through magnetic analysis. This is consistent with the value of $(R_{\text{ext}}-R_0)/R_0=0.027$, where R_0 is the average range, and R_{ext} is the extrapolated range, taking into account that range straggling is of the order of 2.2%.

3. DISCUSSION

It is worth while to point out that the $Al^{27}(d,\alpha p)Na^{24}$ reaction is in competition with the $Al^{27}(d,p)Al^{28}$ reaction (2.3-min half-life). Data already obtained on the latter reaction by us show that the $(d,\alpha p)$ cross section starts rising when the (d,p) starts dropping. Although the shape of the excitation function for the $(d,\alpha p)$ reaction resembles the curves obtained through the compound nucleus assumption, additional work will be done using the nuclear scattering equipment in order to clarify the reaction mechanism, as it is suspected that direct reactions are important around 28 Mev.

TABLE I. Extract of values for the $Al^{27}(d,\alpha p)Na^{24}$ reaction cross-section.

Energy Mev	Cross section mb	Energy Mev	Cross section mb
11.0	0.35	21.1	44.0
12.0	0.60	22.1	46.4
12.9	1.61	23.0	50.0
14.0	4.38	24.1	50.8
15.1	9.04	24.25	51.4
16.1	14.0	25.1	51.2
17.0	20.6	26.1	48.2
18.1	26.4	27.0	47.6
19.1	35.5	28.1	42.2
20.1	38.8		

4. ACKNOWLEDGMENTS

We wish to thank Dr. J. H. Capaccioli of the Chemistry Department for his analysis of the aluminum foils, and J. Garanzini, S. Tejero, M. Professi, and B. Ietri of the synchrocyclotron crew for their able assistance.

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High Altitude Neutron Intensity Diurnal Variation*†

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Two balloon flights in which boron-trifluoride neutron counters were carried aloft were launched from Brownwood, Texas, during September, 1958. The flights attained altitudes of 86 000 and 79 000 feet at a conventional geomagnetic latitude of 41°N. They showed that the slow-neutron intensities in the atmosphere had decreased by about 12% since the time of minimum solar activity in 1954. They also show that this decrease was mainly in the low-energy end of the spectrum, as the mean free path for absorption had increased from 180 ± 25 g/cm^2 to 240 ± 30 g/cm^2. A high-altitude decrease apparently associated with the geomagnetic storm of September 25, 1958 was also detected. After achieving altitude, the balloons floated at a constant elevation through sunset. A sharp peak in the intensity which occurs just before sunset at balloon altitudes was detected on both flights. The origin of this phenomenon, which results in a doubling of the intensity for about 25 minutes, is unexplained, although some possible mechanisms are discussed.

INTRODUCTION

AN experimental search for a diurnal variation of cosmic-ray neutrons has been conducted at balloon altitudes in order to determine if primary neutrons exist in the cosmic radiation. These neutrons, if present, would originate in the sun. This is because of the relatively short half-life of the free neutron.[1] This 13-minute lifetime precludes a very distant origin for all but the most energetic neutrons. Extremely relativistic particles could reach the earth from elsewhere in the galaxy because of time-dilatation effects, but their numbers are likely to be quite small.

Since the distance between the sun and the earth is only 8.3 light-minutes, a fairly fast neutron does have a reasonable probability of surviving the trip. Of course, this assumes that these neutrons are produced high up in the solar corona, so that their probability of absorption within the sun is small.

Because neutrons are uncharged, they propagate in straight lines, like light. Thus, the existence of solar neutrons would be expected to give rise to day-night and eclipse effects.[2]

Several possible processes leading to neutron production by the solar corona have been considered. Biermann, Haxel, and Schlüter[3] have shown that if a solar flare

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† This represents an abridgement of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at New York University, 1959.

[1] J. M. Robson, Phys. Rev. **83**, 349 (1951).

[2] Swetnick, Neuburg, and Korff, Phys. Rev. **86**, 589 (A) (1952).

[3] Biermann, Haxel, and Schlüter, Z. Naturforsch. **6a**, 47 (1951).

occurs, the locally intense magnetic fields may accelerate the protons to 10^8 volts. Star production in the corona then leads to 10^7-volt neutrons, which are fast enough to reach the earth in appreciable numbers. Charge-exchange scattering of these fast protons will also produce energetic neutrons.

The experiments then, employs balloons which carry neutron detectors aloft. The balloons float at a constant elevation through the sunset period, and the neutron intensities are measured during this time. The data are then examined for any statistically significant difference between the day and night intensities.

It is evident that more information can be obtained from this experiment by recording the intensities during the balloon's ascent. These data may be compared with the results of other investigators[4–7] for the altitude variation of cosmic ray neutrons. These previous measurements were conducted during times of minimum solar activity. The IGY period of 1957–1958, was, however, a time of maximum activity. In fact, it appears to have been the most active ever recorded.[8] Thus, a comparison should provide information on any effect of the solar cycle on neutron production within the earth's atmosphere. Such an effect would be observable in terms of a change in the mean free path for absorption of these secondary[9,10] neutrons, and in their intensities.

A slow-neutron measurement was decided on for two reasons. The first factor is that such a measurement eliminates the need for a moderator. Such moderators introduce complicating factors into the experiments because of star production within them. It is generally very difficult to relate such measurements to neutron intensities in the atmosphere. The second factor is that a slow-neutron measurement permits direct comparison with the previous altitude-variation measurements.[6] This is because the experimentally detected energy spectra will be the same.

APPARATUS

Two BF_3 proportional counters were used on each flight. They were identical in all respects, except for the isotopic enrichment of the boron. In order that direct comparison could be made with the results of previous measurements, the size and pressure of each counter was the same as used by Soberman.[6] One counter contained BF_3 with 96% of the B^{10} isotope, while the other used the normal isotopic ratio, which is 19% B^{10}. The plateaus, when measured with the electronics to be used during the flights, were found to be from 100 to 250 volts long, with slopes between 2% and 4% per hundred volts. Since the operating points were all about 2350 volts, it was possible to use a common high-voltage supply for each pair.

Figure 1 shows a block diagram of the flight apparatus. The amplifier is a seven-stage transistorized circuit which functions as a linear amplifier and integral pulse-height discriminator. It produces an output pulse only if the pulse from the counter exceeds 3 millivolts in amplitude. In this way, small pulses, such as those due to gamma rays, are rejected. As can be seen from Fig. 1, two identical, but separate amplifiers are used in each flight set. This permits simultaneous telemetry of the two counting rates.

The output pulse from the amplifier is presented to a biased blocking oscillator. This circuit is normally nonconducting, due to a negative bias supplied by a 6-volt battery. When the amplifier neutralizes this bias with a +6-volt pulse, however, oscillation occurs for the duration of the pulse, which is approximately one millisecond. The subcarrier oscillator in the enriched-counter train is tuned to 30 kc/sec; the regular subcarrier frequency is 9 kc/sec. This provides a method of identification for the transmitted pulse. The output of the oscillators is used to frequency-modulate the carrier frequency.

As noted previously, both counters are powered by a common high-voltage supply. This supply is commercially available.[11] The combined noise and ripple of the transistorized unit does not exceed one millivolt, thus making it suitable for this work. The output of the supply is variable in the range 0 to 3000 volts, and requires a single $1\frac{1}{2}$-volt dry cell for its operation.

A slightly modified Rawin system is used to telemeter the data. The transmitter is of the standard rawinsonde type (*AN/AMT-4B*), and is operated at 135 volts plate potential. Approximately 0.67 watt of 1680 megacycle/sec power are radiated. The receiver is of the *AN/GMD-1A* type, and provides automatic tracking of the balloon in elevation and azimuth. This feature is useful when one wishes to plot the trajectory of the

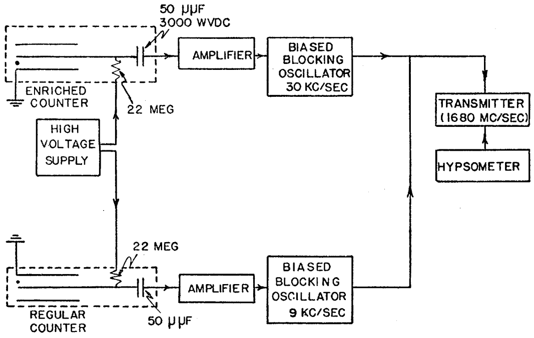

FIG. 1. Block diagram of the airborne apparatus. The two counters differ in the percentage of B^{10} isotope in the BF_3 filling gas.

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[4] L. C. L. Yuan, Phys. Rev. **81**, 175 (1951).

[5] J. A. Simpson, Phys. Rev. **83**, 1175 (1951).

[6] R. K. Soberman, Phys. Rev. **102**, 1399 (1956).

[7] J. D. Gabbe, Phys. Rev. **112**, 497 (1958).

[8] *Solar-Geophysical Data, Part B* (Central Radio Propagation Laboratory, U. S. National Bureau of Standards, Boulder, Colorado, 1958).

[9] Bethe, Korff, and Placzek, Phys. Rev. **57**, 573 (1940).

[10] Y. Fujimoto and T. Tamura, Progr. Theoret. Phys. (Kyoto) **8**, 221 (1952).

[11] Automation Dynamics Corporation, Tenafly, New Jersey.

balloon, or attempt recovery of the apparatus. Since this ultra-high frequency is propagated in a line-of-sight manner, radio range is limited by the horizon.

It is vital, in an experiment of this type, that a correction be made for changes in altitude of the floating balloon. Such changes arise from cooling of the helium at sunset, and from diffusion of the gas.

Conventional techniques of measurement of the atmospheric pressure are subject to large errors at the reduced pressures encountered at balloon altitudes. This is so because these techniques usually involve aneroid cells.[12–15] Such a cell works on an application of Hooke's Law, where a given increment of pressure produces a constant incremental deflection, regardless of the absolute pressure. Thus a cell with a 2-millibar error at 1000 millibars (a negligible error), has a 2-millibar error at 10 millibars, which is a 20% error. Also, the aneroids generally lack sufficient sensitivity to detect pressure changes of less than a millibar.

Accordingly, a hypsometer was developed for this experiment. A hypsometer is a device which measures the boiling point of a liquid, which is a function of the pressure. The device represents an application of Clapeyron's equation; this equation shows that the sensitivity of the device actually increases with decreasing pressure.

Two units are used in this arrangement, for purposes of maximum sensitivity in conjunction with the telemetry system. The first is employed in the range sea level to 100 millibars (55 000 feet). The second unit is used in the range 100 millibars to 2 millibars (140 000 feet). With methylcyclohexane as the hypsometric fluid and a special long condensing tube, lifetimes greatly in excess of 8 hours at 15 millibars are obtainable. Heater power is supplied by a 6-volt dry cell to keep the 1.5 cc of fluid boiling.[16]

The accuracy of this device, when checked against a photoelectrically scanned mercury manometer[17] connected to a chamber which is both evacuated and cooled, has been found to exceed ±0.1 millibar at 10 millibars. The sensitivity of the unit was determined to be greater than that of the manometer, which is 0.05 millibar.

For telemetry purposes, the two thermistors are alternately connected in series with the grid circuit of the blocking oscillator incorporated in the rawinsonde transmitter. This provides an audio-frequency which is then dependent on the absolute pressure, and which amplitude-modulates the carrier. A reference resistor is also switched in briefly once per minute, to provide a reference audio-frequency to allow for drifts in the telemetry system.

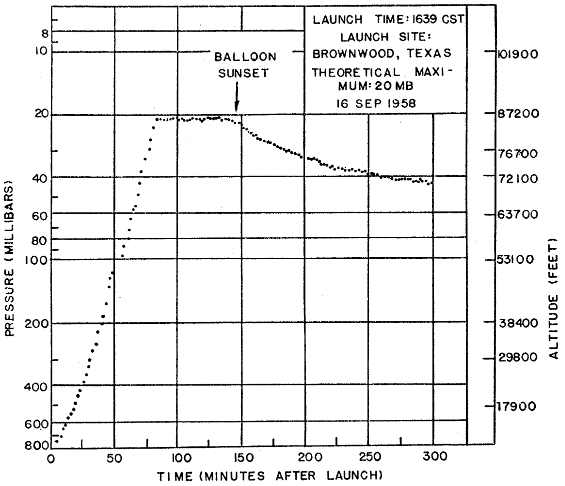

FIG. 2. Time-altitude curve for the first flight. The ceiling altitude was 21.2 millibars, or 86 000 feet.

ENVIRONMENTAL BEHAVIOR

Since any balloon-borne apparatus is exposed to large changes in atmospheric pressure and temperature, it must be insensitive to these parameters in order that correct measurements of the intensity may be made.

In order to eliminate the possibility of corona discharge at high altitudes, without using a large and heavy pressure shield, the high-voltage supply was potted. Solid-dielectric coaxial cable is used to conduct the output to the counters. The end of the counters were hermetically sealed, and contain the load resistor and blocking capacitor.

Because of the temperature sensitivity of the transistor circuits and of the dry-cell batteries, a gondola was constructed of 0.020-in. aluminum with a 4-in. interior lining of Styrofoam. Thermostatically-controlled electrical heaters can supply up to 150 watts to the flight set. In addition, each circuit has an individual Styrofoam jacket and thermostatically-controlled heater. Laboratory tests with a large cold chamber revealed that the performance of this system was insensitive to ambient temperature down to the lowest temperature that the chamber could produce, which was −64°C.

NEUTRON DETECTION

The two-counter technique allows one to eliminate the "background" radiation, and arrive at n, the number of neutrons that would be detected by a counter filled with 100% B^{10}. Real proportional counters filled with BF_3 produce pulses for any event which causes ionization equal to or greater than that produced by the lithium nucleus and alpha particle in the $B^{10}(n,\alpha)$ reaction. Such events are stars formed in the walls of the counter, high-energy recoils, etc.

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[12] Pavalow, Davis, and Staker, Rev. Sci. Instr. **21**, 529 (1950).

[13] N. L. Allen and E. Pickup, Can. J. Tech. **30**, 317 (1952).

[14] H. V. Neher, Rev. Sci. Instr. **24**, 97 (1953).

[15] Diamond, Hinman, and Dunmore, J. Research Natl. Bur. Standards **25**, 327 (1940).

[16] We would like to acknowledge with gratitude the assistance and cooperation of Mr. M. Sapoff, Victory Engineering Corporation, Union, New Jersey.

[17] Haas Bros. Incorporated, Washington, D. C., Model A-1.

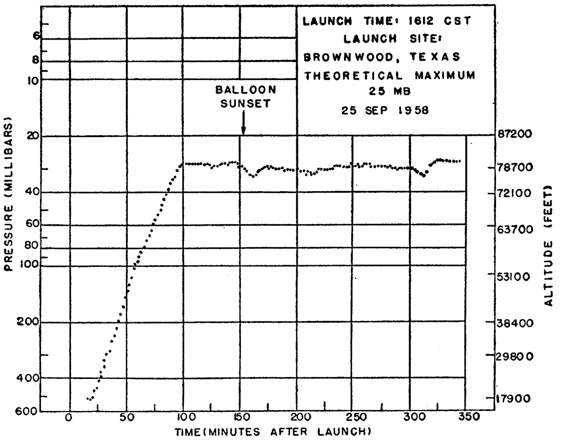

FIG. 3. Time-altitude curve for the second flight. A ceiling of 28.2 millibars (79 000 feet) was achieved. The improved altitude control is the result of a larger supply of ballast.

The counting rate of the enriched counter is

$$E=0.96n+b, \tag{1}$$

and that of the regular counter is

$$R=0.19n+b \text{ counts/min}, \tag{2}$$

where b, the background, is assumed to be the same for both counters because they are at the same point in space at the same time, and have identical geometries. Solution of these two simultaneous equations yields

$$n=1.3(E-R). \tag{3}$$

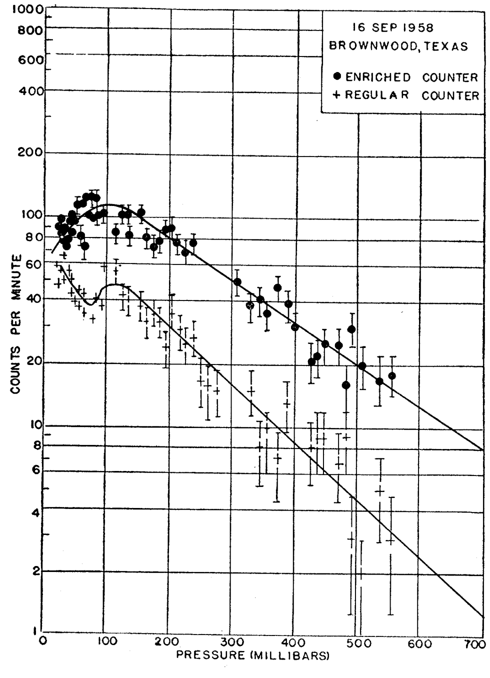

FIG. 4. Counting rates *vs* pressure for the individual counters on the first flight.

This n may be related[9] to the number of neutrons captured by one gram of air per second.

EXPERIMENTAL RESULTS

The two balloon flights were launched from Brownwood, Texas, at a conventional geomagnetic latitude of 41°N. The first flight was launched at 1639 CST on September 16, 1958, and climbed to a ceiling pressure of 21.2 millibars, which corresponds to 86 000 feet.[18] Attached to the gondola was a ballasting system to maintain a constant elevation even when sunset resulted in cooling of the helium. As soon as the balloon commenced to lose altitude, a pressure-activated relay caused ballast to be released until it climbed back to its normal altitude. Unfortunately, insufficient ballast was carried aloft on this flight to completely achieve this objective, but the pressure data from the hypsometer is accurate enough to permit a correction for this. Figure 2 shows the time-altitude curve for the flight. Data reception was free of noise for the period shown on the curve. The gondola was subsequently recovered in operating condition.

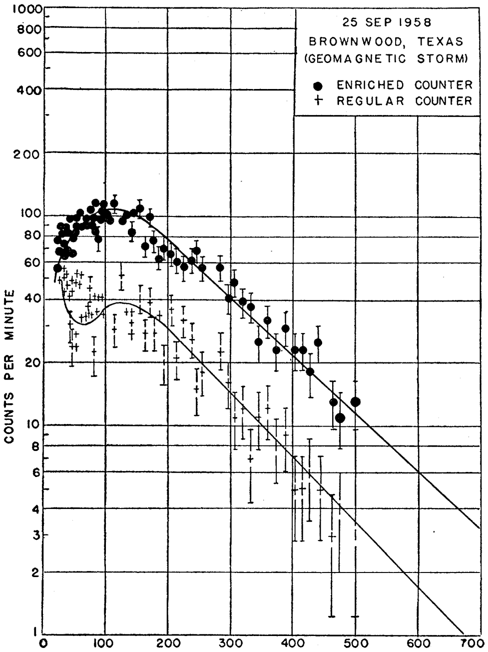

FIG. 5. Counting rates *vs* pressure for the individual counters on the second flight.

The second flight was launched at 1612 CST on September 25, 1958. Like the previous flight, this also used a 69-foot diameter balloon fashioned from $\frac{3}{4}$-mil polyethylene.[19] Considerably more ballast was carried aloft on this flight, and the great improvement in altitude control is apparent from an inspection of Fig. 3.

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[18] U. S. Extension to the ICAO Standard Atmosphere, 1958.

[19] Raven Industries, Incorporated, Sioux Falls, South Dakota.

The greatest departure from the ceiling pressure of 28.2 millibars was only 4.6 millibars, and this lasted for only 3 minutes. As on the first flight, the data transmission was quite good. This gondola was also recovered in operable condition.

Figures 4 and 5 are plots of the counting rate *vs* pressure for the individual counters on the two flights. The uncertainties shown are the statistical standard deviations. The neutron counting rate, obtained by use of Eq. (3), is shown for each of the two flights in Figs. 6 and 7.

Figures 8 and 9 show the pressure-corrected neutron intensity as a function of time for the two flights. These curves start after the balloon has levelled off at its ceiling altitude. An exponential correction factor was employed to correct the intensity to the ceiling altitude.

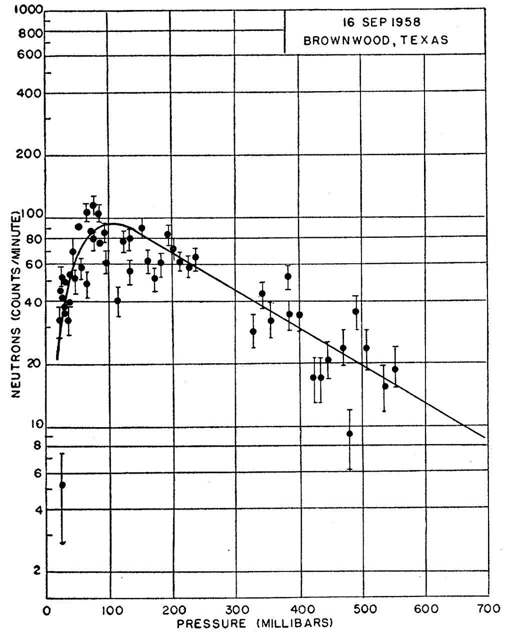

FIG. 6. Slow-neutron counting rate *vs* pressure for the first flight.

In order to interpret the experimental results, an investigation was made of the state of solar, ionospheric, and geomagnetic data for this period.[20,21] These reveal that a small geomagnetic storm ended just before the first flight achieved ceiling, and that this flight may therefore be considered to have taken place during an undisturbed time.

A geomagnetic storm was in progress, however, during the second flight. Figure 10 shows the effects of this storm on the intensity of the nucleonic component at sea level, as observed by the New York University IGY neutron monitor at College, Alaska. It can be seen that this monitor showed only a 2% decrease, even though it is located in the auroral zone at a relatively high geomagnetic latitude (64°N). The Tucson Observatory records show that the horizontal component of the earth's magnetic field had decreased by about 175 gamma during this storm.

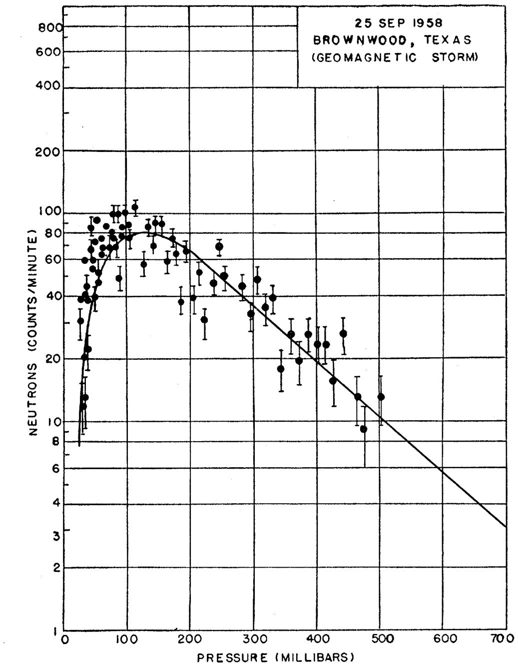

FIG. 7. Slow-neutron counting rate *vs* pressure for the second flight.

DISCUSSION

A. Double Maximum

An examination of Figs. 4 and 5 shows that a pronounced double maximum is exhibited by the curve for

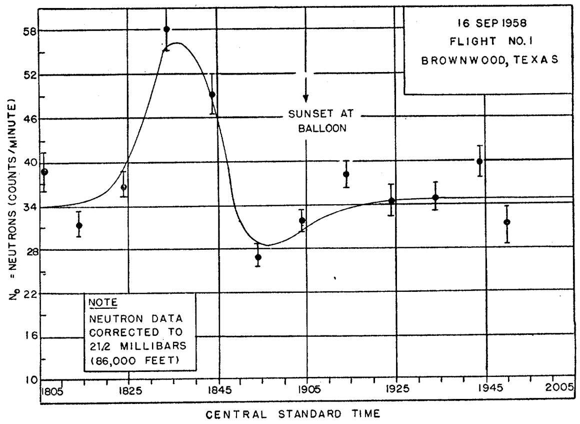

FIG. 8. Neutron counting rate corrected to constant altitude for the first flight. The sharp peak in the intensity is noted mainly in the counter enriched in B^{10}.

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[20] Reports TR-368 and TR-369 of the High Altitude Observatory, University of Colorado. We would like to thank the Observatory staff for making these weekly reports available to us.

[21] The author is indebted to Capt. E. B. Roberts, U. S. Coast and Geodetic Survey, for the magnetograms from the Tucson, Arizona, Observatory.

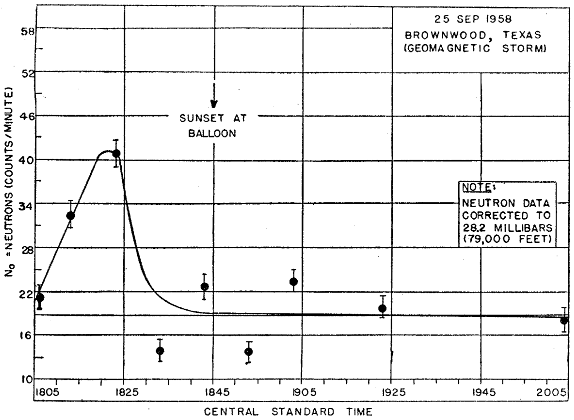

FIG. 9. Neutron counting rate corrected to constant altitude for the second flight.

the counter filled with "regular" (19% B^{10}) BF_3. This effect takes place at pressures between 50 and 100 millibars.

The pulses which are formed in such a counter are largely those due to background. This background is, among other things, due to star formation in the walls of the counter. Thus it appears that the presence of a double maximum in the counting rate is evidence for two components of the star-producing radiation. As Lord[22] has pointed out, those stars formed by fast neutrons reach a maximum at about 70 000 feet, while the remaining stars continue to increase exponentially to at least 94 000 feet (15 millibars).

There is a suspicion of a similar effect in the curves for the two enriched counters. However, the additional counts caused by slow neutrons tend to "smear out" the effect.

B. Variation of Secondary-Neutron Production Throughout the Solar Cycle

The curve shown in Fig. 6 represents the neutron intensity as a function of atmospheric pressure as measured at a geomagnetic latitude of 41°N. This measurement, as noted before, was made on an undisturbed day. Hence it may be directly compared with the curve for 40° shown by Soberman[6] for 1954, a period of minimum solar activity. These two curves are found in Fig. 11.

As may be seen from this figure, the intensity appears to be about 12% lower in 1958 than it was in 1954. Also, when the data for the equilibrium region ($770 \text{ mb} \geqslant P \geqslant 200 \text{ mb}$) are subjected to a least-squares analysis, it is found that the slope of the straight line corresponds to a mean free path for absorption of 240 ± 30 g/cm^2. This compares with a value of 180 ± 25 g/cm^2 found in 1954. The greater standard deviation is due to the fact that the present balloons used a somewhat greater rate of climb than those of previous investigators.[6,23,24]

Several investigators[25–28] have remarked on this inverse relationship between solar activity and cosmic-ray intensity. As can be seen from this work on the neutron component, the greatest change is in the low-energy end of the spectrum. This is evidenced by the increase in the mean free path for absorption between solar minimum and maximum. The picture implies the presence of a great many low-energy particles at the earth during the time of minimum solar activity which are not present otherwise.

C. Effects of a Geomagnetic Storm on the High-Altitude Intensity

As already noted, a geomagnetic storm was in progress during the second flight of September 25, 1958. There appears to have been no effect beyond statistics on the intensity or mean free path in the equilibrium region. Indeed, the effect on the sea-level neutron monitor at College, Alaska, was only a 2% decrease. However, at altitudes in excess of 70 000 feet, a significant decrease in the intensity of the slow-neutron component was detected. As may be seen in Fig. 7, the intensity at 28.2 millibars (79 000 feet) was only 50% of normal. It would appear that this storm was particularly effective at low energies.

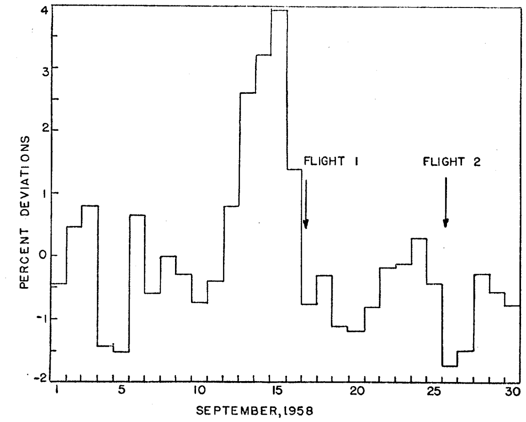

FIG. 10. Neutron monitor record for September, 1958, at College, Alaska. The data have been corrected for fluctuations in the atmospheric pressure.

It is interesting to note that this magnetic storm, the sudden commencement of which occurred at 0408 UT on September 25, followed a Class 2 solar flare by about

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[22] J. J. Lord, Phys. Rev. **81**, 901 (1951).

[23] W. O. Davis, Phys. Rev. **80**, 150 (1950).

[24] W. P. Staker, Phys. Rev. **80**, 52 (1950).

[25] H. V. Neher, Phys. Rev. **107**, 588 (1957).

[26] H. V. Neher and Hugh Anderson, Phys. Rev. **109**, 608 (1958).

[27] P. Meyer and J. A. Simpson, Phys. Rev. **99**, 1517 (1955).

[28] S. E. Forbush, paper presented under auspices of U. S. National Academy of Sciences at the Fifth General Assembly of CSAGI, Moscow, 1958.

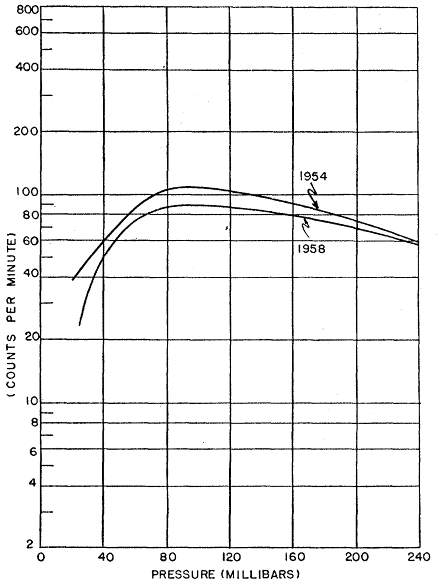

FIG. 11. Variation in the neutron intensity during the solar cycle at geomagnetic latitude 40°N. The statistical uncertainties are too great to permit comparison at lower altitudes.

42 hours. This flare was accompanied by a major burst of radio noise at 500 Mc/sec.[20]

D. Diurnal Variation of High-Altitude Neutron Intensity

The most interesting feature of the constant-altitude intensity curves (Figs. 8 and 9) is the sharp peak in the intensity. As can be seen from the curves, the maximum occurred about 25 minutes before local sunset on both flights. This places the maximum at just a few minutes after sunset at sea level. This increase is believed to be genuine, as no known source of instrumental difficulty could give rise to it. Also, it seems improbable that an instrumental failure would yield the same effect at the same time on two flights.

One explanation that has been proposed for this effect is that it is the result of a transition effect arising from solar neutrons which are incident upon the earth's atmosphere. This maximum would be due to the rapidly-increasing thickness of atmosphere that such neutrons would penetrate near sunset. This thickness amounts to 100 g/cm^2 at the time of maximum intensity.[29]

Other explanations, which avoid the necessity of invoking copious solar neutron production, and which attempt to account for the fact that the night-time intensity equals that found during the day, have also been proposed. These include the possible formation of microscopic ice crystals in the earth's atmosphere below the balloon at sunset.[30] Such crystals, as they increase in size, could, through neutron scattering, give rise to an effect such as the observed one.

Another possibility is that the effect is due to solar protons which are guided by a weak solar magnetic field.[31] These protons would be focused by the combined helio- and geo-magnetic fields on the sunset and sunrise positions at high altitudes. Neutron production would presumably result from the interaction of these protons with the upper atmosphere.

Further investigations of the effect are planned. In particular, longer flight durations, and data taken at sunrise should prove useful in the interpretation. Data acquired at other latitudes may also be significant.

SUMMARY

Two balloon flights launched at a geomagnetic latitude of 41°N during September, 1958, attained altitudes of 86 000 and 79 000 feet, respectively. They showed the following features:

(a) The cosmic-ray slow-neutron intensity had decreased by about 12% since the time of minimum solar activity in 1954.

(b) The effects of the geomagnetic storm of September 25, 1958 were most pronounced at atmospheric depths of less than 50 g/cm^2 (70 000 feet). At 28.2 millibars, the intensity was only 50% of normal.

(c) A sharp peak in the intensity of the slow-neutron component is found at balloon altitudes shortly before local sunset. No diurnal variation in the usual sense was detected.

ACKNOWLEDGMENTS

The author would like to express his gratitude to Professor S. A. Korff, who directed this work. He also acknowledges with thanks the assistance of W. Arthur, H. Blum, and F. LaPeter, as well as Mrs. M. Hommel.

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[29] E. C. Pressly, Phys. Rev. **89**, 654 (1953).

[30] L. B. Borst (private communication).

[31] W. N. Hess (private communication).