, 100 to 1000 times as many neutrons as do interactions at nominal inner-belt energies. For example, neutron multiplicities for protons in air are ≈ 10 at 3 Bev and ≈ 0.06 at 100 Mev.* The low neutron multiplicity at radiation-belt energies implies that local neutron production will be negligible relative to the incident charged-particle flux. The relative count rates from the above two sources—local neutrons and incident charged particles—depend on the relative sensitivities to these sources. In the case of the present experiment it is seen that local neutron production by incident cosmic rays yields a count rate of ≈ 0.005 count/sec, or 30% of the observed rate. In the belt the incident charged-particle flux is larger by a factor of 10^4, while the multiplication factor is lower by 10^2. This yields ≈ 0.5 count/sec as due to local neutrons when in the vicinity of maximum intensity in the inner belt. Observed rates were > 100 counts/sec and are thus seen to be due mainly to incident charged particles.

The count rates based on the spectra presented by HCL and Lingenfelter have been calculated, and the results are shown in Table I for both receiving stations. The observed count rate in the table is the overall average count rate for all the data received. A mean observational magnetic latitude of 40° north was used for Station 3 and 43° north for Station 0. The latitude variation used with the spectra of HCL was that measured by Simpson for disintegration-product neutrons (≈ 2 to 30 Mev) in the atmosphere. The latitude variation presented by Lingenfelter was used in the

TABLE I

OBSERVED AND THEORETICAL NEUTRON COUNT RATES

Observation Station	*Observation Magnetic Latitude*	*Observed Neutron Count Rate** *(counts/sec)*	*Predicted Neutron Count Rate (counts/sec)*	
			HCL	*Lingen-felter*
Silver Spring	43° N	0.0124 ± 0.0039	0.0066	0.0014
Las Cruces	40° N	0.0116 ± 0.0029	0.0056	0.0011

* Corrected for local neutron production.

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[7] R. D. Albert, C. Gilbert, and W. N. Hess, "Measurements of Charged Particles and Neutrons on Discoverer Flights" (abstract), *J. Geophys. Res.*, **67**, 1962, p. 3537.

[8] J. P. Martin, L. Witten, and L. Katz, "Measurement of Cosmic Ray Albedo Neutron Flux Above the Atmosphere," *J. Geophys. Res.*, **68**, 1963, 2613–2618.

* Private communication from R. E. Lingenfelter.

comparisons with his results. The altitude variation used was the $R^{-3.2}$ dependence reported by Hess and Starnes.[9] It is seen in the table that the observed rates are 1.5 to 2 times as high as the values of HCL and 8 to 10 times as high as those of Lingenfelter.

It should be noted that although the equilibrium leakage flux as calculated by Lingenfelter is a factor of 3.5 lower than that of HCL in the energy range pertinent to this experiment, the ratio of the expected count rates is more like 5. The main reason for this is that Lingenfelter postulated inelastic scattering effects that result in the dumping of high energy particles into lower energy portions of the spectrum. This yields lower expected counting rates.

Conclusions

In Fig. 9 we present a comparison of all reported albedo neutron flux measurements with the theoretical work of HCL and Lingenfelter. The open circles are the TRAAC results, and the solid points are results obtained from the work listed in References 7–13. Curves A and B show, respectively, the predictions of HCL and Lingenfelter.

It is evident from this figure that there is much disagreement among the various experimental results and that no conclusion can be drawn as to which of the theoretical treatments is valid.

Because of these discrepancies a conference on "The Earth's Albedo Neutron Flux" was organized and held at APL on October 15–16, 1963. The results of this conference have been reported recently.[14] They are, in brief, that the absolute neutron leakage flux and its spatial distribution are known to a factor of no better than about 5, although a portion of this uncertainty may be due to time variations in the leakage flux of neutrons. A further result, and one which could have far-reaching effects, was that for the first time all the principal researchers in this field were brought together to review past effort, to define present status, and to establish at last a common point of departure for future, cooperative investigations.

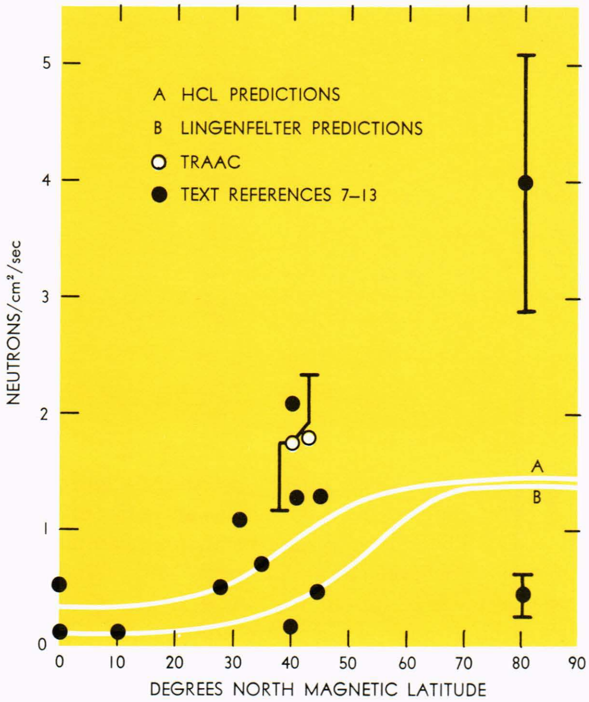

Fig. 9—Comparison of all reported albedo neutron flux measurements above the atmosphere with the theoretical treatments of HCL and Lingenfelter.

To evaluate how important a source the albedo neutron flux is for the inner Van Allen zone, a better understanding of its intensity and behavior is required. Work is now in progress on the design of a neutron detector that will be launched aboard an orbital vehicle.

We gratefully acknowledge the cooperation and assistance of Dr. P. Malmberg, Naval Research Laboratory, and Dr. W. Hornyak, University of Maryland, for the use of their accelerators in calibrating the neutron detector. It is also a pleasure to thank C. J. Monahan, APL, for coding and running the data reduction and analysis programs. The neutron detection experiment was designed in collaboration with our colleague, Dr. G. F. Pieper, recently of APL and now of NASA, to whom we are grateful for continued encouragement during the data reduction and analysis.

We also wish to thank W. S. Carey and J. E. Rogers for their outstanding work in obtaining telemetry reception from 1961$\alpha\eta$2 over their Southern Rhodesia station.

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[9] W. N. Hess and A. K. Starnes, "Measurement of the Neutron Flux in Space," *Phys. Rev. Ltrs.*, **5**, 1960, 48–50.

[10] J. H. Trainor and J. A. Lockwood, "Neutron Albedo and Charged Particle Measurements at 200–400 Km," *Trans. Am. Geophys. Union*, **44**, 1963, p. 73.

[11] W. P. Reidy, R. C. Haymes, and S. A. Korff, "A Measurement of Slow Cosmic Ray Neutrons up to 200 Kilometers," *J. Geophys. Res.*, **67**, 1962, 459–465.

[12] S. J. Bame, J. P. Conner, F. B. Brumley, R. L. Hostetler, and A. C. Green, "Neutron Flux and Energy Spectrum Above the Atmosphere," *J. Geophys. Res.*, **68**, 1963, 1221–1228.

[13] S. J. Bame, R. W. Davis, J. P. Glore, and F. B. Brumley, "Intensity of Neutron Albedo Above the Atmosphere," *Bull. Am. Phys. Soc.*, **5**, 1960, p. 360.

[14] D. J. Williams and C. O. Bostrom, "Conference on the Earth's Albedo Neutron Flux," TG-543, The Johns Hopkins University, Applied Physics Laboratory, 1963; and D. J. Williams, "Albedo Neutron Conference Report," *APL Technical Digest*, **3**, Nov.-Dec. 1963, 25–26.