PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

High-Altitude Cosmic-Ray Latitude Effect from 51° to 65°N Geomagnetic Latitude*

J. R. WINCKLER AND K. A. ANDERSON†
University of Minnesota, Minneapolis, Minnesota

(Received June 28, 1957)

A significant latitude effect of approximately 45% for the total vertical cosmic-ray flux has been found over the region 51°N to 65°N at 10 g/cm^2 atmosphere depth in 1955. No evidence for a primary "knee" can be found separated from the air-path saturation effect with latitude. Since there is evidence that the α spectrum is flat north of 55°, one concludes that the rigidity spectra of primary protons and α's differ over the corresponding rigidity region. Comparison of these data with telescope measurements of Pomerantz and McClure in 1950 does not show the anticorrelation with sunspot numbers found by Neher for ion-chamber measurements. The data are not in disagreement with latitude coordinates 4° higher suggested by studies of α particles, and, in fact, the observed latitude "saturation" effects are in better agreement with these new coordinates. A greatly increased counting rate was observed both at Minneapolis and Flin Flon, Manitoba, on August 26, 1955 at high altitude.

I. INTRODUCTION

THIS paper will describe an experiment to measure the latitude effect for the vertical total cosmic-ray flux at high altitude in central North America. It was considered that a systematic series of such measurements was warranted, as the vertical total-flux data heretofore available consist of the scattered results of various observers[1–3] made over a period of years. The latitude effect has been measured with omnidirectional devices in rockets[4] and in the atmosphere[5] at high altitudes. However, the rocket measurements made with thin-walled Geiger counters have a different significance than vertical measurements, as the contribution of above-the-atmosphere albedo is large. All omnidirectional devices, particularly at high latitudes, may show a latitude effect due to changes in the earth shadow cone. This effect is uncertain to the extent that the earth shadow effects involve complicated cosmic-ray orbits, and there is both experimental and theoretical evidence that the older computations[6] may not be adequate.[7–10] Furthermore, an omnidirectional device, particularly when flown by balloons near the top of the atmosphere, obtains most of its response from particles arriving at large zenith angles and long air paths. At high latitude, where the ionization range of primaries is small, an omnidirectional detector may conceivably reach a latitude "saturation" or "knee" which is not characteristic of the primaries. It has, in fact, been shown by direct experiments at high altitudes[3] that there is no increase of the horizontal component from 52° to 69°, whereas the vertical component in the same experiments was observed to increase approximately 45%. The omnidirectional detectors have the advantage of gathering data quickly and with considerable accuracy, and in many types of cosmic-ray measurements, this is an overwhelming consideration.

The latitude "saturation" effect of omnidirectional detectors should also occur with vertical flux detectors, but at a higher latitude. The vertical detector in balloons is also affected by albedo and atmospheric secondary effects. A particular difficulty is that the vertical flux is determined near the beginning of an atmospheric transition process. These transition curves, "Pfotzer-maxima," very strongly with energy. The relative atmospheric flux builds up most rapidly with increasing depth for high-energy primaries at low latitudes, and the transition effect is much less at high latitudes. This complicates greatly the determination of even the *relative* true primary proton flux from high-altitude balloon measurements. To investigate this effect, it becomes necessary to examine the latitude effect at a series of atmospheric depths. The usual result is that the latitude effect increases as depth decreases at balloon altitudes. Even considering these severe limitations, however, the high-latitude vertical-flux survey can yield useful information, e.g.:

(1) It reveals whether the proton spectrum is increasing with lower rigidity.

(2) It can reveal a true primary "knee," provided this occurs at rigidities lower than the latitude "saturation" rigidity.

(3) By comparison with primary α or heavy-nuclei data made over the same latitude interval, it can establish whether the primary-proton and heavy-nuclei rigidity spectra differ or not at low rigidities.

(4) Time variations may be studied.

---

* This work is supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Now at the State University of Iowa, Iowa City, Iowa.

[1] H. V. Neher, *Progress in Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1952), Chap. 5 (see Fig. 32, e.g.).

[2] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[3] M. A. Pomerantz and G. W. McClure, Phys. Rev. **86**, 536 1952).

[4] Meredith, Van Allen, and Gottlieb, Phys. Rev. **99**, 199 (1955).

[5] H. V. Neher, Phys. Rev. **103**, 228 (1956).

[6] E. J. Schremp, Phys. Rev. **54**, 153, 158 (1938).

[7] J. R. Winckler and K. Anderson, Phys. Rev. **93**, 596 (1954).

[8] J. R. Winckler and L. Peterson, Phys. Rev. **99**, 608 (A) (1955).

[9] R. Danielson, University of Minnesota (unpublished); his conclusions for heavy nuclei are in agreement with references 7 and 8 for protons.

[10] M. Schwartz, Bull. Am. Phys. Soc. Ser. II, **1**, 319 (1956).

II. APPARATUS

In principle, one would like to carry the same vertical detector quickly over a range of latitudes at very high altitude. Time is important because of temporal changes in cosmic-ray intensity, which are known to occur, particularly at high latitudes.[4] Consideration was given to a high-altitude constant-level plastic balloon for this purpose, but the practical difficulties in predicting when a north-south trajectory could be expected on the basis of present meteorological knowledge, combined with the difficulties of long-range telemetering or recovery, made this approach seem unfeasible. Accordingly, it was decided to make soundings from the ground at a number of points distributed over the desired range of latitudes and at the same time to make reference soundings from a fixed station. Since very high altitude was a necessary factor in the experiment, and because of the difficulty of carrying large supplies of helium on a portable operation, it was decided to use an extensible neoprene balloon, Dewey and Almy type JP7000. Considerable success was reported with these balloons at altitudes greater than 100 000 ft. The detector unit was designed so that the load weight would be a minimum and consisted of a vertical telescope containing three trays of thin-walled counters, each tray containing two counters. The geometry is shown in Fig. 1. These counters have a wall thickness of 30 mg/cm^2, and the total stopping power of the telescope with the aluminum box is about 0.2 g/cm^2. The extreme angle of acceptance is 41°, but the half-angle from the vertical is about 20°, although undoubtedly, in terms of primary particles, the effective extreme angle is larger, due to scattering and secondary production above the telescope. The low stopping power makes the telescope sensitive to evaporation star fragments, for example, which are isotropically produced in the atmosphere. But because of the short range of these particles in the atmosphere, their effectiveness is greatly reduced. Because of the low stopping power of the counters, the telescope will give coincidences from a γ-ray source. A Ce^{60} source is routinely used for circuit checks, and it has proved very useful to be able to produce a high coincidence rate at will in the laboratory. The Compton recoils in the forward direction from Co^{60} have energies of about 1 Mev, which is sufficient for them to traverse the telescope. No coincidences are observed from Co^{60} with a 3.4-g/cm^2 aluminum filter placed in the telescope between the counter trays. The efficiency of the telescope for vertically incident Co^{60} γ rays (1.32 and 1.16 Mev) which intersected the top counter tray was determined to be 0.05%. The telescope is equipped with conventional electronics built around subminiature-type tubes, and the signals were transmitted on a subcarrier FM telemetering system. Pressure was telemetered by means of a baroswitch unit equipped with a large Kolsman bellows to extend the sensitivity at very high altitudes. With this arrangement, accurate pressures could be measured down to one millibar. The unit, complete with transmitter and batteries, weighed 5½ lb. The balloon weight was normally about 20 lb and comprised the major part of the flight weight. The radio tracking and tape recording of data were accomplished by a receiving station in a truck, which also contained 45 standard cylinders of helium and electronic analyzing and test equipment. This station was driven by a 2-kilowatt, 60-cycle, 110-volt Onan gasoline generator. Soundings were made between August 16 and September 30, 1955, over a range of latitudes from 55° north geomagnetic (Minneapolis) to 64.5° north (Flin Flon, Manitoba). (Geomagnetic coordinates according to eccentric dipole approximation to surface measurements.) Another point was taken at Ottumwa, Iowa, latitude 51.2°, after the major series was completed. During the main sequence in the series, simultaneous launchings were made at Minneapolis with identical equipment. A number of the telescopes were flown with 3.4 g/cm^2 of aluminum placed between the middle and bottom trays of counters, so that the total stopping power was about 3.6 g/cm^2 in this case. In the case of the field operation, the majority of the flights gave successful records to a pressure altitude of 10 millibars. In several instances, pressures less than this were achieved. The Minneapolis flights were hampered by not having satisfactory balloons, and the majority of these flights reached altitudes of only between 30 and 20 millibars. The telescope has a geometry factor of 9.38 steradian-cm^2 for radiation isotropic over the angular limits of the telescope, and, over the latitude studies, gave counting rates up to 350 counts per minute at the Pfotzer maximum. At the top of the atmosphere, the counting rate in general was about 200 counts per minute. All flights were preceded immediately before launching by a bell-jar pumpdown for barograph calibration and electronic check. Particular attention was given to corona from the 900-volt counter supply at low pressure, as the unit was not pressurized.

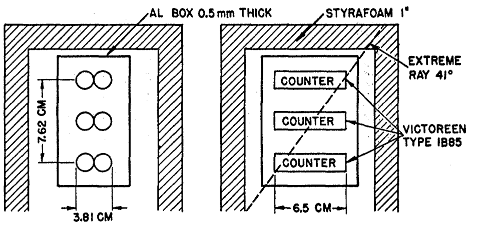

FIG. 1. Counter geometry. Each tray contains two thin-wall Victoreen Type 1B85 counter of 30-mg/cm^2 wall thickness. The total stopping power including the aluminum box is 0.2 g/cm^2. Solid angle = 9.38 sterad-cm^2 for isotropic radiation.

III. NORMALIZATION

A. Ground Level Experiment

Many of the counter telescopes were normalized by the standard method of comparing their counting rates

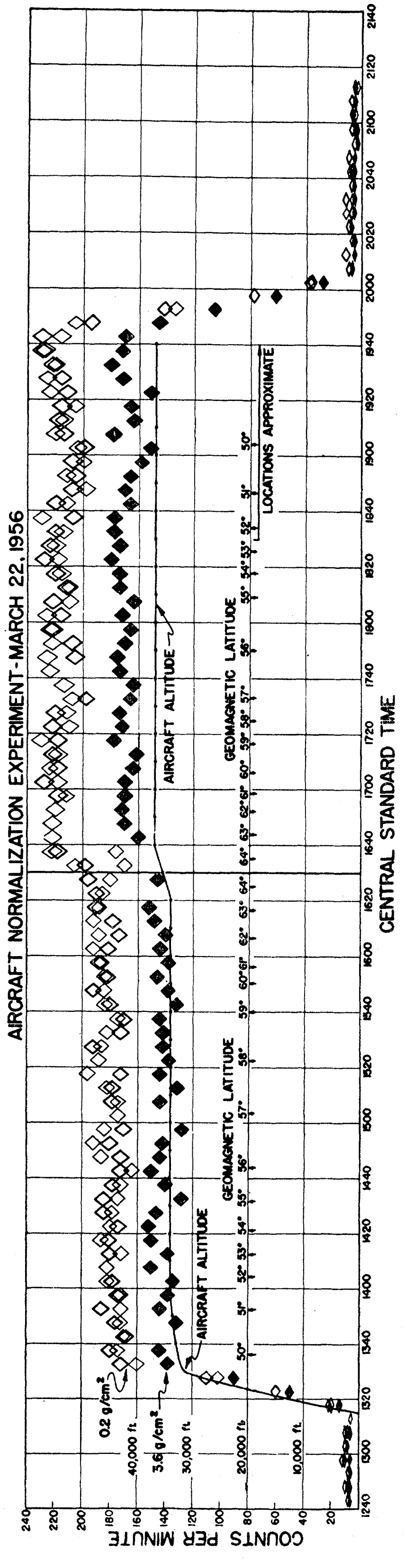

FIG. 2. Profile of counter telescopes flown in aircraft over the same route followed by the balloon soundings. Upper points, telescope without filter. Lower solid points, telescope with 3.6-g/cm² aluminum filter.

at ground level to better than 1% statistical accuracy. Two of the telescopes were kept as reference units and were not flown. The factors given in Table I compare individual units with one of these standards (No. IV).

The spread in values of column 2 of Table I is scarcely more than the expected statistical variations. Furthermore, if two telescopes are compared in various locations in the laboratory and at various times, the counting-rate ratio fluctuates almost as much as the values for different units shown in Table I.

In a number of cases it is not possible to obtain a counting-rate normalization factor, and in these cases the geometry factor compared to Unit IV was assumed to be unity.

B. Aircraft Experiment

When the flight data were plotted, it became obvious that differences existed from flight to flight, particularly at high latitudes, which could not be normalized away by correcting according to the geometry factor of Table I. It was concluded that either (a) the ground level comparison was not a good basis for predicting the relative response of different telescopes at high altitude or (b) the observed differences were real fluctuations in the primary beam at high altitudes and latitudes. An aircraft flight was undertaken for the purpose of relating ground-level and aircraft-level telescope normalizations, and for establishing the latitude effect at aircraft level for comparison with balloon flight data. Through the cooperation of the Strategic Air Command Headquarters, Omaha, Nebraska,[11] three telescopes, two without and one with filter, were flown in the bomb bay of a B-47 aircraft from Ottumwa, Iowa, to Flin Flon, Manitoba, at 34 000 ft (250 g/cm²) and from Flin Flon to Ottumwa at 37 000 ft (217 g/cm²), on March 22, 1956. The aircraft covered the same route taken by truck for the balloon soundings. The results are given in Fig. 2. The two units without filter (0.2 g/cm² stopping power) have closely the same counting rate (180 counts/min) and show a very small increase in rate between 50° and 64° of latitude. The counting

TABLE I. Telescope normalization factors.

Unit No.	Rate/rate IV	Used on flight No.	Date	Geo. lat.
V	1.043	12	August 21	60.3
VI	1.050	18	August 26	64.2
VIII	0.998	17	August 24	64.2
IX	1.020	15	August 23	62.3
X	1.006	19	August 26	64.2
XII	0.968	10	August 19	58.6
XIV	0.972	16	August 23	62.3
XVI	1.000	14	August 21	60.3
XVII	1.000	9	August 17	57.3

---

[11] We are indebted to Colonel Martin C. McWilliams, Colonel Francis W. Nye and Dr. W. A. Dwyer of Headquarters Strategic Air Command, Omaha, Nebraska for assistance in arranging the flights.

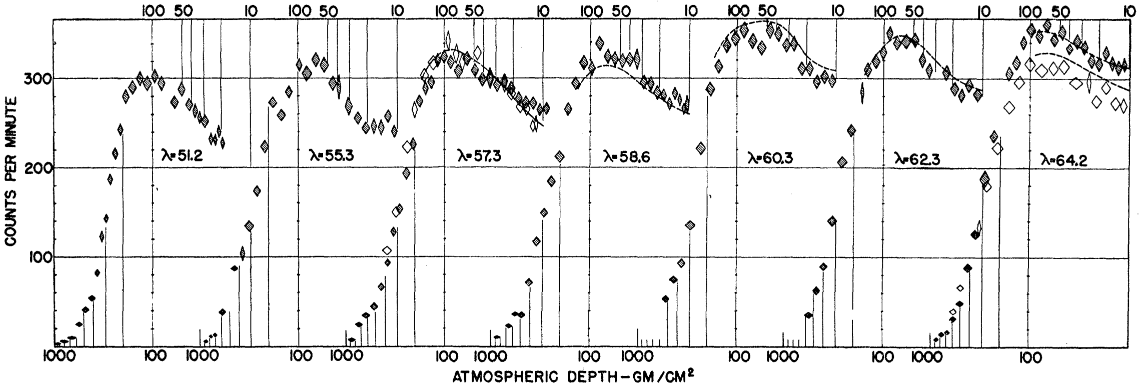

FIG. 3. The balloon soundings without filter showing the latitude effect from 51.2° to 64.2° geomagnetic.

rate at this altitude (250 g/cm^2) of 180 counts/min is less than that observed in the balloon soundings, which gave about 200 counts/min. This difference is probably due to the location of the apparatus in the aircraft. The 3.6-g/cm^2 stopping-power aircraft telescope also counts at a slightly lower rate than the balloon units with 3.6 g/cm^2. At the higher aircraft altitude the aircraft and balloon rates are nearly the same, but the latitude effect from 64° to 51° is also very small. Below 51° the aircraft locations were approximate, and there is evidence from the dip in counting rates that the trajectory went slightly below the latitude "knee" at this altitude and then returned north before the plane began its descent to the ground. The aircraft experiment establishes, (a) that the latitude effect from 51° to 64° at 250–217 g/cm^2 is small (less than 5%), and (b) an opportunity for comparing the ground-level and high-altitude counting rates of two similar telescopes shown in Table II. One notes that the units that differed by 4% on the ground gave nearly identical rates at high altitude, the effect in this case being quite significant statistically.

Normalization of balloon flight data at aircraft altitude (250–200 g/cm^2) has the difficulty that the balloon soundings change rate very rapidly with relative pressure in this region. Small errors in pressure may be very important, whereas at high altitude the counting rate varies slowly with relative pressure and is insensitive to pressure errors. If all balloon flight data were normalized in counting rate to the aircraft curve at 250 g/cm^2 or at 217 g/cm^2, balloon-pressure errors at that depth would be converted into serious counting-rate errors at high altitude.

TABLE II. Comparison of two telescopes on ground and at high altitude.

Unit	Ground counts	250-g/cm² counts
XX	25 958	39 050
XXII	24 901	39 250
XX/XXII	1.042±0.006	0.995±0.005

C. Simultaneous Flights

The flights made at Minneapolis simultaneous with the expedition will be discussed under experimental results. If the fluctuations in the primary beam are not spatially dependent, then in principle one can remove the effect of such fluctuations by comparing always with a fixed station. We have not found evidence for this situation in the present series, although the sample of cases is small.

D. Conclusions Concerning Normalization

In reviewing the entire procedure of ground-level comparison runs, at least with the telescope described here, one is tempted to conclude that these runs lead to rather erratic results, and that probably one does as well by constructing the telescopes closely the same, using Geiger counters from the same batch and then assuming all units to have equal geometry factors. Ground-level counting runs with these units may be complicated by their sensitivity to γ rays, which may vary with position in the laboratory while counting the presence of radioactive sources, accelerating machines, atmospheric precipitation, or other effects known to vary γ-ray backgrounds.

IV. RESULTS AND DISCUSSION

The series of soundings are collected in Fig. 3, and soundings are arranged in order of increasing latitude. Atmospheric depth from 10 to 1000 g/cm^2 is plotted on a logarithmic scale. The original curves are formed by the plotted points. The original curves corrected by the normalization factors when available are dashed. A less complete set of soundings with a 3.5 g/cm^2 aluminum filter in the telescopes was obtained and is shown in Fig. 4.

The general effect is of a continually increasing intensity superposed on fluctuations from sounding to sounding not removable by the normalization factors.

In Fig. 5 the results are summarized at 10 g/cm^2, 100 g/cm^2 (Pfotzer maximum regions), and 217 g/cm^2 (aircraft altitude). The latitude effect at 10 g/cm^2 from

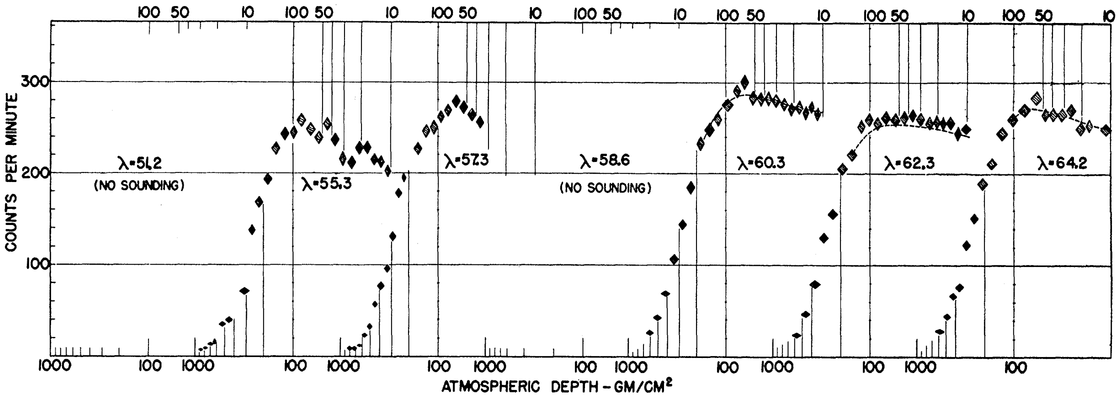

Fig. 4. Soundings with aluminum filter.

51° to 65° amounts to about 45%. There is no evidence for a true primary knee in this curve, but rather it flattens off between 60° and 65°, which may be accounted for on the basis of the latitude saturation effect. The magnetic coordinates of Fig. 5 are derived from surface measurements,[12] and there is evidence that the cosmic-ray cutoff rigidities agree better with coordinates giving latitudes 4° higher, at least at the geographical region of central North America.[13,14] On this basis, the atmospheric cutoff at 10 g/cm^2 would appear at 61°, instead of 65° on the scale of Fig. 5. The present data are just compatible with this effect, in view of the scatter of the points in Fig. 5 at high latitude.

At the Pfotzer maximum (100 g/cm^2) the latitude effect is greatly reduced and little or no change appears above 55° in Fig. 5. At aircraft altitudes there is no significant change north of 51° in Fig. 5. It is perhaps significant that the latitude saturation effect at 100 g/cm^2 range for protons should occur at 59.5°, and the data of Fig. 5 would be in agreement with this if plotted against the new coordinates, rather than those shown. Likewise, at 217 g/cm^2 range for protons, saturation should occur at 56.2°, which is also in better agreement with the new coordinates. However, ionization-range type considerations may have little significance at this latter depth, which is three nuclear collision mean-free-paths for protons in air below the top of the atmosphere. Furthermore, the propagation of the primary effects into the atmosphere in nonionizing steps, e.g., neutrons or γ rays, probably greatly reduces the validity of range-type considerations at these energies.

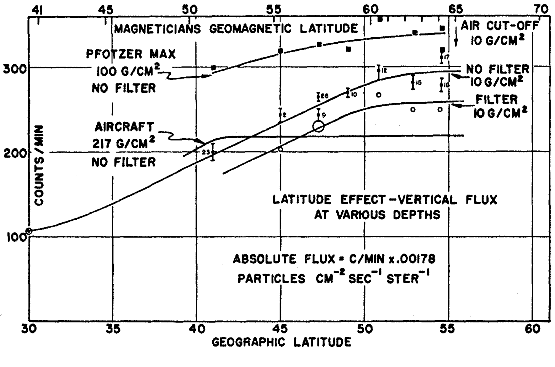

Fig. 5. Latitude effect for vertical flux at various depths.

Recent emulsion comparisons of primary α's at Saskatoon (61°) by the Minnesota group (Freier, Naugle, and Ney) and at Minneapolis (55°) by the Bristol group[15] (Fowler and Waddington) show that both the spectra and the intensities were the same at these two locations in 1954. These authors conclude that any rise in the total cosmic-ray intensity greater than a few percent north of the cosmic-ray latitude of Minnesota would imply that the cosmic-ray protons have a different rigidity spectrum than the α particles. MacDonald,[14] from a spectrum obtained at Minneapolis with combined scintillation and Čerenkov counters, infers that the same situation exists from counter measurements in 1955. Since the present results show an approximate 25% increase over this same region, one concludes that the proton spectrum differs from the α spectrum over this region of rigidities. The proton latitude increase may continue beyond the range saturation effect of the present experiment.

Rocket measurements with single counters by Van Allen[4] show a latitude knee at approximately 55°, but cannot be readily compared in detail with the present measurements.

Pomerantz and McClure[3] in 1949 and in 1950 measured the vertical flux in a series of flights at 51° and at 69° and their curves near the top of the atmosphere show an increase of about 45%, excellent agreement with the present values. The present results indicate that their high-latitude vertical measurements were made well above the latitude saturation point, which evidently sets in at about 60°.

---

[12] E. H. Vestine *et al.*, Carnegie Institute Publication 578, Washington D.C., 1948; J. Bartels, Terrestrial Magnetism and Atmos. Elec. (1936).

[13] Freier, Fowler, and Ney, Bull. Am. Phys. Soc. Ser. II, 2, 191 (1957).

[14] F. MacDonald, State University of Iowa (unpublished).

[15] P. H. Fowler and C. J. Waddington, Phil. Mag. (to be published); Freier, Naugle, and Ney, Phil. Mag. (to be published).

Although the absolute values may not readily be compared between Pomerantz and McClure's measurements and the present series (Pomerantz and McClure's vertical telescopes contained 4.0 cm Pb minimum as compared with 0.2 g/cm^2 in present experiments), it is clear that the relative latitude effect for the vertical telescopes at 10 g/cm^2 depth from 52° to 65° in 1949 or 1950 is closely the same as that in 1955. There appears to be a real difference between this result and ionization-chamber measurements made by Neher[5] in the years 1937, 1951, and 1954. For example, in Fig. 4 of reference 5, at 15 g/cm^2 depth, we find an increase of ionization with latitude from 52° to 65° of about 10% in 1951, which in 1954 has increased to about 25%. Since 1937, 1951, and 1954 represent years of successively lower sunspot numbers, this means an anticorrelation with solar activity. However, Pomerantz and McClure's telescope measurements in 1949 and 1950, made about $\frac{1}{3}$ the way down from the peak of the last solar cycle, and the present measurements in 1955, at the beginning of the climb in the present cycle, do not show a similar anticorrelation with the sunspot number indices. These conclusions are firm enough to be outside statistical, instrumental, or other similar experimental factors, and may be attributable to one of the following reasons: (a) There existed a temporal short-period variation in primaries at the time of measurement; this was not observed by Pomerantz and McClure over a period of one month. Present results did detect variations. The latitude effect is an average. (b) There exists a radiation having an inverse correlation with sunspot numbers and a very high ionization per particle which would give a much larger relative effect in ion chambers than counters.

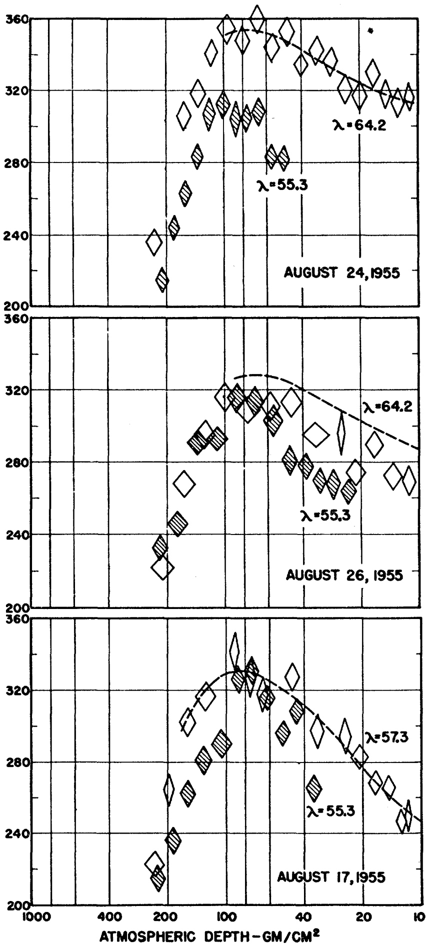

Fig. 6. Simultaneous flights at Minneapolis (55.3°) and two other latitudes (57.3° and 64.2°). At 64.2° a variation is observed not seen at 55.3°.

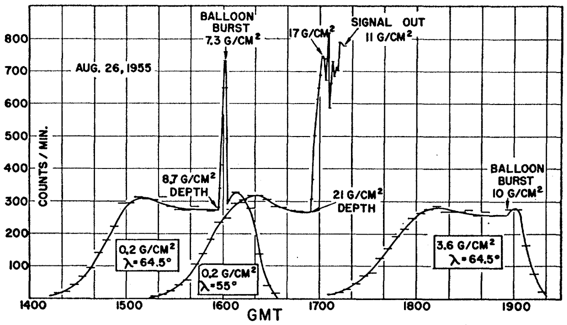

Fig. 7. Time-counting rate plot showing increases observed at Flin Flon (64.5°) and Minneapolis (55°) on the same day, but differing one hour in time. Note that the Flin Flon flight retraced its profile over the Pfotzer maximum while descending on the parachute. A flight later in the day showed no increase.

The absolute flux values computed from Fig. 5 at 10 g/cm^2 range from 0.36 particles/cm^2 sec sterad at 51° to 0.52 particles/cm^2 sec sterad at 64.5°. These flux values are considerably higher than those reported elsewhere.[2] Such high flux values seem characteristic of low-stopping-power telescopes with small physical dimensions. Experiments to study this point are underway, but the situation has not been resolved as yet.[16]

The telescopes flown with 3.5-g/cm^2 aluminum filters show a lower counting rate, especially at the Pfotzer maximum (see Fig. 4). The most significant result is that flights with filtered units were flown on the same days as flights 2, 9, 12, 15, and 18 and vary from day to day in the same direction (see Fig. 5). This indicates that the fluctuations observed were due to real changes in primary intensity and not instrumental effects which escaped detection.

Some of the flights at high latitude were accompanied by simultaneous flights at Minneapolis, and the higher portions of these are plotted in Fig. 6. Evidently the high-latitude fluctuations were not accompanied by corresponding changes at Minneapolis in these few cases. Neher has reported this result in some cases, but in others the fluctuations occur at both high and medium latitude stations.[5]

On one day, August 26, 1955, large increases were

---

[16] K. A. Anderson, University of Iowa and J. R. Winckler, University of Minnesota (unpublished results).

observed near the highest altitude reached on a flight at Flin Flon (64.5°) and also at Minneapolis (55.4°) but one hour later (see Fig. 7). The Flin Flon increase occurred at 1557 GMT and began when the balloon was at 8.7 g/cm^2. The increase at Minneapolis began at 1656 when the balloon had reached 21 g/cm^2. The Flin Flon flight was recorded as the balloon burst and until the telescope had descended to the ground on the parachute. The Pfotzer maximum is evident both on ascent and descent and other indications are that the unit was functioning properly. This flight profile resembles those obtained by Van Allen and co-workers with rockets.[17] It may be significant that a considerable auroral display was seen the previous night, although no significant solar flares or cosmic-ray neutron increases were noted.[18]

The spatial and temporal differences for this increase between Flin Flon and Minneapolis are difficult to explain on a simple model. In approximately 30 soundings with this equipment through 1955–56, including those reported here, no other such increases have been found except the great increase on February 23, 1956, which has been reported elsewhere.[19] In this latter case, the effect extended down to 300 g/cm^2 late in the flare when the sounding was taken, and did not resemble the behavior on August 26, 1955. A sounding later in the day on August 26 showed no effect. (See also Fig. 7.)

V. ACKNOWLEDGMENTS

Many thanks are due to Mr. Roger Aagard for major help before and during the expedition, and to Ray Maas, James Stoddart, and Robert Howard for construction of the electronic equipment. The cooperation of the Canadian Government and national park officials is greatly appreciated.

---

[17] Meredith, Gottlieb, and Van Allen, Phys. Rev. **97**, 201 (1955).

[18] Climax neutron data was furnished through the kindness of J. A. Simpson, University of Chicago. Solar reports from the High Altitude Observatory, University of Colorado.

[19] J. R. Winckler, Phys. Rev. **104**, 220 (1956).