Low-Energy Primary Cosmic-Ray Particles in 1954*

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The experiments herein described support and extend the relationship found by Forbush, namely, that there is an inverse relationship between solar activity and cosmic-ray intensity. During the summer of 1954 the sun was at a minimum of activity. Ionization chambers set up in the Arctic as well as at intermediate latitudes showed a considerable increase in intensity, during the period, compared with 1951. Atmospheric absorption combined with magnetic rigidity requirements indicate that protons with energies down to at least 150 Mev were coming to the earth in the summer of 1954. We conclude that there was no cutoff of primary particles, i.e., no "knee," at least for protons down to this energy. Using the increased areas under the ionization-depth curves, combined with geomagnetic calculations, an estimate may be made of the numbers of primary particles coming in near the poles in 1937 (solar maximum), 1951 and 1954 (solar minimum). These values are 0.10, 0.14, and 0.24 cm^{-2} sec^{-1} $sterad^{-1}$, respectively. The fluctuations in 1954 were also small compared with those measured in 1937, 1938, and 1951. The evidence points to low intensity and large fluctuations of cosmic rays when the sun is active and vice versa. These changes may be understood qualitatively by assuming a modulating mechanism in the form of clouds ejected from the sun and varying with the solar cycle.

I. INTRODUCTION

THE present experiments are a continuation of those made[1] in 1951 and were undertaken to continue the study of how the low-energy part of the cosmic-ray spectrum changes with time. It was quite apparent even before the summer of 1954 that large changes were taking place in the primary radiation over long periods of time and it was also apparent that the low-energy particles were subject to much more change than those of high energy. A study of Fig. 3, reference 1, which gives the measured changes at Bismarck over a period of years, shows the chief characteristics of these changes. The presence of the additional radiation in 1951 compared with 1937 or 1938, resulted in an ionization-depth curve which did not pass through a maximum. This behavior is to be expected if the radiation causing the difference is composed primarily of particles which do not multiply appreciably in the atmosphere, i.e., low-energy particles.

There was no obvious correlation of these large changes taking place at Bismarck with any terrestrial or solar phenomena. It was Forbush[2] who showed, from the long series of observations at the several Carnegie stations, that there is an inverse correlation between solar activity and cosmic-ray intensity. The data at Bismarck were consistent with this relationship except for the flights in August, 1940. These will be discussed later in this paper. It was apparent that the summer of 1954 was an ideal time to make another series of balloon flights, especially at high latitudes, since it was quite certain that the sun would be at a minimum of activity during this period and according to Forbush's relationship, the intensity of cosmic rays should be at a maximum.

As in 1951, two expeditions were organized and simultaneous flights were made by the two groups. The one again went to Bismarck, the other went from Boston to Thule on the icebraker U.S.S. Atka, then transferred to the U.S.C.G.C. Eastward and continued on north to geographic latitude 83°N, or 4° beyond the geomagnetic pole. All the balloon flights were made from shipboard except that made near Boston prior to boarding the ship.

II. DESCRIPTION OF APPARATUS

The equipment used was essentially the same as that used previously.[1] Some modifications were made, however, to secure a higher degree of accuracy and reliability. The changes made in the ionization chambers have been described elsewhere.[3] Seven of these chambers have been set aside and are used for calibration purposes. They have been compared with our older photographically recording chambers which were used in past years on balloon flights. They have also been carefully compared with each other, using the gamma rays from thorium C''. Over a period of nearly two years, no systematic changes in any of these seven instruments relative to the others have been detected. Three of these instruments were taken by the Bismarck group and four were used by the group going to Greenland. The instrument sent up was carefully compared with these standards just prior to the flight. The error in calibration was probably no more than $\pm 0.2\%$.

The ionization chambers were found to have a temperature coefficient, due to the nonuniform thickness of the gold coating on the quartz fiber. Each of 42 instruments was run at three different temperatures, namely 44°, 22°, and 4°C, when subject to the same intensity

* Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).

[2] Scott E. Forbush, J. Geophys. Research **59**, 525 (1954). The first announcement of this important discovery was made at the Duke Cosmic-Ray Conference in November, 1953.

[3] H. V. Neher and Alan R. Johnston, Rev. Sci. Instr. **25**, 517 (1954).

TABLE I. Repeatability of readings of ionization chambers from one day to another, at a temperature of 22.2°C.

Instr. No.	t_1 (sec)	t_2 (sec)	$\Delta t/t$ (%)
71	19.902	19.894	0.04
72	20.945	20.945	0.00
73	23.793	23.819	0.11
74	16.980	16.935	0.27
75	26.030	26.030	0.00
76	16.733	16.703	0.18
77	22.125	22.102	0.10
78	17.300	17.293	0.04
79	17.577	17.574	0.02
80	16.796	16.801	0.03

of gamma radiation. A thermostatically controlled refrigerated room was used. To illustrate the consistency of measurement, the sample data of the first ten instruments are given in Table I. The times between chargings given in columns two and three were taken on two different days inside the thermostated room. The temperatures were the same, namely 22.2°C. The fourth column gives the percentage difference between the two readings. Repetition at other temperatures shows equal reproductivity.

A temperature coefficient of each instrument was thus determined. By means of an Olland cycle, using a bi-metallic strip, the temperature information was transmitted to ground at intervals of 8 minutes during a flight. The temperature control of the instrument and the temperature coefficient were such that for no flight was the correction to the ionization greater than 1%. It is estimated that errors caused by temperature were in no case greater than 0.1%.

To illustrate the degree to which the temperature of an instrument may be controlled by using the sun and the "green-house" effect, Fig. 1 is given. The essential details of the cage and wrapping were as follows: Two layers of one-half inch thick mineral wool were wrapped around the instrument. It was then suspended inside a light bamboo cage around which was wrapped two layers of clear cellophane. The spacing between the light colored mineral wool and the cellophane was 1 to 2 inches. If the flight is made near the middle of the day, a 30% covering of aluminum foil is used, for otherwise the instrument becomes too warm.

A further change in the 1954 instruments over those used in 1951 was in the barometer units.[4] It was found that some hysteresis was being introduced by the guiding phosphor-bronze strip on the front of the bellows. Owing to the fact that the barometer was calibrated by reducing the pressure at the rate expected during a flight, a hysteresis effect should not introduce an appreciable error. However, it was found that the strip could be dispensed with, and hence it was not used on the present units.

The over-all performance of the equipment is illustrated in Fig. 3. Here the ionization *vs* atmospheric depth is given for five flights at geomagnetic latitudes of 81° and higher. The abscissas of curve A are correct. The other curves have been shifted successively 10 g cm^{-2} to the right to separate them. If plotted one on top the other, none of these curves departs more than 0.5% from the average of the other four in the middle part of their range.

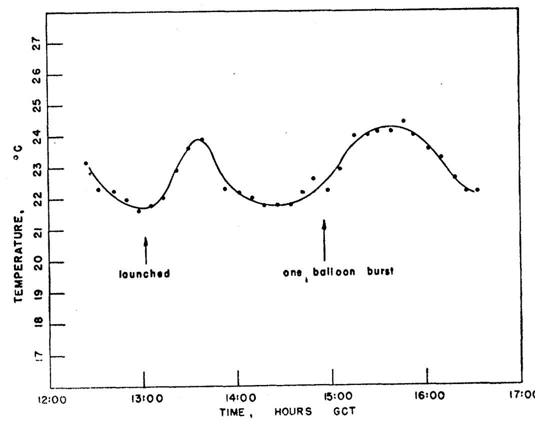

FIG. 1. Temperature record of Flight 82K1, July 28, 1954. With proper insulation and covering the instrument may be kept close to a constant temperature during a daytime flight.

Fluctuations in the primary radiation during the summer of 1954 were expected to be low because of the very low activity of the sun. We prefer to interpret the curves of Fig. 3 as showing that the combination of instrumental errors and fluctuations in the primary radiation at the times of these flights, which covered a three-week period, were less than 0.5%.

The performance of the equipment sent up with balloons was such that the only failure in the ionization record of the 25 flights made was the result of a hurricane which resulted in an antenna being knocked off by a tree just after launching near Washington, D. C. The major difficulty encountered on the other flights was in the premature bursting of the Neoprene balloons used.

III. EXPERIMENTS PERFORMED

Most of the flights made by the mobile station are listed in Table II. Seven other flights were made but the altitudes reached were too low to add useful information.

In Fig. 2 are plotted the data from the flights made by the roving station on July 11, 17, 19, and 28. These flights covered the geomagnetic latitude range from 53° to 81°N. The data for the flight of July 19 have been increased by 2% to allow for the fluctuation measured that day at Bismarck.

In Table III are shown the values of the ionization at 100 g cm^{-2} taken from the flights at Bismarck. From this table it will be seen that July 19 and 28 are not consistent with the other days. July 19 was low not only at Bismarck but also for the station on shipboard.

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

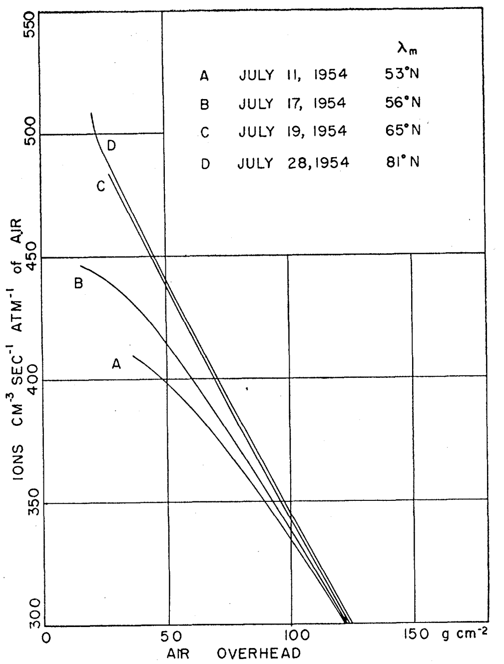

FIG. 2. Data taken by the mobile station on the trip from Boston, Massachusetts north to Greenland.

Hence this latter flight was corrected as indicated in the foregoing. The July 28 flight at Bismarck seems to be anomalous and may represent the same kind of non-simultaneous change found between Bismarck and Thule in 1951.[1]

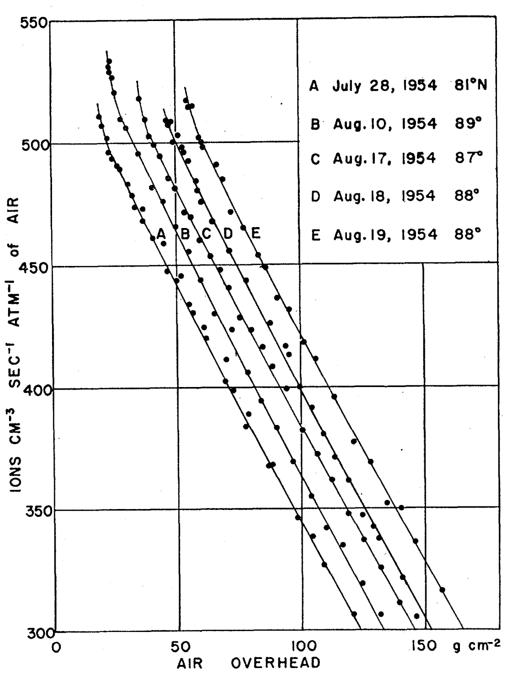

FIG. 3. Comparison of five flights taken in the Arctic. Curves *B*, *C*, *D*, and *E* have been shifted to the right successively 10 g cm^{-2} to separate them.

TABLE II. Times at which instruments reached maximum height, minimum pressure, and geomagnetic latitude for the mobile station.

Instr. No.	Date (1954)	t_{max} GMT	P_{min} g cm^{-2}	Geomag. lat.
117	July 11	14:27	40	53°N
91	17	14:59	18	56
90	19	14:48	30	65
82	28	14:55	20	81
84	Aug. 3	15:54	50	88
93	10	14:35	13	89
78	17	14:56	16	87
83	18	15:53	16	87.5
96	19	14:54	14	89

The flights made on July 28, August 10, 17, 18, 19 in the arctic region are shown in Fig. 3. To separate the curves, beginning with the second from the left, each curve has been shifted successively 1% of one atmosphere, or 10 g cm^{-2}, to the right. The accuracy of these curves has been discussed previously in connection with the performance of the equipment. The tendency for the slope to increase at the lowest pressures is evident in all five curves. Whatever is responsible for causing this behavior was present on these five days which extended over a period of three weeks.

To find the dependence of the ionization on latitude at a given atmospheric pressure, one may pick off the proper values from the curves of Fig. 2. These are plotted in Fig. 4, which is taken from an earlier paper[5] and is here reproduced for completeness.

In Fig. 5 we have collected pertinent data at 15 g cm^{-2} over a period of years taken at various latitudes. Instruments used in 1951 and 1954 were compared directly with the photographically recording instruments used in other years.[6] Hence it is believed that the results over the years may also be compared. The 1937 curve is a composite one. The point at 85°N was taken from the flight made by Carmichael and Dymond[7] in 1937 within 10 days of the flights made by Bowen, Millikan, and Neher[6] at 60°N. The curve of Carmichael and Dymond was fitted to that of Bowen, Millikan, and Neher by making them cross at the same point as was found necessary in the flights of Neher, Peterson, and Stern[1] in 1951 when they compared the simultaneous flights made at Bismarck (56° geomagnetic

TABLE III. Ionization at 100 g cm^{-2} pressure at Bismarck for the indicated days of 1954.

Date	I at 100 g cm^{-2}	Date	I at 100 g cm^{-2}
July 11	331	Aug. 3	334
17	331	10	334
19	324	19	333
28	348		

[5] H. V. Neher and E. A. Stern, Phys. Rev. **98**, 845 (1955).
[6] Bowen, Millikan, and Neher, Phys. Rev. **53**, 855 (1938).
[7] H. Carmichael and E. G. Dymond, Proc. Roy. Soc. (London) **A171**, 521 (1939).

north) and Thule, Greenland (88°N). The points at 38°N and 3°N were taken in 1936 while that at 17°N was taken in 1939.

A further comparison of the 1954 data with that obtained in 1951 for the Arctic region is shown in Fig. 6. Here also the curve of Carmichael and Dymond is given, adjusted as stated above. A similar comparison of flights made at Bismarck in 1951 and 1954 is given in Fig. 7. The 1937 curve is from the flight made at Saskatoon, Canada at geomagnetic latitude 60°N referred to above.

IV. DISCUSSION OF DATA

It is evident from Figs. 4–6 that large changes took place in the amount of radiation measured at high altitudes and high latitudes between 1951 and 1954. Still larger changes took place from 1937 to 1951. Taking Forbush's finding that cosmic-ray intensity is inversely related to solar activity, we see that the data herewith presented corroborate his result. For, as shown in Fig. 8 where we have plotted the relative sunspot numbers, as a measure of solar activity, we see that 1937 was a period of high sunspot activity, 1951 was during the waning part of the last period of activity, while the summer of 1954 was a time when the sun was less active than it had been for several cycles. Thus, while Forbush's result was obtained with ionization chambers at ground level, where the average energy of primary particles contributing to the ionization is probably in excess of 40 Bev, we see that instead of the 4% change which he obtained, the changes at high altitudes and latitudes in the ionization is at least 50%, or a ratio of over 12 to 1 in the relative changes.

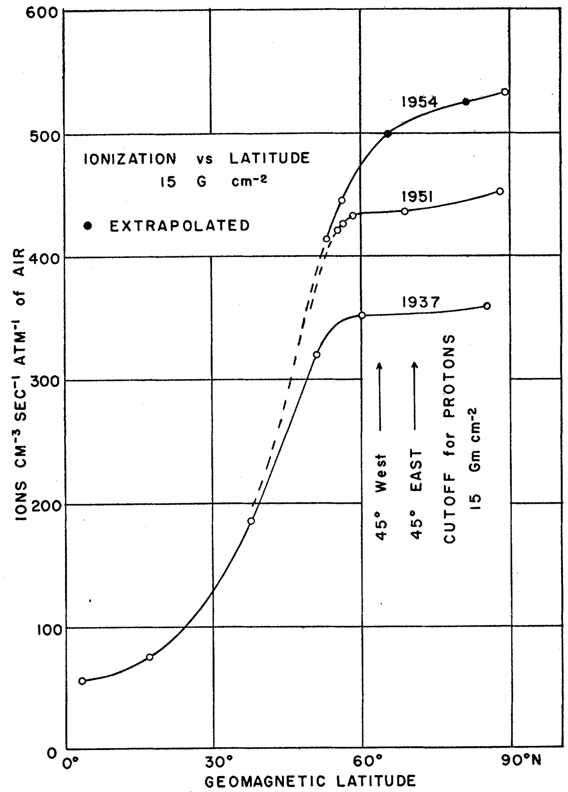

FIG. 5. Latitude curves for constant pressure for three different years. In 1937 the sun was at a maximum of activity while in 1954 it was at a minimum.

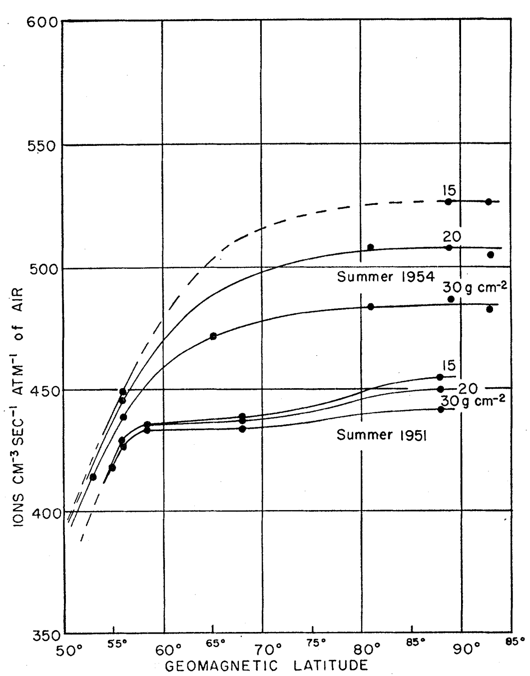

FIG. 4. Ionization *vs* geomagnetic latitude at the atmospheric depths indicated. The latitude "knee" present in 1951 has disappeared in 1954.

Indeed, this is one of the chief characteristics not only of this particular cosmic-ray fluctuation, but of others also, namely that the percentage change in the low-energy radiation, which comes in at high altitudes and latitudes, is much more than occurs in the high-energy primaries. The ratio given previously[8] was 7 to 1 for the relative changes at 50 g cm^{-2} at Bismarck as compared with ground level, and since the changes at Thule were the same as at Bismarck,[1] this same ratio held for the changes in the Arctic, at this pressure, compared with sea level. Thus the lower the energy of primary involved, the larger was the percentage change compared with that in the high-energy primaries.

From Figs. 4 and 5 it is seen that in 1937 and in 1951 a quite sharp break occurs in the ionization *vs* geomagnetic latitude curves at around 55°N. This has been called the "knee" of the latitude curve and has been taken in the past as evidence that there is a cutoff of primary particles below a rather definite magnetic rigidity. In 1951 this cutoff[1] was placed at 58°N which corresponds to a minimum energy for protons of 0.8 Bev. The latitude at which this cutoff occurs shifts

[8] H. V. Neher and S. E. Forbush, Phys. Rev. 87, 889 (1952).

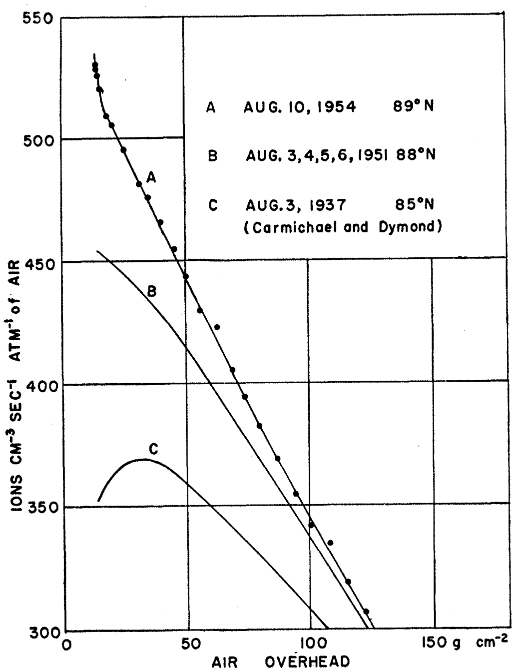

FIG. 6. Ionization curves near the geomagnetic north pole for three different years.

to higher latitudes as more lower energy particles are admitted, as is demonstrated very nicely by the airplane neutron data of Meyer and Simpson.[9]

Using the calculations on the effect of the earth's magnetic field on incoming charged particles, one finds from the 1951 and 1937 curves of Fig. 5 that the additional radiation responsible for the increase had rigidities lying primarily between 4 and 1.5 Bev/Zc, but nothing less than 1.5 Bev/Zc. In 1954 there was practically no additional radiation with rigidity above 1.5 Bev/Zc and there appeared to be no cutoff of low-rigidity particles at all.

Combining the range of protons in air with geomagnetic calculations enables one to plot the mass of air overhead that new protons, admitted by the earth's magnetic field, can penetrate at various zenith angles, *vs* geomagnetic latitude. This is done in Fig. 9 for 45°E and W. The energies of the protons involved above 60°N are such that the additional particles admitted lose most of their energy by ionization rather than by nuclear collisions. At 15 g cm^{-2}, using an omnidirectional device, very little effect of additional protons admitted by the earth's magnetic field will be measured beyond 68°N. The slow, continued rise of the curves in Figs. 4 and 5 above 68° we have attributed to the shadow-cone effect, modified by the albedo effect[1] and is present in 1937 as well as 1951 and 1954.

We therefore interpret the curves for 1937 and 1951 as shown in Figs. 4 and 5 to mean, if not a complete absence of low-energy primaries in 1937 and 1951, certainly a scarcity of particles having rigidities below 1.5 Bev/Zc. In contrast, in 1954, the ionization *vs* latitude curves, at the lowest pressures, continue to rise, up to the latitude where the atmosphere above the instrument would cut out the least absorbable particles. We therefore interpret these data to mean that there was no cutoff of primary particles in the summer of 1954 at least down to a rigidity of 0.54 Bev/Zc which corresponds to an energy for protons of 150 Mev. We have here used the minimum rigidity for particles affecting our instrument as those coming from 45° E.

That these low-rigidity particles are protons rather than heavier nuclei may be seen as follows: An α particle having a rigidity of 0.54 Bev/Zc would have an energy of 160 Mev and its range would be about one-fourth as large as that of a 150-Mev proton. Heavier nuclei would have even less range for the same rigidity. We therefore conclude that in 1954, the particles responsible for the rise of the latitude curve at high altitudes between 60° and 68° N and also for the turn up of the curves at the lowest pressures in Fig. 3 are protons.

As an illustration of the kind of behavior to be expected of low-energy protons, an attempt has been made to build up curves at various latitudes which are consistent with the latitude curves found experimentally and therefore also consistent with the increase in area under the curves from one latitude to another.

In such an attempt, one must take account of the change in ionization along the path of the particle,

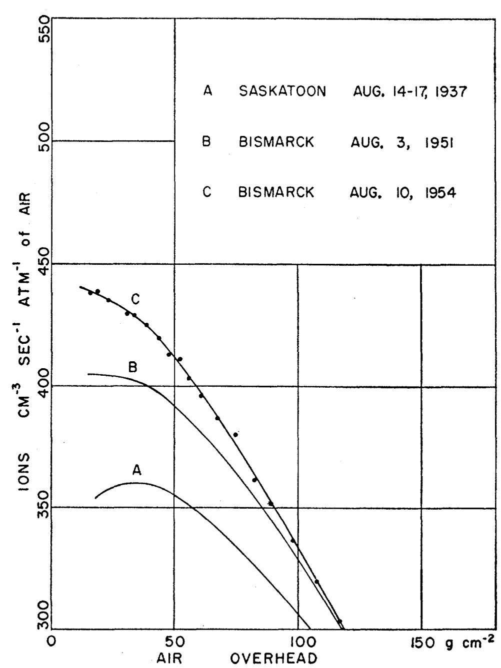

FIG. 7. Ionization curves at Bismarck for the same years as for Figs. 5 and 6. (Except curve A, which is for Saskatoon.)

[9] Peter Meyer and John A. Simpson, Phys. Rev. **99**, 1517 (1955).

since we are here dealing with protons which primarily lose their energy by ionization and which come to the end of their paths high up in the atmosphere. We must also integrate over a solid angle of 2π since our instrument is omnidirectional.

We start first from the fact that the increase in area under the ionization *vs* depth curve in 1954 from 56° to 90°N was 5500 ions cm^{-3} sec^{-1} atmos^{-1} of air$\times$g cm^{-2} in air at normal pressure and temperature. We next assume a differential energy distribution of the particles. A number have been tried. One of the simplest is the following:

$$N(E)=b/E, \quad 0.15<E<0.85 \text{ Bev for protons.}$$

Hence

$$\int_{E_1}^{E_2} EN(E)dE=b(E_2-E_1)$$
$$=5500 \text{ ions cm}^{-3}\text{ sec}^{-1}\text{ atmos}^{-1}\text{ of air}$$
$$=0.13 \text{ Bev cm}^{-2}\text{ sec}^{-1},$$

where we have taken the value of 32 ev per ion pair. Using the value of b thus determined together with calculations on the energies of protons involved, one finds the additional energy brought in from one latitude to another. Using, then, the expected change of ionization along the path of the particle and the omnidirectional requirement, one may build up the curves to be expected starting with $\lambda_m=56°$ as a base. The result is shown in Fig. 10. The crosses in the figure are the points obtained from the flight of August 10, 1954 at 89°N. We have used the minimum energy of protons as that to be expected at the vertical at a given latitude. A somewhat better fit might have been obtained at the lowest pressures if higher energy particles toward the east had been taken into account.

Although the agreement of the calculated and the experimental curves is not perfect, it is clear that the turn-up of the ionization-depth curve at the lowest pressures found in 1954 is consistent with what is to be expected from a continuous distribution of primary particles and is nothing anomalous.

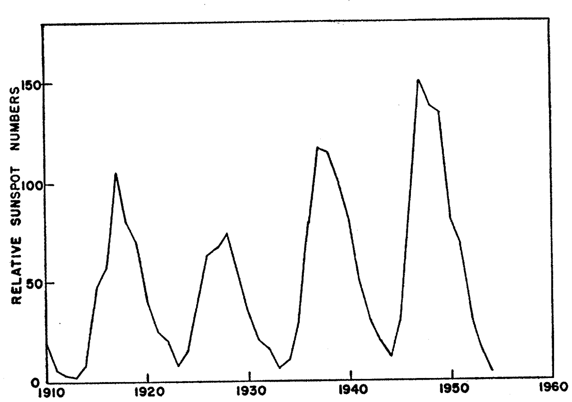

FIG. 8. Solar activity as measured by the relative sunspot numbers.

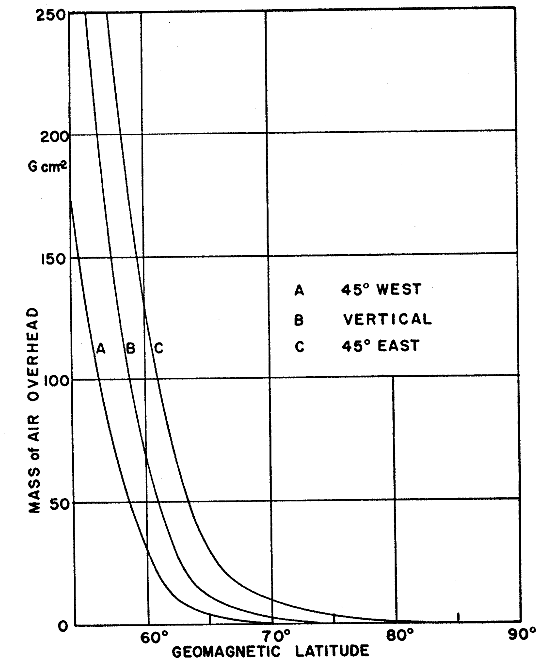

FIG. 9. Range in the atmosphere for protons which can just get through the earth's magnetic field as a function of geomagnetic latitude.

Taking the above number distribution we find the number of particles between E_2 and E_1 to be $b \ln(E_2/E_1)$ $=0.32$ cm^{-2} sec^{-1}. If one assumes isotropy at the top of the atmosphere, this corresponds to 0.10 cm^{-2} sec^{-1} sterad^{-1}. The average energy of protons, responsible for the difference between curves A and B of Fig. 6, then is $0.13/0.32=0.40$ Bev, or not far from the mean of 0.85 and 0.15 Bev.

An estimate of the numbers of particles responsible for the difference between curves B and C of Fig. 6 may also be made. The area of the difference extended to all depths is approximately 8000 ions cm^{-3} sec^{-1} atmos^{-1} of air$\times$g cm^{-2} or 0.20 Bev cm^{-2} sec^{-1}. Assuming an average energy of particle, causing the difference, of 1.5 Bev, we find 0.04 particle cm^{-2} sec^{-1} sterad^{-1} as the number of particles, assuming protons, responsible for the difference.

In a previous estimate[10] based upon data taken in 1937 and 1948, the number of primary cosmic-ray particles, assuming protons, down to an energy of 1.0 Bev was found to be 0.10 cm^{-2} sec^{-1} sterad^{-1}. Referred to 1951, we find from the above that this should be increased to 0.14. We must add another 0.10, giving 0.24, to arrive at the total number coming in near the geomagnetic poles in 1954. It is clear from the behavior of the curves of Fig. 3, that still more low-energy particles would have been measured had our balloons gone higher. We therefore believe that the

[10] H. V. Neher, Phys. Rev. 83, 649 (1951).

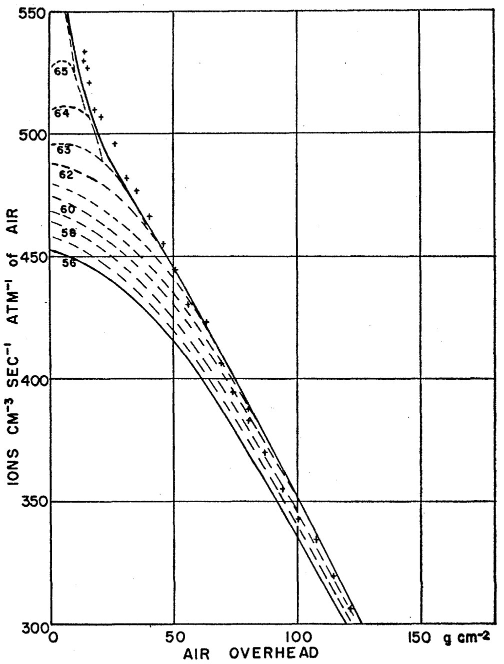

FIG. 10. The expected ionization curves at various latitudes, constructed by using geomagnetic calculations and a differential number distribution, $N(E)=bE^{-1}$, assuming protons, and using $\lambda_m=56°$N as a base. The crosses are the data for August 10, 1954 at $\lambda_m=89°$N.

number of primary particles changed by at least a factor of 2.4 from the solar maximum of 1937 to the solar minimum of 1954.

It is interesting to compare the number of primary cosmic-ray particles calculated from areas under ionization curves with direct measurements using rockets carrying Geiger counters. While in principle the rocket-borne equipment should give a much more accurate determination of this quantity, in reality it suffers from much more uncertainty. This is due primarily to the effect of the albedo, i.e., to particles ejected upward from the atmosphere, many of which are caught by the earth's magnetic field and are returned to the atmosphere.

Meredith, Van Allen, and Gottlieb[11] have recently summarized their rocket data and have attempted to correct them for albedo effects. In Table IV we give their data for various latitudes, both before (column a) and after (column b) correcting for albedo. The values given in columns c are those derived from ionization data.[10] Units are particles cm^{-2} sec^{-1} sterad^{-1}.

The chief uncertainty in the ionization method is in the energy going into neutrinos. An error is also made in assuming that all of the primaries are protons. The effect of these two errors on the calculated numbers is in the opposite sense and probably of nearly the same amount. The area under ionization curves is independent of albedo effects since the location in the atmosphere where the energy is lost is not important. It is interesting to observe that the two methods are now in quite good agreement.

V. INTERPRETATION

The inverse relationship between solar activity and cosmic-ray intensity points to some indirect influence of the sun rather than to the sun itself acting as a source of cosmic-ray particles. In effect the activity of the sun somehow suppresses the numbers of particles, their energy, or both. In fact, during most of the time low-energy particles seem to be kept away from the earth more or less completely and it is only during very quiet periods of the sun that they are permitted to enter. Even when protons down to 150 Mev are admitted they are not there in the numbers that might be expected. Thus, although a differential distribution $N(E)=bE^{-1}$ appeared to hold for the low-energy particles coming in in 1954 that were not present in 1951, this is a much less rapid dependence on E than is found at the higher energies. The reason for this may lie in a further mechanism, either in the acceleration process, or in some other modulating effect (see below).

When the fluctuations and intensity measured in 1954, are compared with those of 1937,[7] 1938,[12] 1947,[13] and 1951,[1] it is seen that not only was the intensity low when the sun was active, but the fluctuations were much more pronounced. Thus it appears that when the sun is active, the intensity of cosmic rays is down and the fluctuations are up, and conversely, when the sun is least active, the intensity of cosmic rays is up and the fluctuations are down.

Although much further work is required to give this general relationship a sound basis, it appears at the present time that most of the recognized fluctuations in cosmic rays (excluding flares) are of this type, namely, when the sun becomes active, the cosmic-ray intensity is suppressed and the fluctuations are increased.

Qualitatively this behavior may be understood by a modulating mechanism in the form of clouds of gas being emitted by the sun. These clouds, ionized and carrying with them magnetic fields, would presumably

TABLE IV. Comparison of numbers of primary particles measured with rockets (column a before correction for albedo, column b, after correction) compared with values calculated from ionization data (columns c).

λ_m	$E_{\min}$ protons	a	b	c 1937	c 1954
0°	14	0.052	0.018	0.012	...
41°	3.8	0.126	0.048	0.042	...
54°	1.0	0.31	0.11	0.10	0.14
87°	0.0	0.48	0.27	0.11	0.24

[11] Meredith, Van Allen, and Gottlieb, Phys. Rev. **99**, 198 (1955).

[12] R. A. Millikan and H. V. Neher, Am. Phil. Soc. **83**, 427 (1940).

[13] Biehl, Montgomery, Neher, Pickering, and Roesch, Revs. Modern Phys. **20**, 360 (1948).

affect low-energy particles more than those of high energy. At the same time such clouds, by their random distribution in the planetary system, varying size, and random emission from the sun would result in larger fluctuations than when they are absent. Morrison[14] has worked out a detailed theory of the effect of such clouds which has many attractive features.

Whatever the mechanism involved, in addition to the requirements stated previously, it now appears that it must also satisfy the following requirements:

(1) It must give the proper ratio of the changes in the low-energy particles to those of high energy.

(2) It must account for the world-wide character of these changes.

(3) While suppressing the total energy by something like 14% and holding the numbers of particles down to 0.4 of their value during a quiescent period of the sun, the mechanism, during an active period, must not allow large changes to occur from one day to another. In terms of clouds of solar origin, they cannot be present for a few days during large solar activity and then disappear.

(4) As the sun passes through the waning part of its cycle, the mechanism must permit the cutoff rigidity to move toward lower and lower values, permitting to pass most particles above this value, but still excluding those whose rigidity is below a certain value.

A conclusion one might be tempted to draw from the above picture is that during a very quiescent period of the sun, such as existed during the summer of 1954, all possible cosmic-ray particles should be able to get to the earth. In other words, if 150-Mev protons were able to get in, one might think that certainly all particles with higher rigidity would be able to enter. We should like to point out that this is not necessarily true and that other agencies of quite an unknown character may be at work. In 1940 a series of balloon flights, using ionization chambers, was made at Bismarck, North Dakota, Omaha, Nebraska, Oklahoma City, Oklahoma, Fort Worth, and San Antonio, Texas.[15] These same instruments are now used to calibrate those now employed, and it is believed that the results of 1940 may be compared directly with data obtained in recent years. The curves found, at all the stations except San Antonio, during the period, were higher than values obtained in 1937 and 1938 and higher than is to be expected from the present known solar cycle change. These changes, however, are consistent with those measured at Cheltenham and Huancayo by the Carnegie instruments. Forbush[2] has plotted the departures from balance of the Huancayo meter against the values taken from our curves, over a period of years, at 140 g cm^{-2}. The Bismarck point, which came from an average of 3 flights made on August 21, 1940, falls on a straight line that is consistent with the other points

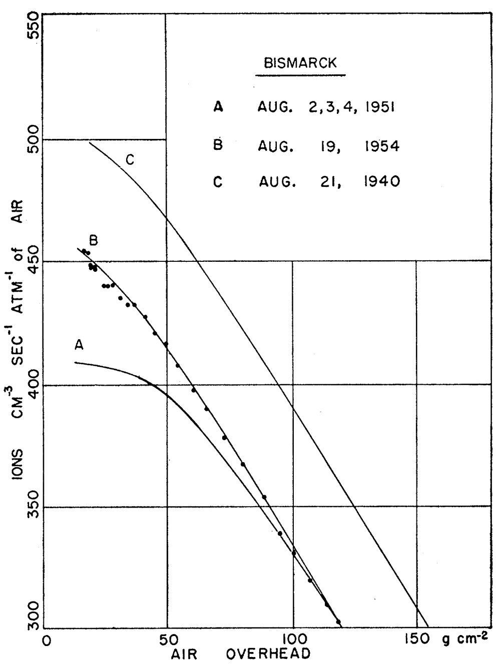

FIG. 11. Comparison of ionization curves of 1954 and 1940. All possible particles were not getting to the earth in 1954, as indicated by curve C taken in 1940.

for other years. Thus these 1940 data for Bismarck are completely in accord with what was found at Huancayo for the same day. In Fig. 11 this flight of 1940 is reproduced and compared with the flight of August 19, 1954, at Bismarck.

From this evidence, we conclude that on certain occasions at least 10% more energy may be brought to the earth by cosmic-ray particles than during normal times of very low solar activity. This is not the solar-flare type of increase, since it persisted for a number of days. We must indeed remember that the tacit assumption has been made up to the present discussion that cosmic rays are constant at some distance from the solar system. Such, of course, may not be true and other agencies may be at work.

VI. CONCLUSIONS

Evidence is presented to show that, in contrast to the usual idea that cosmic rays remain essentially constant, there are indeed large changes over a period of years. During a solar maximum the intensity appears to be least. From the solar maximum of 1937 to the minimum of 1954, the energy being brought to the earth near the poles increased by 14% and the numbers of incoming particles by at least a factor of 2.4. The appearance of the "knee" of the latitude curve during an active period of the sun and its disappearance during a quiet period seem to be manifestations of the fluctuations which are much more pronounced in the low-energy particles compared with those of high energy. If these changes are to be ascribed to a modulating

[14] P. Morrison, Phys. Rev. **101**, 1397 (1956).
[15] Millikan, Neher, and Pickering, Phys. Rev. **66**, 299 (1944).

effect due to ionized clouds being ejected from the sun, then we might expect the density of ionized matter in the vicinity of the earth to change during a solar cycle also. Besides correlations with magnetic activity, one might expect to find correlations of cosmic-ray intensity with other phenomena which depend on the presence of ionized matter in the vicinity of the earth.

Although the solar influence is probably the most important, the possibility of other modulating mechanisms must be borne in mind. The situation of August, 1940, where 10% more cosmic-ray energy was coming to the earth than during the solar minimum of 1954, is cited as a case in point. This was not the solar-flare type of increase for it not only lasted for a number of days but it was measured at Huancayo, Peru also.

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Spallation of Yttrium by 240-Mev Protons*

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The individual cross sections of 36 nuclides resulting from the inelastic interaction of 240-Mev protons on yttrium were determined. The results were found to be in agreement with the current theories of high-energy nuclear reactions. By means of interpolated cross sections for the stable nuclei produced in the reactions, it was possible to estimate the total inelastic cross section for yttrium with 240-Mev protons. By use of this value and application of the optical model, r_0 for Y^{89} was found to 1.21×10^{-13} cm and the nuclear transparency about 17%.

INTRODUCTION

INVESTIGATIONS of the interaction of high-energy particles with complex nuclei are made to seek answers to the following: (1) the mechanism by which high-energy reactions take place, (2) the total inelastic cross section, (3) the distribution of energy transferred.

Two experimental approaches may be used. One is the study of the particles emitted in these reactions by means of emulsions, cloud chambers, and counter telescopes. The second is the radiochemical approach whereby the products formed are isolated chemically and identified.

In this study, yttrium was bombarded with 240-Mev protons, the reaction products were separated and their yields determined by the radiochemical approach. Inherent in this approach is the disadvantage that the primary process is not observed directly but must be deduced from the end products. However, it has the advantage that it is possible to detect the effects of the emission of neutral particles.

Other studies on the interaction of high-energy particles with complex nuclei, as approached by the radiochemical method, are given in a recent review.[1]

EXPERIMENTAL

Yttrium in the form of spectroscopically pure yttrium oxide[2] was irradiated in the University of Rochester 130-in. synchrocyclotron at a radius corresponding to 240-Mev protons. Each target was prepared by wrapping 100 mg of yttrium oxide in a 5-mil aluminum foil envelope, 3 mm$\times$3 mm$\times$3 cm, the latter dimension perpendicular to the radial direction of the beam.

Two 1-mil aluminum foils were placed before and after the target foil, of which the two inside foils served to monitor the integrated proton beam through use of the known cross section for the reaction $Al^{27}(p,n)Na^{24}$. A value was used for the cross section for this reaction of 11.0 mb, which is based on an interpolation of the values determined by Hintz and Ramsey[3] at 110 Mev

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[1] D. H. Templeton, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, pp. 93–104.

[2] The yttrium oxide, supplied through the courtesy of Ames Laboratory, Iowa State College, Ames, Iowa, was better than 99.9% pure.

[3] N. M. Hintz and N. F. Ramsey, Phys. Rev. 88, 19 (1952).