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Balloon Study of High-Altitude Radiations during the International Geophysical Year[1]

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Abstract. The results of a series of 85 constant level balloon flights conducted during the IGY period to measure cosmic rays and other types of radiation at high altitude are summarized. Each flight carried an ionization chamber, a Geiger counter, and nuclear emulsions, and remained at approximately 10 g/cm² depth for times between 2 and 24 hours. The majority of flights were made at Minneapolis, Minnesota. The large decrease in primary cosmic-ray intensity between 1956 and 1958 was observed at high altitude. The high-altitude measurements correlate with sea-level neutron instruments. Many special events were detected, including X rays produced by electrons incident on the atmosphere during strong aurorae and solar cosmic rays detected on ten occasions and correlating with other known observations made in the polar regions. In one case γ rays originating on the solar surface were detected in a short burst. Several cases of radioactive layers in the atmosphere at low level resulting from nuclear explosions were found. This paper summarizes the entire program, and gives the instrumental details, a summary of published information, and detailed analysis of many data not heretofore published.

1. *Introduction.* This paper will summarize the results of an extensive series of balloon flights carried out as part of the United States program for the International Geophysical Year. The balloon flights carried instruments suitable for studying cosmic rays and other types of radiation found in the atmosphere up to heights of 30 km, or 10 mb pressure level. The balloons were of the constant-level polyethylene type, so that about 2 hours of each flight is required for the equipment to be carried to high altitude, and after that it remains at constant level for up to 20 hours. Most of the flights were launched from Minneapolis, Minnesota, and drifted in the prevailing winds in an east or west direction. Some were launched from other locations, including Cuba, Texas, and Alaska, and near-by sites in Missouri and South Dakota. Some of the measurements were made by attaching the radiation units to ONR 'Skyhook' balloons whose principal purpose was high-altitude experiments for other laboratories.

The equipment on these flights consisted of a spherical integrating ionization chamber, a Geiger counter, a recording package containing a small aerial camera and a pressure transducer, a telemetering transmitter, and a package of nuclear emulsions. The details of the apparatus have been described in a number of publications [*Ney and Winckler*, 1958; *Winckler, Peterson,*
tions, to X rays and γ rays, and also to radia-
Arnoldy, and Hoffman, 1958; *Peterson, Howard, and Winckler*, 1958]. The equipment is sensitive to primary cosmic rays and their time variations associated with radioactive clouds from

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nuclear weapons tests. Detailed analyses of a number of such events have been published and will be referred to later.

This summary of the results of the flights will be grouped into a number of categories as follows:

1. The high-altitude ionization rate and the total atmospheric energy integral as a function of time during the period of the IGY.
2. Changes of intensity observed as a function of latitude.
3. Observations of solar cosmic rays.
4. Observations of X rays associated with aurorae.
5. An observation of solar γ rays.
6. Observation of radioactivity from the testing of nuclear weapons.

This paper will discuss the data obtained with the various electronic detecting instruments. The results of the nuclear emulsion analysis have been recorded in a number of publications by Ney and others [*Freier, Ney, and Waddington,* 1959*a*, 1959*b*; *Freier, Ney, and Winckler,* 1959; *Fowler, Freier, and Ney,* 1958]; this analysis is continuing. An extensive analysis of the upper winds obtained from trajectories from the aerial camera photographs has been carried out by *Mantis* [1959]. The balloon trajectories thus obtained have been used for correlation with the cosmic-ray radiation data.

TABLE 1. Balloon Flight Summary

Flight	Date, UT	Launch Time, UT	Launch Location	Duration, launch to termination	Instrumentation*
	1957				
1	May 23	1201	Minneapolis, Minn.	11 hr 30 min	SC, IC, NE
2	June 6	0220	Minneapolis, Minn.	21 hr 40 min	SC, IC, NE
3	July 1	0107	Minneapolis, Minn.	21 hr 35 min	SC, IC, NE
4	July 4	0416	Minneapolis, Minn.	15 hr 40 min	SC, IC, NE
5	July 28	0217	Minneapolis, Minn.	16 hr 48 min	SC, IC, NE
6	Aug. 1	1037	Minneapolis, Minn.	10 hr 44 min	SC, IC, NE
7	Aug. 10	0150	Minneapolis, Minn.	8 hr	SC, IC, NE
8	Aug. 13	0200	Minneapolis, Minn.	9 hr 47 min	SC, IC, NE
9	Aug. 17	0118	Minneapolis, Minn.	19 hr 40 min	SC, IC, NE
10	Aug. 20	0818	Minneapolis, Minn.	14 hr 17 min	SC, IC, NE
11	Aug. 24	0315	Minneapolis, Minn.	1 hr 40 min	SC, IC, NE, PC
12	Sept. 1	0126	Minneapolis, Minn.	17 hr 50 min	IC, NE, PC
13	Sept. 4	1459	Minneapolis, Minn.	5 hr 30 min	Double IC
14	Sept. 10	1729	Minneapolis, Minn.	9 hr 43 min	Double IC, NE
15	Sept. 13	0207	Minneapolis, Minn.	4 hr 30 min	SC
16	Sept. 21	0040	Minneapolis, Minn.	4 hr 43 min	SC
17*a*	Sept. 22	0542	Minneapolis, Minn.	3 hr	SC
17*b*	Sept. 22	0344	Minneapolis, Minn.	1 hr 30 min	SC, IC, NE, PC
18	Sept. 23	0558	Minneapolis, Minn.	11 hr 50 min	SC, IC, NE, PC
19	Sept. 30	0315	Minneapolis, Minn.	8 hr 45 min	SC, IC, NE
20	Oct. 19	0445	Huron, S. D.	6 hr	SC, IC, NE
21	Nov. 6	1339	Minneapolis, Minn.	3 hr 45 min	Triple IC, NE
22	Dec. 3	1406	Minneapolis, Minn.	>4 hr 45 min	SC, IC, NE
	1958				
23	Jan. 2	1545	Sioux Falls, S. D.	8 hr 9 min	SC, IC, NE
24	Jan. 22	1129	Minneapolis, Minn.	9 hr 11 min	SC, IC, NE
25	Feb. 9	0202	Minneapolis, Minn.	19 hr 35 min	SC, IC, NE
26	Feb. 11	0440	Minneapolis, Minn.	14 hr 45 min	SC, IC, NE
27	Mar. 21	0745	Minneapolis, Minn.	6 hr 35 min	SC, IC, NE
28	Mar. 26	1136	Minneapolis, Minn.	6 hr 38 min	SC, IC, NE
29	Apr. 8	1109	Minneapolis, Minn.	9 hr	SC, IC, NE
30	Apr. 18	0329	Minneapolis, Minn.	6 hr 50 min	SC, IC, NE
31	May 16	1213	Minneapolis, Minn.	>14 hr	SC, IC, NE
32	May 30	0033	Minneapolis, Minn.	21 hr 58 min	SC, IC, NE
33	June 18	0235	Minneapolis, Minn.	18 hr 30 min	SC, IC, NE
34	June 20	0505	Minneapolis, Minn.	20 hr	SC, IC, NE
35	June 21	0100	Minneapolis, Minn.	21 hr	SC, IC, NE

TABLE 1. (Continued)

Flight	Date, UT	Launch Time, UT	Launch Location	Duration, launch to termination	Instrumentation*
36	June 27	1153	Minneapolis, Minn.	13 hr 25 min	SC, IC, NE
37	July 10	0757	Minneapolis, Minn.	2 hr 3 min	SC, IC, NE
38	July 11	0137	Minneapolis, Minn.	20 hr 40 min	SC, IC, NE
39	July 13	0049	Minneapolis, Minn.	19 hr 30 min	SC, IC, NE
40	July 18	2201	Minneapolis, Minn.	22 hr 15 min	SC, IC, NE
41	July 22	0040	Minneapolis, Minn.	16 hr 10 min	SC, IC, NE
42	July 25	0215	Minneapolis, Minn.	19 hr 16 min	SC, IC, NE
43	July 26	0041	Minneapolis, Minn.	23 hr	SC, IC, NE
44	July 27	0251	Minneapolis, Minn.	19 hr 24 min	SC, IC, NE
45	Aug. 17	0528	Minneapolis, Minn.	1 hr 30 min	SC, IC, NE
46	Aug. 22	0816	Minneapolis, Minn.	14 hr 40 min	SC, IC, NE
47	Aug. 24	0420	Minneapolis, Minn.	17 hr 45 min	SC, IC, NE
48	Aug. 27	0436	Minneapolis, Minn.	40 hr	SC, IC, NE
49	Sept. 4	0424	Minneapolis, Minn.	11 hr (approx.)	SC, IC, NE
50	Sept. 22	0518	Minneapolis, Minn.	9 hr	SC, IC, NE
51	Oct. 13	1332	Minneapolis, Minn.	7 hr 20 min	SC, IC, NE
52	Oct. 21	1115	Minneapolis, Minn.	6 hr 10 min	SC, IC, NE
53	Oct. 23	0644	Minneapolis, Minn.	6 hr	SC, IC, NE
54	Oct. 31	1148	Minneapolis, Minn.	17 hr (approx.)	SC, IC, NE, PIC
55	Nov. 22	0838	Minneapolis, Minn.	2 hr 15 min	SC, IC, NE
56	Nov. 24	0827	Minneapolis, Minn.	13 hr 30 min	SC, IC, NE
57	Nov. 27	0058	Minneapolis, Minn.	20 hr 42 min	SC, IC, NE
58	Dec. 18	1248	Minneapolis, Minn.	7 hr	SC, IC, NE, SCI
A	8/14/56	2138	Minneapolis, Minn.	>2 hr 22 min	SC, IC
B	9/18/56	1225	Crosby, Minn.	9 hr 36 min	IC, NE
C	10/16/56	1300	Minneapolis, Minn.	11 hr 10 min	SC, IC, NE
D	2/12/57	2110	Guam	2 hr 56 min	SC, IC
E_1	2/19/57	1549	Gaum	5 hr 40 min	SC, IC
E_2	4/8/57	1334	Minneapolis, Minn.	41 min	SC, IC
F	4/27/57	1348	Minneapolis, Minn.	7 hr 10 min	SC, IC
G	9/5/57	1306	South St. Paul, Minn.	>2 hr	IC, NE
H	11/10/57	Unknown	Huron, S. D.	Unknown	IC
I	10/27/57	1301	South St. Paul, Minn.	6 hr 38 min	SC, IC
J	10/19/57	1240	Brownwood, Tex.	10 hr 20 min	SC, IC, NE
K	2/16/58	1410	South St. Paul, Minn.	7 hr 12 min	SC, IC, NE
L	12/19/57	0832	Guantanamo, Cuba	7 hr 13 min	SC, IC, NE
M	3/20/58	0842	Guantanamo, Cuba	8 hr	SC, IC, NE
N	3/21/58	0740	Guantanamo, Cuba	9 hr	SC, IC, NE
O	3/21/58	0911	Brownwood, Tex.	Negligible	SC, IC, NE, GT
P	3/26/58	1204	Brownwood, Tex.	7 hr 20 min	SC, IC, NE
Q	6/27/58	1047	Moberly, Mo.	11 hr 55 min	SC, IC, NE
R	7/2/58	1220	Minneapolis, Minn.	10 hr 40 min	SC, IC, NE
S	8/23/58	0545	Fairbanks, Alaska	17 hr 30 min	SC, IC, NE
T	8/24/58	1045	Fairbanks, Alaska	17 hr 50 min	SC, IC, NE
U	8/27/58	0655	Fairbanks, Alaska	38 hr 50 min	SC, IC, NE
V	9/22/58	1944	Fairbanks, Alaska	2 hr	SC, IC, NE, PIC
W	9/10/58	2236	Fairbanks, Alaska	>16 hr	SC, IC, NE
X	9/23/58	0330	Fairbanks, Alaska	1 hr 40 min	SC, IC, NE

* *Key*:

SC = single Geiger counter.
IC = ion chamber.
NE = nuclear emulsion.
PC = photon counter.
PIC = pulse ion chamber.
SCI = scintillation counter.
GT = Geiger telescope.
\> = termination time not known accurately at time of this report.

The lettered flights are hitchhikes on ONR 'Skyhook' flights, or flights made by our project at field locations (Cuba, Fairbanks, etc.).

In Table 1 are summarized the flights made up to December 31, 1958. It will be of use for persons interested in comparing other types of data with the radiation data obtained on the balloon flights, and accordingly gives the time and latitude at which balloon exposures were obtained. Most flights carried the standard equipment of ionization chamber, counter, and emulsions, but in the last column of the table a notation is made of the exact instrumentation. A tabulation of all the balloon data obtained with the counting instruments is being completed and will be available as a Technical Report; it will also be made available to the IGY Data Centers. In general, the balloon flights rise in about 2 hours from launch to the floating altitude in the vicinity of 10 mb and remain approximately at this altitude until the indicated cut-down of the flight. A few of the flights have indefinite terminations, owing to a timer failure. The numbered flights are those made on our standard program at Minneapolis; lettered flights are those flown from field locations or as 'hitchhike' loads on Skyhook balloon flights.

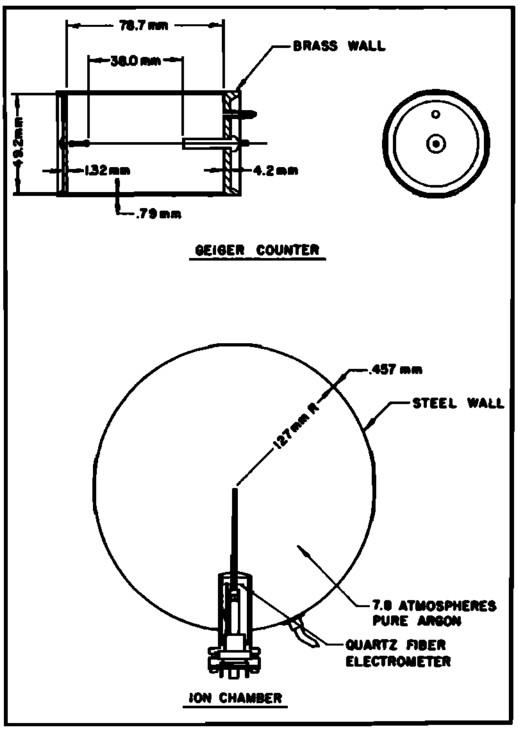

Fig. 1. Scale drawing of Geiger Müller counter and ionization chamber. See the text and Table 2 for further detailed specifications of these instruments.

2. *Summary of high-altitude intensities during the IGY.* One of the principal objects of the program was to observe the day-to-day intensity of galactic cosmic radiation at high altitude. For this purpose the counting rates of the ion chamber and Geiger counter have been standardized using a Co^{60} γ-ray source which provides photons of about 1-Mev energy. The geometry of the Geiger counter and ion chamber is closely the same from flight to flight, and this fact alone might be used for normalization. In the case of the ion chamber, however, the electrometers differ considerably from one chamber to another, which necessitates careful calibration with the radiation source. In Figure 1 is a scale drawing of the two instruments. It will be noted that the Geiger counter has a sensitive length less than its diameter, and this is so chosen that the response of the counter to particles is approximately isotropic. The omnidirectional projected area of the counter is 24.2 cm^2. The rates of the two instruments under the calibration source after correction for the decay of the cobalt were normalized to a standard rate of 50 c/sec for the counter and 50×10^{-3} pulse/sec for the ion chamber. The normalization factors thus derived were then applied to the flight data. The rates of the instruments after normalization were plotted as a function of pressure for the ascending part of the flight up to the point where the balloon floats level at ceiling altitude.

From these soundings the high-altitude intensity was read off at 10 mb for each flight. Figure 2 shows a set of soundings chosen as an example during the period of the March 25, 1958, intensity decrease. With the normalization factors and scale chosen, the counter curve generally lies above the ion chamber in rate but crosses somewhere near the ceiling altitude. The counter on all the IGY flights shows a considerable Pfotzer maximum in intensity, and the ion chamber likewise shows a mild maximum. It was noted that, on several of the very earliest flights in the series made in the fall of 1956, this maximum was absent and at the same time the intensity was much larger. In Figure 2, the curve of flight IGY-27 on March 21, 1958, is typical of the lowered level of intensity at solar

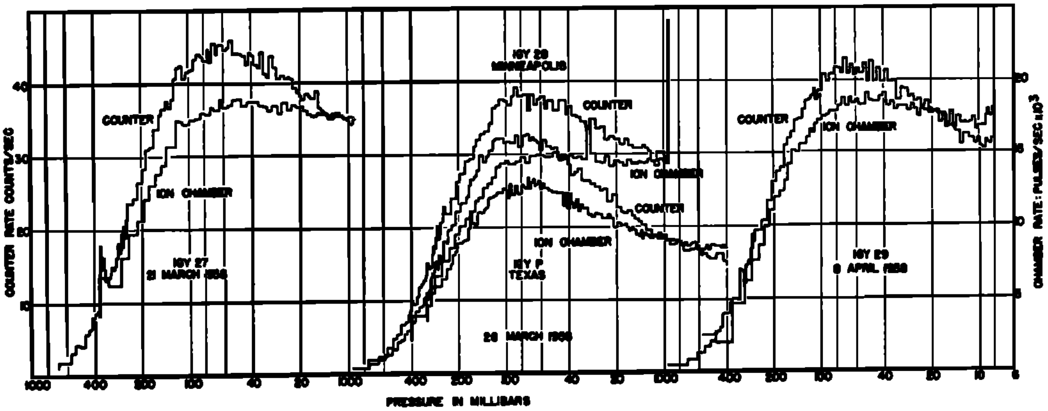

Fig. 2. A group of ion-chamber and counter soundings during the Forbush decrease and low-energy solar cosmic-ray event of March 26, 1958. Left-hand curves typical of solar maximum before the Forbush decrease. Note the spike on both instruments at about 350 mb, which is a radioactive layer in the atmosphere. Center set of soundings: upper, Minneapolis ion chamber and counter during the Forbush event; lower, ion chamber and counter at Texas at the same time. Right-hand sounding: ion chamber and counter after the recovery of the Forbush event.

maximum. On the ascent part of this flight, at about 350 mb, both the ion chamber and the counter show an increase associated with a radioactive layer from a bomb test. This event will be discussed in section 5. On March 26, the center set of soundings in Figure 2, both the ion chamber and the counter at Minneapolis show a decreased intensity, throughout the atmosphere, due to the Forbush event then in progress. Shortly after reaching ceiling, this particular flight encountered a large increase in flux which has been analyzed as incident solar protons in the low cosmic-ray energy range. This and similar events are discussed in section 3. On this flight some large spikes were observed on the ion chamber, and one of these occurs, as can be seen, at about 10 mb. The origin of these spikes is not at present understood.

Simultaneously with the Minneapolis flight IGY-28, a balloon was launched in Texas numbered IGY-P; the sounding is shown on the same pressure scale in Figure 2. It will be observed that there is a large latitude effect between Minneapolis and Texas. At Texas the intensity measured with both instruments is lower and the transition effects are bigger, which is to be expected as the average energy is higher. The Texas flight reached a considerably higher altitude of 4 mb, further displaying the atmospheric transition effect. A later flight, IGY-29, on April 8, is also shown (in Fig. 2) to illustrate the recovery of the high-altitude intensity from the Forbush-type event which occurred on March 25. In this figure, and in the graphs that follow, the counter rate is given in counts per second and the ion-chamber rate in pulses per second multiplied by 10^3, each on the normalized scale. The average omnidirectional flux may be obtained from the normalized Geiger counting rate according to the equation

$$\text{Flux} = \text{Normalized rate (c/sec)} \times 0.00725 \text{ Particles/(cm}^2\cdot\text{sec}\cdot\text{ster)} \qquad (1)$$

This assumes upper hemisphere response only.

The number of ion pairs per second, per cubic centimeter of standard air (76 cm Hg, 24°C), may be obtained from the normalized ion-chamber rates, R_m (pulses/sec $\times$ 10^3), according to the expression

$$N = 12.3 \times R_m \qquad (2)$$

In determining the 10-mb rates, in a few cases a short extrapolation is needed. In others, changes of intensity encountered at high altitude associated with various kinds of temporary radiation often made the ion-chamber rate increase as the balloon reached ceiling. In such cases an attempt was made to estimate the galactic cosmic-ray background. In addition, we have

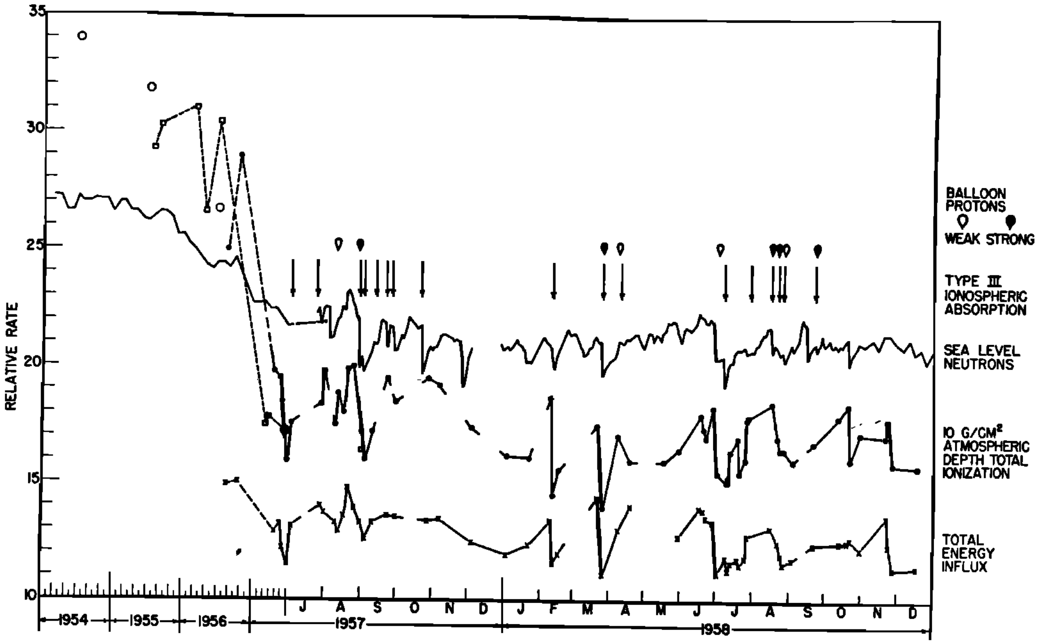

Fig. 3. Summary of high-altitude measurements during the IGY period compared with sea-level cosmic-ray detectors. Upper curve, neutron monitor intensities; middle curve, total cosmic-ray ionization at 10 g/cm² atmospheric depth; bottom curve, total energy influx measured as ionization. The dotted curve covering the period July 1955 to January 1957 with the data indicated as square points was obtained with small Geiger coincidence telescopes. We have normalized to our data the values obtained by Neher close to the geomagnetic pole and extending back to solar minimum in 1954 (circles). The arrows at top represent times when solar-generated low-energy cosmic rays were known to be incident over the polar region. The balloon above the arrow indicates a direct measurement of these solar cosmic rays with balloons, either at Minneapolis or at high latitude.

computed the atmospheric integral of the ionization according to the relation

$$P = 2.5 \int_0^{\infty} R\, dp \qquad (3)$$

for each of the ion-chamber curves. R is the normalized chamber rate in pulses/sec $\times$ 10^3, and dp the pressure increment measured in millibars. The value P of these atmospheric integrals is plotted along with the high-altitude values in Figure 3. The total energy dissipated in an atmospheric column 1 cm² in cross section is given by the relation

$$E = P \times 1.42 \times 10^8 \quad \text{ev/cm}^2\cdot\text{sec} \qquad (4)$$

The ratio (normalized ion rate)/(normalized count rate) is proportional to the mean omnidirectional ionization of the combined cosmic-ray primaries and secondaries in the atmosphere. In Table 2 are given average observed values under 'normal' conditions at various depths in the atmosphere. The calculated value for isotropic minimum ionizing particles is 3.19. Observed values are higher, and increase with altitude, as would be expected.

Figure 3 presents a summary of the high-altitude data obtained in the manner described

TABLE 2. Normalized Ion Rate/Normalized Count Rate under Various Conditions

Atmospheric Depth, g/cm²	Ratio × 10^4
300	3.36
200	3.84
100	4.03
50	4.21
10	5.02
Isotropic minimum ionizing particles calculated	3.19
Co^{60} γ rays uniform flux	4.03

above. We have compared our absolute values of ionization with those obtained by Neher, and this is discussed later in this section. During the IGY from July 1, 1957, to December 31, 1958, we have used a wide scale but for comparison have included some values reaching back to solar minimum in 1954, and this part of the scale is contracted. The flights on this program began in the fall of 1956 and extended through the IGY period. In Figure 3 is seen, at the bottom, the atmospheric integral for each of the flights; next above, the 10-mb total ionization rate; and on the top line, for comparison, the Deep River neutron monitor rates for the period. These last data were furnished through the IGY Data Center A for Cosmic Rays by courtesy of Hugh Carmichael. For comparison with the earlier values, back to solar minimum, we have used a summary prepared by *Forbush* [1958]. The neutron monitor data are those of the Ottawa neutron monitor, normalized to the Carmichael monitor about August 1, 1957. High-altitude ionization points with ion chambers similar to the ones used on this program and obtained by H. V. Neher are also plotted for comparison. They are normalized to our ionization points in June 1957. The justification for normalizing together Neher's Thule data with our Minneapolis data is the absence of a latitude effect between these points in 1957. This is discussed in later paragraphs.

In addition to the data of Rose and Neher as summarized by Forbush, we have also plotted data obtained at Minnesota with small Geiger counter coincidence telescopes flown at the 10-mb level. The results of this series of flights have been reported in the literature [*Winckler and Anderson*, 1957; *Winckler and Peterson*, 1958]. These Geiger-telescope points have likewise been normalized to the high-altitude ionization values in June 1957. One striking feature shown in Figure 3 is the large decrease in intensity accompanying the solar maximum period. This is shown by the data in Figure 3 prior to July 1, 1957, both by the high-altitude ionization and counting rate and by the sea-level neutron monitor. By comparing Neher's data, it is seen that the solar-cycle modulation between June 1954 and June 1957 is a factor of 2 in the high-altitude ionization. The change in the sea-level neutron rate over the same interval is about 20 per cent. The atmospheric ionization integral, although the data extend back only to August 1956, appears to agree more closely with the neutron monitor data, and the effect is not nearly as large as the high-altitude ionization effect. The anticorrelation of galactic cosmic-ray intensities with solar activity or sunspot numbers has been much discussed in the literature; see, for example, *Forbush* [1958], *Lockwood* [1958], *Simpson and Meyer* [1957], *Neher* [1956].

Another striking feature of the data is the many large, sudden intensity decreases which show in all the instruments. In examining the data in Figure 3, one must keep in mind that, although many balloon flights were made, the intensity record is nevertheless crude compared with the continuous sea-level monitoring instruments, and so some of the intensity decreases as shown by the neutron monitor will be missed on the high-altitude record. An attempt has been made to draw the high-altitude lines broken where it is obvious that details are lost, but a number of the high-altitude intensity decreases have good balloon data before, during, and after the decrease, and these show a striking correlation with the neutron monitor data. The arrows at the top of the figure refer to measurements of solar-generated cosmic rays; they are discussed in section 3. An examination of solar data shows that all the large Forbush decreases shown here are associated with intense solar flares that occurred between 1 and 2 days before the decrease.

It is important to examine the data to see what quantitative facts can be obtained about the nature of the modulation of the galactic cosmic rays over the period of the solar cycle and also during the sudden intensity decreases. The relative data as shown by the various instruments during these types of decreases are summarized in Table 3. We tabulate the fractional decrease in the sea-level neutrons, in the 10-mb-level total ionization, and in the total atmospheric integral ionization. These values are read off for a selected number of events for which data are available. Unfortunately, our balloon flight sequence does not extend back to solar minimum, but we have compared the 10-mb ionization with Neher's data that are available to that time.

TABLE 3. Comparison of Measurements during Cosmic-Ray Intensity Decreases

		Fractional Decrease			Ratios		
Date UT	Event	Sea-Level Neutrons	10-mb Total Ionization	$\int I\,dp$	Ions/Neutrons	$\int I\,dp$/Neutrons	Ions/$\int I\,dp$
7/54–7/57	Solar-cycle decrease	0.18	0.50	...	3.7	...	...
8/56–7/57	Solar-cycle decrease	0.10	0.32	0.17	3.1	1.6	1.9
8/29/57	Forbush decrease	0.11	0.20	0.089	1.8	1.2	2.2
2/11/57	Forbush decrease	0.05	0.22	0.13	4.6	2.8	1.6
3/25/58	Forbush decrease	0.06	0.20	0.23	3.3	3.7	0.90
6/28/58	Forbush decrease	0.07	0.15	0.16	2.1	2.3	0.92
8/17/58	Forbush decrease	0.05	.11	0.13	2.4	2.8	0.84

The last three columns of Table 3 give, respectively, the ratio of the 10-mb ionization to the sea-level neutrons, the ratio of the total atmospheric integral to the neutrons, and, last, the ratio of the 10-mb ionization to the atmospheric integral. The change in the 10-mb ionization for all seven cases discussed shows a factor of increase over the change in sea-level neutrons of approximately 3. There does not seem to be a striking difference in this case between the solar cycle decrease between 1954 and 1957 and the sudden intensity decreases, although some of the latter show smaller ratios. But, for example, the highest ratio observed is for the February 10, 1958, solar storm, where the relative value between 10-mb and sea-level neutrons is 4.0. This reflects the rather small change in the sea-level neutrons during this event. The average ratio of 10-mb ionization change to sea-level neutron changes for decreases throughout the IGY period is 2.8.

The ratio of the atmospheric integral to the sea-level neutrons seems to show a tendency to increase during the progression of the solar cycle through maximum. On the other hand, the 10-mb ionization compared with the atmospheric integral shows a tendency to decrease during the solar cycle, reflecting the fact that the atmospheric integral energy is sensitive to the high-energy part of the primary spectrum. A considerable fraction of the value of the integral is obtained from the low-altitude part of the flight, where the pressure is high and the intensities due to high-energy primaries are not negligible. The 10-mb ionization level, on the other hand, is sensitive to primaries down to the geomagnetic cutoff at Minneapolis. One must note that most of the ionization produced in the chamber floating at 10 mb, or about 100,000 feet of altitude, is caused by secondary particles in the atmosphere. Some effect is produced by the heavy elements in the primary spectrum because of their high Z and high relative ionization. These components, however, are rapidly attenuated at large zenith angles, where the chamber has its largest solid angle, and therefore do not contribute a very large fraction of the total effect.

As was also pointed out earlier, the 10-mb ionization level is sensitive to various kinds of soft particles such as the solar cosmic rays discussed in the next section, auroral X rays, and other types of radiation. Because these effects often appear during geomagnetic storms when the intensity of galactic cosmic rays is depressed, this contributes an error in the direction of increasing the high-altitude ionization at a time when the galactic cosmic-ray effect is to decrease the ionization. It appears that such effects may account for some of the fluctuations in the ratio, for example, of ionization to sea-level neutrons. The August 29 event, listed in

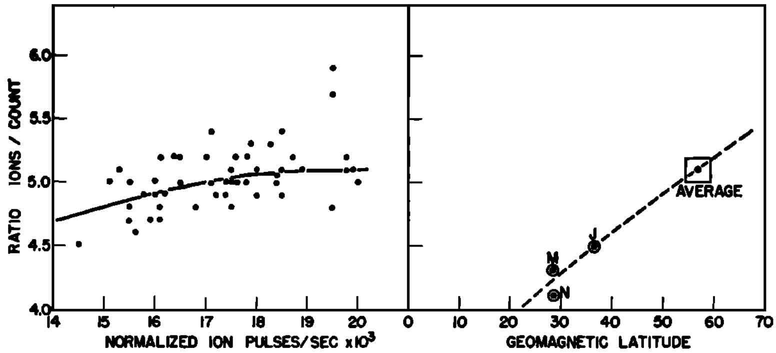

Fig. 4. Comparison of the ratio (normalized ion rate)/(normalized counter rate) as a function of ion-chamber intensity at Minneapolis, left curve; as a function of geomagnetic latitude, right curve. The fluctuations seen on the left curve are principally due to Forbush-type events during the IGY. The maximum change in ratio of such events is seen to be equivalent to a latitude change on the average of about 12°.

Table 3, shows a very low ratio, and the February 10 one a high ratio.

The most self-consistent data are those contained in the last column, where the high-altitude ionization is compared with the atmospheric integral. This ratio is sensitive to the extremes of the cosmic-ray spectrum, and it shows a progressive hardening as the solar cycle proceeds. The sudden intensity decreases, coupled with whatever continuous decrease may be superposed, flatten the spectrum more and more as the solar cycle progresses. The reader should remember, however, that considerable errors creep into the ratios given in Table 3. For example, the fractional decreases of the 10-mb total ionization given during the sudden intensity decreases are often in error because the time of the decrease coincides with the geomagnetic storm when solar cosmic rays, auroral X rays, or other effects are present at high altitudes, and this perturbs the readings due to the galactic cosmic-ray background. Errors creep into the measurement of the integral of ionization in the atmosphere on both the high-altitude and the low-altitude end, because in the former we have to integrate to infinity using the observed value at the last pressure point at the ceiling of the balloon. Also at the high-pressure end at low altitude the pulsing rate of the chamber is low enough so that an extrapolation is necessary, based on an average for many curves to fill out the ionization integral. These procedures lead to appreciable uncertainties. The error is difficult to estimate, but, in general, in the last column of Table 3 a significant effect is observed above the errors. That is, the continual decrease of the high-altitude ionization divided by the atmospheric integral appears to have a significant trend.

Some further information is available from the flight series on the intensity decreases. For example, we have compared the ratio of the 10-mb ionization rate to the 10-mb Geiger counter rate. In Figure 4 this ratio is plotted as a function of the level of intensity read by the ion chamber. There is considerable scatter of the points, and only a small trend is noticeable at the lowest values of ion-chamber rates. A much clearer effect is observed if the ratio of the ionization chamber to the counter is plotted as a function of the geomagnetic latitude for the few flights made on the program at lower latitudes compared with Minneapolis. This is shown also in Figure 4 in the right-hand section. The trend toward lower ratios at lower latitudes reflects the higher average energy and the decrease in heavily ionizing secondaries in high atmosphere. By comparing the two parts of Figure 4, the change in primary energy at Minneapolis during Forbush decreases is seen to be, at most, equivalent to a shift in latitude of about 12°, under the cosmic-ray conditions at solar maximum.

The same value is obtained from Figure 5, where the total ionization at 10 g/cm² is plotted as a function of latitude during normal levels

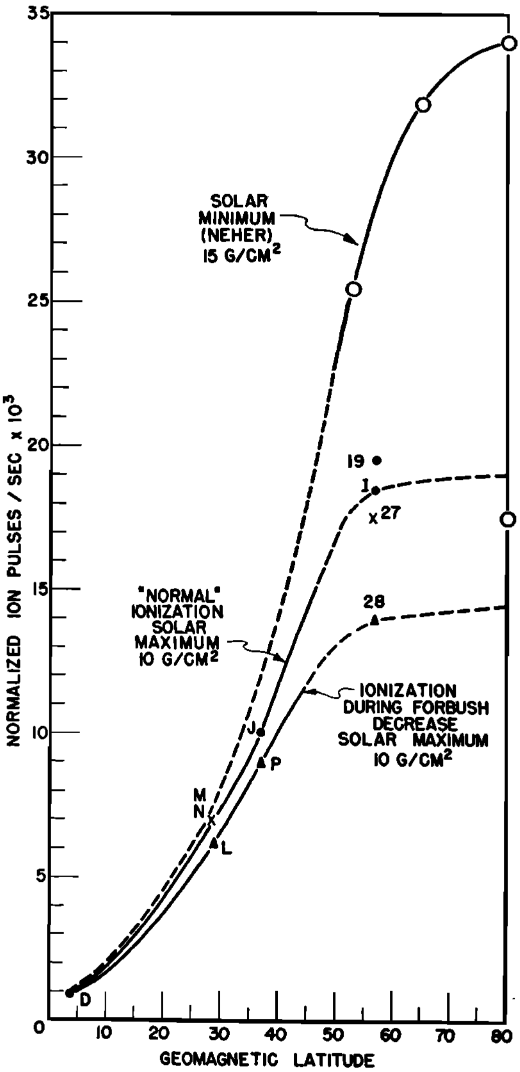

Fig. 5. Total ionization at 10 g/cm² depth as a function of geomagnetic latitude at solar minimum and for normal and Forbush decrease intensities measured at solar maximum. The numbers and letters refer to the various applicable flights of the present series. The circles are data obtained by Neher.

at solar maximum and during depressed levels following Forbush decreases. Unfortunately, the points on the two curves are not all for the same decrease, but on account of the paucity of data it was not possible to fill out complete latitude curves with the balloon data during a single intensity decrease. Also shown in Figure 5 are the high-latitude values of total ionization measured by Neher in 1954 at solar minimum at 15 g/cm² [*Neher*, 1956]. An approximate latitude curve is shown dotted, which normalizes with our data at the equatorial point, flight D, where it is known that the solar-cycle and intensity-decrease effects are of such size as to be inconspicuous on the present plot. Figure 5 shows immediately that both the solar-cycle effect and the Forbush-decrease effect operate selectively on the low-energy end of the spectrum. The question is whether the basic mechanism of these two is the same, that is, whether it is possible that the solar-cycle effect is compounded of many Forbush decreases from which recovery is not complete or whether the two mechanisms are basically different in their action on the primary cosmic-ray spectrum. The difficulty of getting good answers to this problem is obvious if the data shown in Figure 5 are carefully considered. First of all, the solar-cycle modulation removes the majority of the low-energy particles in the spectrum, and the effect of the Forbush decrease on these particles cannot, therefore, be studied in detail, at least with these data. It does appear that the qualitative effect of the solar cycle is similar to the effect of the sudden intensity decrease on the rest of the spectrum, but because of the crudeness of the data shown in Figure 5 this is not a very firm conclusion. It should be noted that Figure 5 is plotted as a function of geomagnetic latitude, which means that the data are representative in some way of the integral rigidity spectrum. However, the 10-mb ionization measured by the integrating ion chambers consists mostly of secondary particles in equilibrium with the primaries in the high atmosphere, and in some complicated way is related to the number energy spectrum of the primaries. It is very difficult to get point-by-point relations between the 10-mb ionization and the flux of particles because of the large effect of the secondaries. It does not seem wise to try to extract further information of this type from these data.

We have attempted several other means of comparing the different parts of the primary energy spectrum during the IGY period. One additional method is to plot the 10-mb ionization against the total energy influx calculated as the ion chamber ascends into the atmosphere. The results for all the flights are shown in

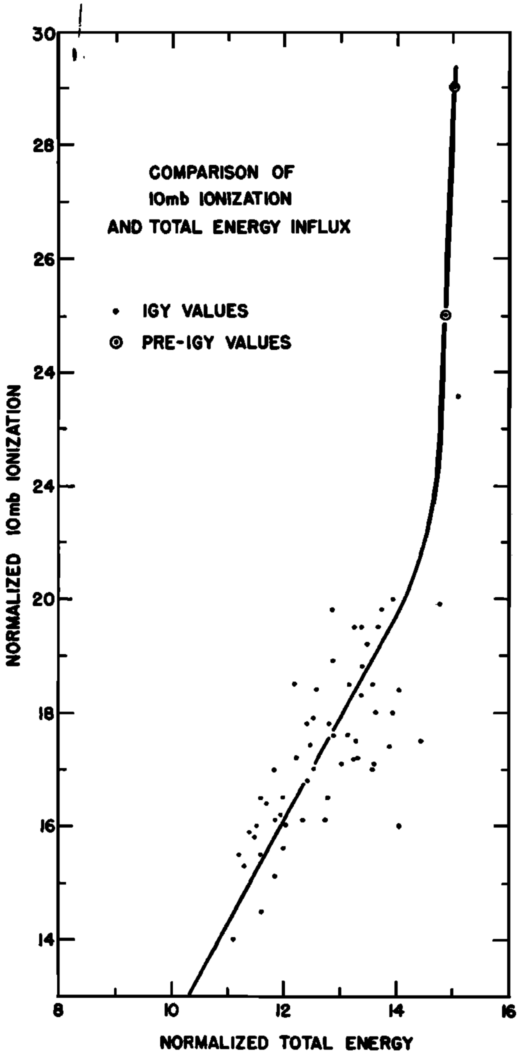

Fig. 6. The comparison of two parts of the primary energy spectrum obtained from 10-mb ionization and the normalized total atmospheric energy integral. Most of the points are during the IGY period, but the two high points represent pre-IGY values before the intensity had dropped to the low value during sunspot maximum.

Figure 6. Two points are available before the main solar cycle decrease in the winter of 1956–1957; all the other points are during 1957–1958. It can be seen that there is a rough proportionality during 1957–1958 but that the curve steepens a very large amount at the high-intensity values of the 10-mb ionization. These high-intensity values refer to points taken in the fall and winter of 1956. Figure 6 reflects again netic latitude effect, although generally present, the depletion of the low-energy part of the spectrum relative to the high-energy part.

We have also compared the 10-mb total ionization with ground-level neutron monitors as shown in Figure 7. The upper part of Figure 7 is for the Churchill neutron monitor (Churchill neutron rates obtained from U. S. Data Center A for Cosmic Rays, courtesy of D. C. Rose, 1958). The lower part of Figure 7 is for the Climax neutron monitor (Climax neutron monitor neutron data through U. S. Data Center A for Cosmic Rays, courtesy of J. A. Simpson, 1958). In the lower figure we have connected the points in temporal sequence by straight lines. We see that there is a general proportionality but that there are large excursions, for example those connected with flights 18, 19, I, and 21, which occur in a fairly short region of time and show deviations from the neutron monitor in the same sense, in this case corresponding to the temporary return of a more highly ionizing but lower than average energy radiation. In the upper part of Figure 7 the encircled points refer to pre-IGY values comparing the Ottawa monitor and the 10-mb ionization. The Ottawa and Churchill monitors are on the same scale. This curve, showing the large change in the relative spectrum between fall 1956 and summer 1957, is very similar to Figure 6. (Note difference in scale proportion in abscissas of Figure 6 and 7.)

Since the balloons frequently drift somewhat in geomagnetic latitude during a particular flight, and since the trajectories are known accurately over a considerable part of each flight from the aerial camera photographs, it is possible to measure differential latitude effects from many of the flights as long as the altitude remains sufficiently constant so that an altitude effect is not superposed. Figure 8 shows data from a number of flights which meet satisfactory criteria of having trajectories at constant level. The geographic latitude and longitude have been converted to geomagnetic latitude using the earth's centered dipole approximation.

From these differential segments is noted a trend from the latitude of Minneapolis, where most of the flights cluster, toward latitude 41° in Texas, where several flights were made. However, at the latitude of Minneapolis the geomag-

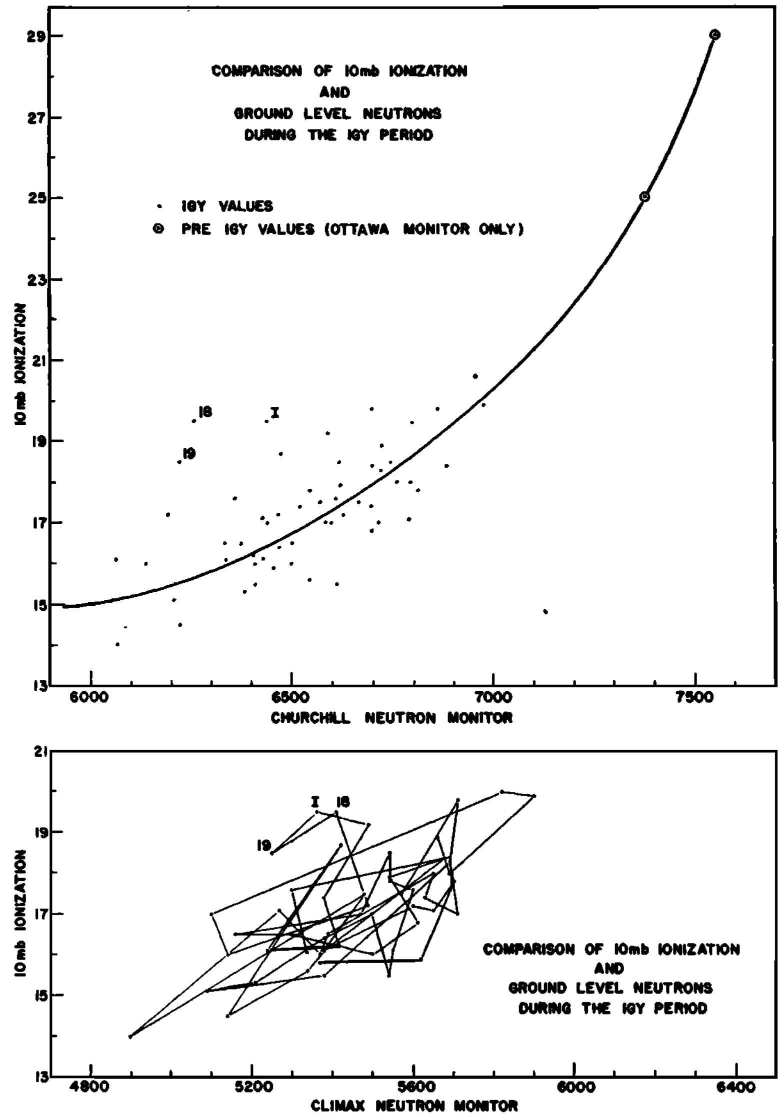

Fig. 7. Comparison of two parts of the primary energy spectrum using the 10-mb ionization and the sea-level neutron data.

is highly variable. The absolute intensity fluctuates a great deal in accordance with the maxima and minima in the over-all cosmic-ray intensity, and the latitude effect varies strikingly from one flight to another. For example, flights 19, 27, and 28 show very steep latitude effects attributable to the presence of some low-energy solar particles, which, having a very steep spectrum, produce such a latitude effect. This is in contrast, for example, with flight I over the same region, which shows no latitude effect at all and was during a time when solar particles were absent and the intensity was fairly high for the sunspot maximum period. Several high points shown in Figure 8 at values of 25 and 29 on the normalized rate scale which date back to the fall of 1956 show some features of the large intensity decrease with the solar-cycle effect. The weight of the evidence is that, except for times when low-energy solar cosmic rays are present, the

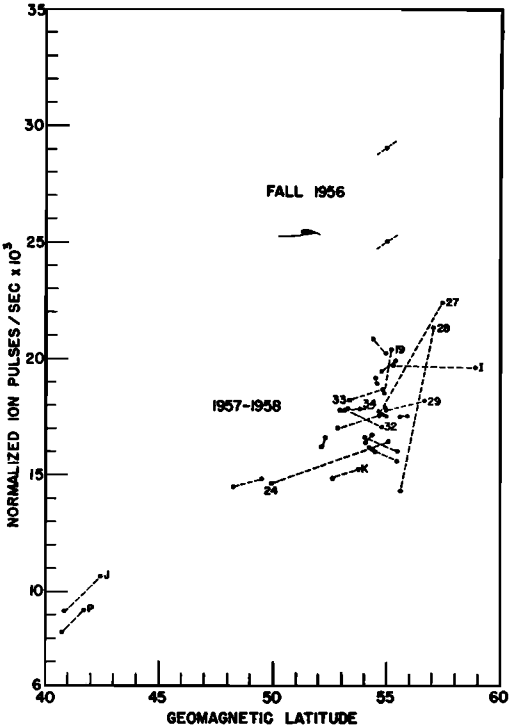

Fig. 8. Differential latitude effects from single balloon flights which remain at constant altitude. Two flights were made in the fall of 1956 as shown in the upper part of the figure. All the other flights were made in 1957 and 1958 following the large decrease at solar maximum. There is a general latitude-effect trend, but for the flights in the neighborhood of Minneapolis large differences are observed on different days. In particular, flights 27 and 28 seem to show the presence of very latitude-sensitive radiation. Flight I shows no latitude effect.

latitude effect is negligible at Minneapolis or at more northerly points during the period of the low intensity at solar maximum. Some flights show even a negative latitude effect, probably due to a specific time variation during the flight.

During the summer of 1958 *Neher* [1958] conducted a series of sounding flights at Bismarck, N. D., using integrating ionization chambers. The atmospheric ionization rate was given at the location of the ionization maximum (approximately 50 g/cm²). In Table 4 Neher's results are compared with flights made in this series on the same or adjacent days. The values have been read from our curves also at the ionization maximum, and are computed using equation 2. Table 4 thus represents an absolute comparison between the two investigations. In the last column, giving the ratios of the measurements, we note that the Minnesota values are on the average 16 per cent lower than Neher's. We do not believe that this discrepancy is caused by the geographical difference of Minneapolis and Bismarck, as cosmic-ray latitude effects were essentially zero over this range of latitudes in 1958. The packaging of the Minnesota ion chamber for night flights required several inches of Santo Cell powder and an exterior aluminum can. For very soft radiation a small effect might be produced, as the thickness was about 0.5 g/cm², but it does not seem possible to account for more than a few per cent by this means. In December 1959 we directly compared the standardization of the California Institute of Technology and the University of Minnesota laboratories by measuring the rate of the same ion chamber under the Co^{60} calibration sources at the two locations. Again we found the same 16 per cent discrepancy. The two laboratories are rechecking all fundamental calibration procedures to determine the cause of the difference. The absolute work at Minnesota has been carried out by *Hoffman* [1960].

It is interesting to examine the flights for regular diurnal variation; the large number of flights which stay at high altitude during the night and day hours give an opportunity to set limits on such a variation. The result is very simple: none has been found under normal conditions, and the upper limit to the effect is of the order of about 2 per cent in the total ionization or counting rate of the Geiger counter. On at least one occasion, however, a strong diurnal effect was observed during a geomagnetic disturbance in the low-intensity period of a Forbush-type decrease. This diurnal wave is shown in Figure 12 in section 3. Diurnal variations of this type following the sudden intensity decreases have been known in the past. They are apparently connected with an anisotropy of outer space to the galactic cosmic rays, and in time, with proper analysis, it may be possible to examine the causes of the anisotropy in terms of solar magnetic fields. During the time of measurement of the low-energy solar cosmic rays, discussed in a later section, the geomagnetic storm variations on these particles at

TABLE 4. Comparison of California Institute of Technology and University of Minnesota Ionization Measurements at High Altitudes

Bismarck (Neher)			Minneapolis (Univ. Minn.)				
Date	Time	I, ion pair/ $cm^3 \cdot sec$	Date	Time	Normalized Rate	I, ion pair/ $cm^3 \cdot sec$	Ratio, UM/CIT
			6/21	0200	18.2	218	0.83
6/22	1323	251					
6/24	1301	256					
6/26	1431	260					
6/27	1310	259	6/27	1310	19.0	228	0.85
6/29	1313	256					
6/30	1402	252					
7/2	1828	248	7/2	1330	17.5	210	0.85
			7/10	0900	16.6	199	
			7/11	0250	16.6	199	
7/12	1522	241					
			7/13	0200	18.0	216	0.89
7/14	1527	243					
7/15	1531	246					
7/17	1536	247					
			7/18	0240	16.8*	202	0.805
7/19	1527	251					
7/20	1550	251	7/20	0145	17.0	204	0.81
						Average	0.839

* Shows increase to 10 g/cm^2.

Minneapolis are unfortunately so large that they mask any regular diurnal effect, and it has not been possible to determine whether solar particles vary as a function of local time.

3. *Solar cosmic rays.* Probably the single most significant finding of the entire series was the frequent occurrence of intense low-energy solar cosmic rays. They originated from large solar flares but had an energy spectrum so steep that the particles were not detected by the extensive network of sea-level cosmic-ray monitors established during the IGY. The particles were measured directly, however, by means of balloons at altitudes greater than 20 or 25 km; they showed very strong ionospheric effects over the polar-cap regions. The recognition of the relationship between the high-latitude ionospheric blackouts and these influxes of solar cosmic rays has been extremely useful in predicting the time at which balloon soundings could be made to study these events in detail.

Before the solar cosmic-ray events described here, five other solar increases observed at sea level were known; they occurred on February 28 and March 7, 1942, July 25, 1946, November 19, 1949, and the largest increase of all, on February 23, 1956. This last event received world-wide study from numerous sea-level observatories, and some high-altitude experiments were carried out. It has generally been thought that such cosmic-ray flares are infrequent, as shown by the above-mentioned dates, namely, about once every 3 years on the average. The development of high-altitude ballooning techniques and riometer-type integrated absorption measurement over the polar regions has brought to light many additional cases, smaller in intensity and with a maximum energy less than that of the sea-level events. The speculations based on the first five events, to the effect that the cosmic-ray outbursts were either very large or not present at all, have not been confirmed, and as more sensitive measurements are made it is found that many flares generate solar cosmic rays over a wide range of intensity.

One of the remarkable features of the great cosmic-ray increase of February 23, 1956, was the observation that ionospheric absorption was

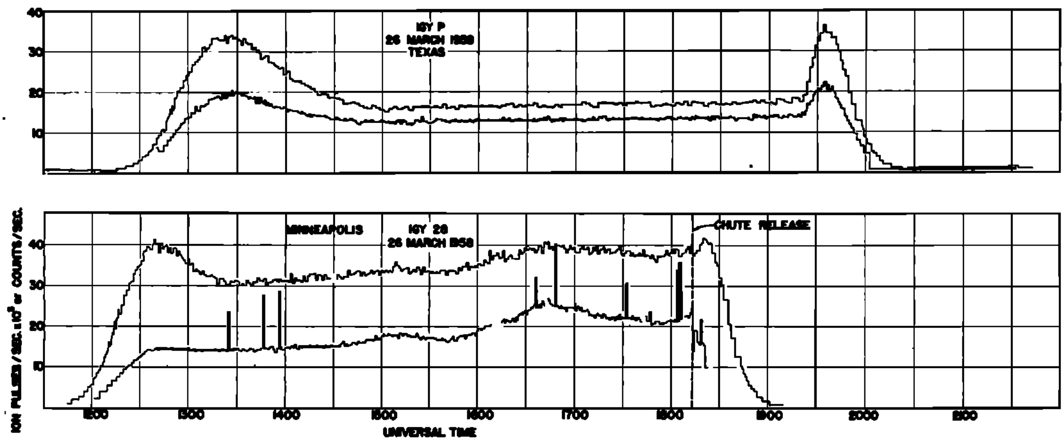

Fig. 9. Ionization and counter measurements at two latitudes, showing the increase due to low-energy solar cosmic rays measured at Minneapolis on March 26, 1958 (see also Fig. 2). The Texas flight, upper, shows a normal undisturbed behavior and the Pfotzer maximum on ascent, and on parachute descent both show clearly. The Minneapolis flight shows the Pfotzer maxima on ascent and then, at constant level, a continual increase in the ionization and counting rate until the time of parachute release at about 1830 UT. The relative ionization is consistent with the low-energy protons.

generated on the dark side of the earth which could only be caused by the cosmic-ray particles entering the *D* layer of the ionosphere. An excellent analysis of the manner in which the cosmic-ray-particle spectrum is related to the electron density of the ionosphere has been carried out by *Bailey* [1959].

The first direct evidence for the solar cosmic rays with IGY balloon programs was an event occurring on March 26, 1958. A preliminary analysis of this event has been published [*Freier, Ney, and Winckler,* 1959]. The event occurred during a coordinated series of balloon flights between Minneapolis, Texas, and Cuba. A simultaneous pair of flights was made at Texas and Minneapolis, which by chance occurred about a day after the start of a very large Forbush-type intensity decrease. When the Minneapolis instruments were analyzed, it was found that the ionization and counting rate, which at the beginning of the flight was at a low level corresponding to that of the low intensity during the Forbush decrease, increased during the 5-hour period of the flight in a fairly smooth manner to a value about twice the normal cosmic-ray-ionization and counting-rate background. An analysis of the simultaneous flight at Texas showed no detectable effects.

The ionization and counting rates during these two flights are shown in Figure 9. The readings of the ionization chamber and counter on the March 26 flight were at first interpreted as a possible X-ray event. The peculiar behavior of this event compared with other X-ray events, however, cast some uncertainty on the assumption that the increase was due to X rays. When the nuclear emulsions recovered from this flight were examined several months later, it was immediately apparent that a large increase had occurred in the low-energy proton flux present at high altitudes. This event was discussed informally with other investigators, and other geophysical measurements pertinent to the event were accumulated, including: (1) the magnetic records of a magnetic storm in progress at the time of the balloon flight; (2) the great intensity decreases of sea-level cosmic rays, shown by sea-level cosmic-ray neutron monitors; (3) the presence over the polar cap of very strong *D*-layer ionospheric absorption—the absorption has been measured by *Leinbach and Reid* [1959] using the riometer technique at Fairbanks, Alaska; (4) the probable source of the event in a large flare occurring March 23, 1958, beginning at 0950 UT.

The association with this flare was suggested by J. S. Denisse of Meudon Observatory. The flare was observed and studied by the Belgian

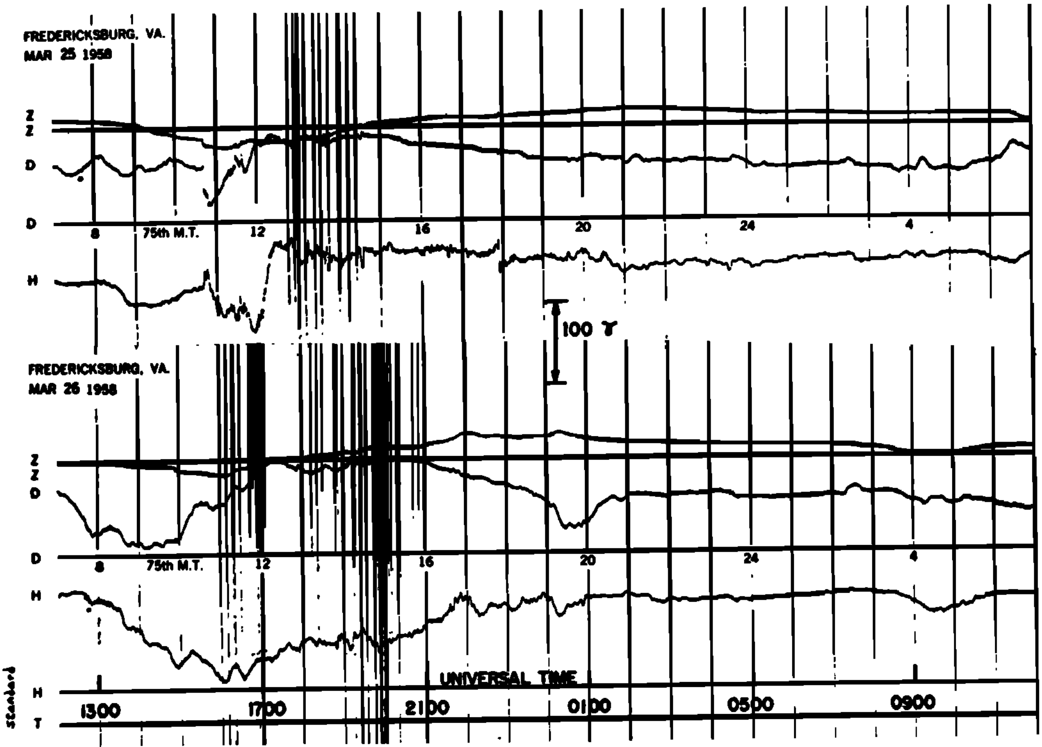

Fig. 10. Fredericksburg magnetic record during the magnetic storm of March 25–26, 1958, when low-energy solar cosmic rays were observed at Minneapolis. The sudden commencement is at about 1540 UT on March 25. The cosmic rays at Minneapolis were observed during the balloon flight which was in the air on March 26, and the increases coincided with the bay disturbance in *H*, beginning at 1300 UT and lasting until 2100 on March 26.

Royal Observatory [*Koeckelenbergh*, 1958]. A search was made for solar-activity time coincident with the balloon event, but none could be found; therefore it seemed necessary to attribute it to an event occurring earlier, and with the presence of delayed emission or storage of the observed particles. In Figure 10 is shown the magnetic record obtained from Fredericksburg Observatory. The sudden commencement at 1540 UT on March 25 is quite evident, followed by a disturbed condition, and on March 26 a considerable negative phase developed in the storm at the time at which the protons were seen on the Minneapolis balloon flight. Figure 11, reproduced from our first publication on this event, shows the temporal sequence of events associated with the cosmic-ray increase. The sudden increase in polar-cap cosmic noise absorption is seen to occur, not at the time of the flare, but at the time of the magnetic sudden commencement. This is a very unusual occurrence for these events, as further detailed analysis will show, and may be taken to indicate that the protons arrived trapped in a beam from the flare which was in transit from the sun for about 2 days. The Forbush-intensity decrease comes with the usual association with the magnetic sudden commencement and occurs within a few hours of it.

The ionization points in Figure 11 on March 21 and 26 and on April 8 were obtained from the soundings shown in Figure 2 above. The energy spectrum of the protons observed in this event is obtained from the emulsion analysis, which is discussed in a previous publication [*Freier, Ney, and Winckler*, 1959]. The protons were observed down to an energy of 120 Mev, which is the air and apparatus cutoff for the balloon flight at Minneapolis. One of the important features of the event is that the energy seems to be much lower than any assumed geomagnetic cutoffs for this latitude. We shall

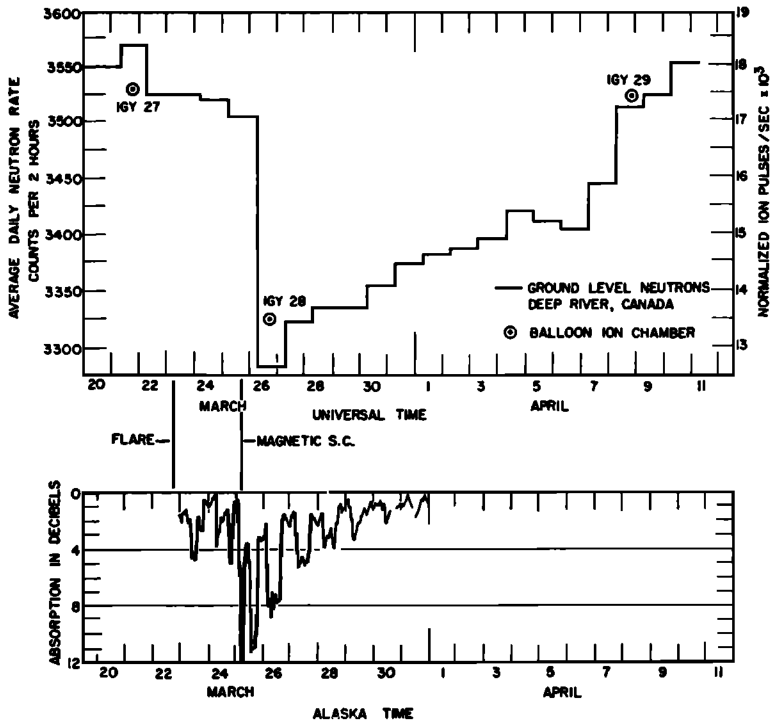

Fig. 11. Temporal sequence of events during the solar cosmic-ray event of March 25–26, 1958. Upper curve, ground-level neutrons compared with the balloon ionization-chamber readings for galactic cosmic radiation on this occasion, showing the large Forbush-type decrease. Lower curve, absorption in decibels of the riometer at Fairbanks, Alaska courtesy of Leinbach and Reid). The lower curve represents a complete time history of the solar cosmic rays over the polar cap and shows that they began at the time of the sudden commencement on March 25 and lasted for 5 or 6 days afterwards.

see that this is a characteristic of these events, that the presence of the protons at Minneapolis is associated with the geomagnetic storm, which in some way alters the cutoffs and allows the solar particles to enter into otherwise forbidden ranges of latitude. The complete lack of an effect on the Texas flight is consistent with the strong connection between these particles and the presence of the aurora. The latitude of Texas is definitely below the latitude of most auroras. The lack of an effect at Texas also permits the deduction that less than 10 per cent of the effect at Minneapolis could have been due to direct solar photons (γ rays).

If the observed increase is assumed to be due to protons, it is possible to deduce their flux and mean energy from the ionization chamber and counter readings. If we assume isotropic incidence above the atmosphere, and monoenergetic protons of range R_0 g/cm^2, the solid angle in which particles may be received by the ion chamber and counter at depth h is a cone of semiapex angle θ_0, such that $R_0 = h \sec \theta_0$. The mean ionization compared with minimum ionization measured by the instruments is then

$$\frac{\bar{I}}{I_{\min}} = \frac{1}{1-\cos\theta_0}\int_0^{\theta_0} \frac{I}{I_{\min}}(\theta) \sin\theta \, d\theta \qquad (5)$$

$I/I_{\min}(\theta)$ is determined from range-ionization curves for protons for each value of θ and R, using the fact that the residual range $R = R_0 - h \sec \theta$. Numerical integration of the above equation for various values of R_0 shows that the observed $\bar{I}/I_{\min}$ of three times minimum corresponds to protons of $R_0 = 33$ g/cm^2 range, 220 Mev energy, and 0.69 bv rigidity. The peak flux at 1810 UT is then 0.11/cm^2·sec·ster, and the average flux during the flight period is 0.058/cm^2·sec·ster.

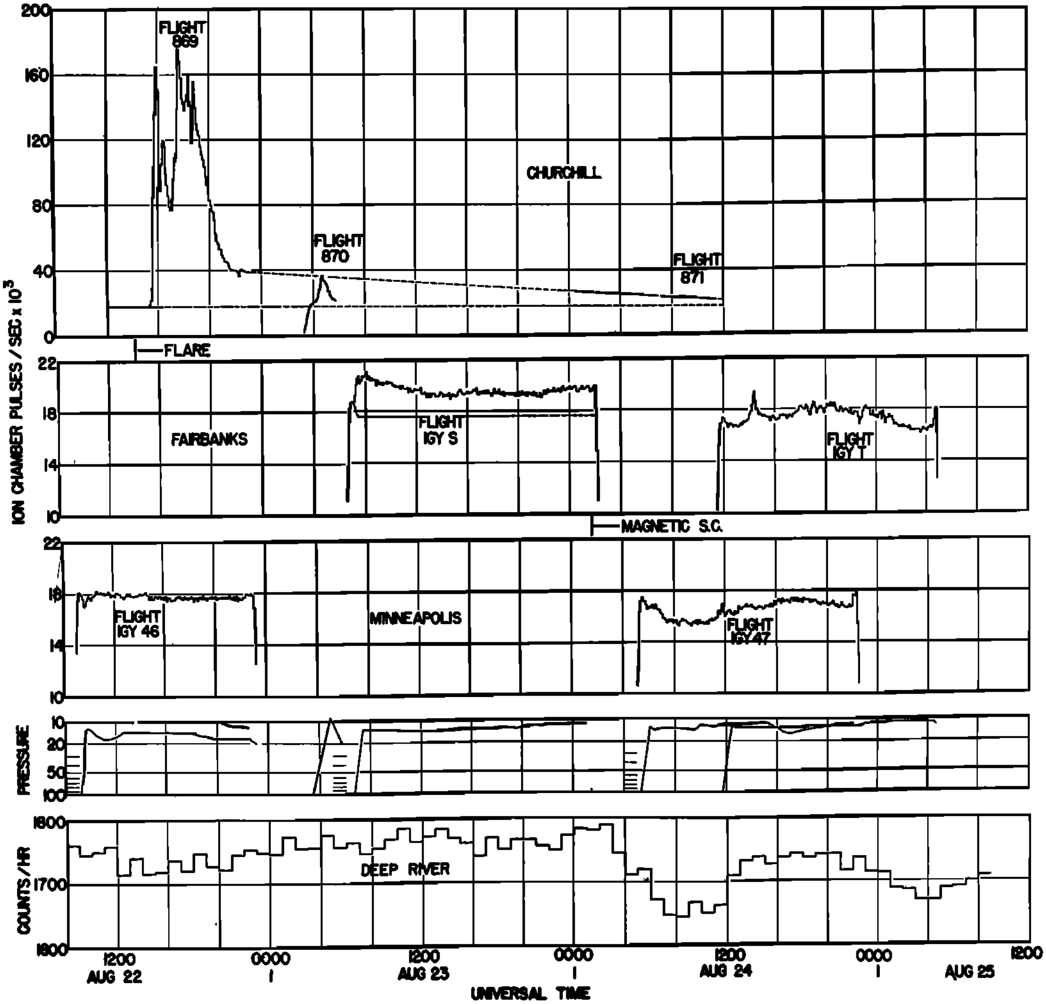

Fig. 12. Balloon observations and correlated data during the cosmic-ray event of August 22, 1958. Top line, observations at Churchill; next lower, observations at Fairbanks; center, observations at Minneapolis; next lower, balloon pressure curve; and bottom, Deep River sea-level neutron monitor.

As was pointed out in our previous paper [*Freier, Ney, and Winckler*, 1959], these values are in good agreement with those obtained from the emulsion data on this flight. The understanding of the March 26 event was greatly aided by a direct observation by Anderson of similar solar-flare protons during a balloon flight at Churchill on August 22, 1958. In this event a considerably larger increase was observed, which was directly associated with a very large solar flare. A preliminary report has been made by *Anderson* [1958]. Simultaneous flights during the event were being conducted by the Minnesota group at Fairbanks, Alaska, and also at Minneapolis, and a complete correlation of all these experiments on this occasion has been published [*Anderson, Arnoldy, Hoffman, Peterson, and Winckler*, 1959]. We reproduce here from this paper the figure showing the balloon observations at various times and various latitudes (Fig. 12). The direct flare increase observed at Churchill is not accompanied by any observable effects at Minneapolis. This is consistent with the known energy spectrum for the flare particles and reasonable knowledge of the geomagnetic cutoffs at Minneapolis. It should be noted that the geomagnetic storm associated with this event occurred on August 24. At the time of the flare on August 22 there was no strong geomagnetic disturbance in progress. This event was also observed by Leinbach and Reid to produce D-layer ionospheric absorption. It is apparently of considerably lower inherent intensity than the event in March, although the balloon records, being at a more favorable time and latitude, show a larger effect. Also, the solar particles come with a delay from the flare consistent with their direct time of flight, not the long time delay of 2 days seen on the March event. This may be due to the more favorable location of the August 22 flare nearer the center of the disk. The flare that accelerated the particles on August 22 produced a strong geomagnetic storm and aurora on August 24, accompanied by a Forbush-type decrease in the galactic cosmic rays, as did the event in March. These features are well shown in Figure 12 both by the balloon flights at high altitudes and by the sea-level neutron intensities. In contrast to the March event, even during the geomagnetic storm flare particles were not seen at Minneapolis, probably on account of the much lower intensity of the August 22 event and the more rapid decrease of the particles.

Anderson's Churchill balloon flights did not carry emulsions, but, because one of the flights, no. 870, rose through the atmosphere into the flare radiation at a time when the intensity was reasonably constant, it is possible to unfold the omnidirectional ionization indicated by the ion chamber to give the spectrum of protons. The differential proton energy spectrum so derived may be written

$$N(E)\,dE = K(t)E^{-5.0\pm0.2}\,dE \qquad \text{(Particles/cm}^2\cdot\text{sec}\cdot\text{ster}\cdot\text{Mev)} \qquad (6)$$

This spectrum is very steep and in that respect resembles the spectrum obtained on the March 26 event over a small energy interval by nuclear emulsion analysis [*Freier, Ney, and Winckler*, 1959]. The integral energy spectrum is found to be

$$N(>E) = 5 \times 10^8 E^{-4} \quad \text{(Particles/cm}^2\cdot\text{sec)} \qquad (7)$$

The energy E is expressed in Mev. An analysis of the United States satellite Explorer IV by *Rothwell and McIlwain* [1959] has definitely shown increases in rates associated with the August 22 event. The particles were observed at high latitude, and the intensity increased with increasing latitude. The fluxes observed in the satellite, considering the stopping power of the Geiger counters used, fall on the same spectrum as derived from the balloon measurements. This correlation is discussed in the complete paper by *Anderson, Arnoldy, Hoffman, Peterson, and Winckler* [1959]. The Explorer satellite also detected two other occurrences of solar cosmic rays, on August 16 and on 26, which had similar properties. Both these events were associated with large flares similar to the events detected by the high-altitude balloon measurements.

In a recent compilation *Reid and Leinbach* [1959] list 20 type III ionospheric absorption events which they believe are associated with flare-produced cosmic-ray protons. For comparison with the type III tabulation of Leinbach and Reid we have examined all the IGY balloon flights for events in which the ionization increases at high altitudes as the balloon rises on the last part of its ascent. This provides a critical test for the presence of the low-energy protons, because of their rapid absorption in the atmosphere. Ten flights in all were found in which high-altitude increases occurred; they are listed in Table 5. For illustration, typical ionization rate soundings are shown in Figure 13, for the events on September 1, 1957, and August 17, 1958. The normal curve without low-energy protons (see for example Fig. 2) goes through a mild maximum and drops slightly toward the highest altitude reached. The curves of Figure 13, however, show an increase of ionization which on the September 1 event begins at 15 mb and on the August 17, 1958, event begins as deep as 30 mb. If the high-altitude increase is statistically accurate, the spectrum of protons may be unfolded using the atmospheric depth dependence. This procedure has been carried out for the August 22 event for the Churchill and Fairbanks, Alaska, data, and is discussed in detail in that reference [*Anderson, Arnoldy, Hoffman, Peterson, and Winckler*, 1959].

On August 17, the magnetic sudden commencement occurred at 0622 UT associated with the great flare on August 16 which produced the solar cosmic rays on this occasion. On the

TABLE 5. IGY Flights that Show Increases on Arrival at High Altitudes

IGY Flight	Location	Date, UT	Time of Observation, UT	Approximate Increase, %	Pressure, g/cm²	Observed Polar Region Type III
7	Minneapolis	8/10/57	0345	10	10	No
12	Minneapolis	9/1/57	0300	10	12	Yes
28	Minneapolis	3/26/58	1315	100	10	Yes
29	Minneapolis	4/8/58	1300	5	8	No
R	Minneapolis	7/2/58	1400	5	6	No
45	Minneapolis	8/17/58	0700	15	8	Yes
S	Fairbanks, Alaska	8/23/58	0715	15	12	Yes
48	Minneapolis	8/27/58	0610	5	10	Yes
U	Fairbanks, Alaska	8/27/58	0845	5	14	Yes
V	Fairbanks, Alaska	9/22/58	2125	15	8	Yes

August 17 flight the solar cosmic rays were seen at Minneapolis after the beginning of the geomagnetic disturbance. Of the ten events listed in Table 5, seven were also reported by Leinbach and Reid as showing polar region type III absorption. Furthermore, all those listed by Leinbach and Reid in which balloons were at high altitude showed an increase attributable to solar protons. Table 5 includes, of course, the several occurrences discussed in detail such as those of March 26 and August 22, 1958.

In all the occasions on which the solar proton effects were seen at Minneapolis, a geomagnetic storm was in progress. In at least one, on August 22, the event referred to previously, no effect was seen at Minneapolis when large high-latitude effects were in progress, and here the geomagnetic storm was absent. Most of the increases reported in this series in Table 5 are small, the largest one, which is twice cosmic-ray intensity, being the March 26 occasion. However, recently, in May and again in July 1959, very large increases of solar protons have been observed with omnidirectional intensities at balloon heights reaching several hundred times the ionization produced by normal cosmic rays. One

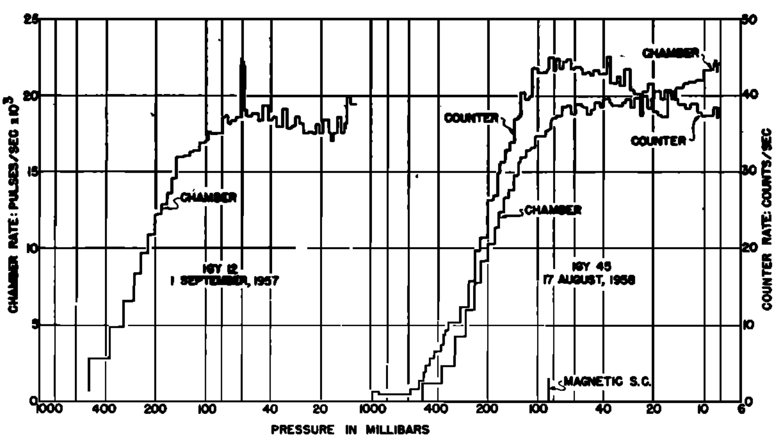

Fig. 13. Two events showing a detectable amount of low-energy radiation, presumably solar protons, at high altitude at Minneapolis occurring during a time when ionospheric effects at high latitude showed the presence of the low-energy solar particles. These soundings are typical of a series of such weak events seen in balloons during the IGY period.

of these events has been reported in the literature [*Ney, Winckler, and Freier*, 1959]. The phenomenally intense July 1959 series will be reported later. In many respects they have characteristics similar to the events discussed here and are evidently of the same variety but with enormously higher intensity.

During the IGY and IGC periods, Vernov, Charakhchian, and collaborators have made a large number of sounding flights using meterological balloons and single Geiger counters or Geiger counter coincidence trains from three latitudes in the Soviet Union, 64° geomagnetic, 51°, and 41°. Extensive measurements were made on many of the solar cosmic-ray events that are on record. The Russian workers in particular have studied in detail the great events in May and July 1959 which were referred to earlier [*Charakhchian, Tulinov, and Charakhchian*, 1960; *Rymko, Tulinov, and Charakhchian*, 1959; *Vernov, Tulinov, and Charakhchian*, 1958]. The comparison of the Minnesota results and the results of Charakhchian and collaborators will yield much additional information about these events, but a discussion of the 1959 events will be reserved for later communications.

The balloon observation by *Rymko, Tulinov, and Charakhchian* [1959] on July 8, 1958, of a high-latitude increase in the cosmic rays corresponds to a polar-cap absorption event reported by *Reid and Leinbach* [1959]. The July 1958 event was of moderate intensity but exhibits in the balloons the very steep spectrum and sharp latitude dependence shown by the other events. The July event was observed by Rymko, Tulinov, and Charakhchian at latitude 64° but not at latitude 51° or 41°. These workers find that the incidence of the solar protons coincides with a large Forbush-type decrease in the geomagnetic cosmic radiation which appears at all the stations. They find that the directly measured cosmic rays at balloon altitudes are delayed from the time of the associated chromospheric solar flare by several hours but not as long as the geomagnetic storm delay. Evidently the time of passage of the cosmic rays from the sun is considerably longer than the straight transit time and must, therefore, involve a partial trapping even in the early stages of the event.

Continued study of these events shows clearly, however, that, in the overwhelming majority, one cannot consider that the solar-accelerated cosmic rays are contained with any degree of efficiency by the low-energy plasma from the flare. If they were, large changes in the solar cosmic rays would be observed at the highest latitudes over the polar cap of the earth at the time of the sudden commencement of magnetic storms. With one exception, such changes are not observed. On the other hand, as mentioned above, the particles do not come in a straight line from the source on the sun but travel over a tortuous path as if scattered by many minor irregularities in space between the sun and the earth. Further discussion of this question as well as the very interesting problem of the decay of the particles after the acceleration will be reserved for later publications.

4. *Analysis of auroral X rays.* The initial discovery of the X rays at balloon levels directly coincident with visible auroras occurred on July 1, 1957, during the strong storm at the beginning of the IGY. Several further observations of these auroral X rays were made during 1957 and 1958, some of which have been reported in detail in the literature [*Winckler, Peterson, Arnoldy, and Hoffman*, 1958; *Winckler, Peterson, Hoffman, and Arnoldy*, 1959]. The identification of the increased rates of the cosmic-ray detectors as X rays has been made on a number of occasions in which special counting devices were flown during auroras. These devices, including shielded Geiger counters, arranged to be sensitive only to photons, and scintillation counters, have a much higher relative efficiency for X rays than an ordinary Geiger counter and, as expected, showed a very much larger intensity during the auroral storms than the single Geiger counter or ionization chamber which was normally flown on the balloon flights.

We should like now to summarize all the occurrences of auroral X rays observed during the IGY and to discuss several of them in detail. Figure 14 summarizes the X-ray bursts observed in all events recorded during 1957 and 1958. The bursts are plotted with the cosmic-ray background subtracted and the ionization rates normalized to a common scale. Only the ionization-chamber data are shown in Figure

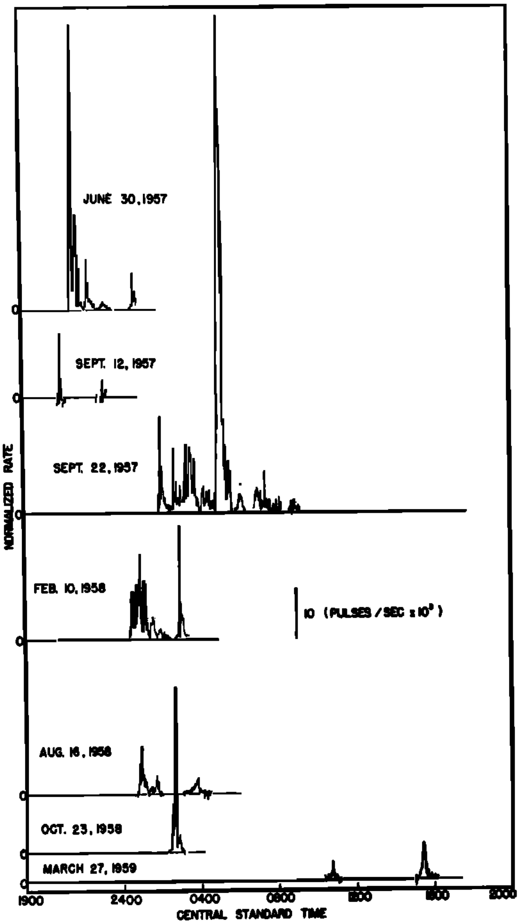

Figure. 14. Summary of auroral X-ray bursts observed with ionization chambers during the IGY period. The bursts are plotted as a function of local time in the central standard time zone at Minneapolis. The ion-chamber rate is on the same normalized scale adopted throughout this paper with the cosmic-ray background subtracted. With the instrumental data given in Table 2, above, the absolute X-ray intensities can be computed. Cosmic-ray rates with the same chamber are between 15 and 20 pulses/sec 10^3. Only the September 12 event represents the Geiger counter curve, as the ion chamber was not available on this flight.

14 (with one exception; see the figure legend). These data give some insight into the time distribution of energetic auroras measured at Minneapolis. It is seen that most X-ray bursts are observed during the night but that they can be observed during daylight. The sample is somewhat biased, as balloons are normally launched about sunset, so that activity starting before that time would have been missed. All these storms are classified as very strong, with large magnetic fluctuations. It can be seen that the auroral X-ray burst vary enormously in size, which is probably an indication in some way of the intensity of the solar bombardment. Although the characteristic of the time constant of the bursts is similar from one burst to another, being about half an hour, the bursts show considerable fine structure with variations down into the 1-minute range. The most intense X-ray burst observed occurred just before dawn CST on September 23, 1957.

The following general observations are of use in understanding the nature of the X-ray bursts:

1. When the skies are clear and visual observations can be made at the time of the balloon X-ray bursts, it is found that the bursts correspond to intensification of auroral luminosity close to the zenith at Minneapolis. This observation in effect associates the electrons producing the X rays with the visual forms of the aurora. This follows because the absorption coefficient for the observed X-ray energies of 50–100 kev is approximately 0.2 cm^2/g. For example, at the nominal balloon ceiling height of 10 g/cm^2 the ratio of the expected intensity from the vertical compared with a 60° zenith angle for a uniform source of X rays is 7. This implies that X rays in general will be seen only from electron currents incident close to the zenith considering the nominal auroral height of 100 km. X rays will be seen from electrons striking the atmosphere only within a radius of about 100 km from the balloon.

2. A careful comparison between the X-ray bursts and auroral all-sky camera photographs shows that the time of the burst is associated within times of the order of 1 minute with the passage across the zenith of regions of high luminosity. See for example the discussion in *Winckler, Peterson, Hoffman, and Arnoldy* [1959], Figure 3, for the aurora of February 10, 1958. Also see paragraphs below for a discussion of the September 22–23, 1957, aurora. The apparent velocity of the luminous regions across the sky is often found to be of the order of 0.5 to 1 km/sec from the all-sky camera records. This is consistent with the agreement within a minute or so between the appearance

of the luminosity and the X-ray bursts considering the 100-km-radius criterion mentioned in paragraph 1 above for detecting the X rays.

3. The energy of the X rays that is accessible to measurement at balloon levels begins at about 40 kev and extends upward; however, by examining the ratio of the instruments [*Winckler, Peterson, Arnoldy, and Hoffman,* 1958], the energy of the X rays at balloon levels in many cases is estimated to range from 50 to 100 kev. The shape of the spectrum cannot be determined from the ion chamber and Geiger counter, but it is believed to be that of a bremsstrahlung spectrum of electrons striking air plus the energy-sensitive absorption of the atmosphere which attenuates strongly the very low-energy X rays. This in effect produces a maximum in the spectrum at about the energies mentioned above. From the observed sizes of the bursts in the ion chamber it is possible to estimate the electron flux, assuming that the flux is uniform over the restricted region near the zenith to which the instruments are sensitive. The relation between the electron flux incident on the atmosphere and the normalized ion-chamber rate shown in Figure 14 is discussed below.

4. The X-ray bursts studied at Minneapolis are associated with subauroral zone auroras. None of the observations therefore, are associated with the phenomenon called a 'quiet arc,' as such phenomena are rarely seen at the zenith at Minneapolis. Rather, the X rays are associated with rayed forms such as rayed arcs, rayed bands, and corona which represent a phase of the auroral storm accompanying the motion of the luminosity either in latitude or in longitude.

5. There is known to be a close association between the presence of magnetic bays at a given latitude and the advance or retreat of the aurora across that latitude [*Gartlein, Bless, Kimball, and Sprague,* 1959]. It is therefore understandable that the presence of the auroral X rays is associated with the presence of bays on the magnetic records. We have already pointed out such an association for the February 10 aurora [*Winckler, Peterson, Hoffman, and Arnoldy,* 1959]. Other such cases are known [*Akasofu,* 1959].

6. The power available in the electrons inferred from the X rays is very large, comparable with that required to produce the visual luminosity of an aurora. It is therefore probable that the electrons are a major contributor to the excitation of the auroral spectrum as observed.

7. The observation of electrons at 100-kev energy as a direct part of the visual aurora raises an interesting question about the origin of these electrons. It is known that strong auroral storms are frequently associated with violent solar flares occurring about a day earlier; in fact, such was the case in the storms summarized in this paper. The 100-kev electrons cannot have come directly from the flare with a speed characteristic of their velocity, which is about 0.9 the speed of light. Therefore, either (*a*) the electrons were trapped in the plasma cloud and traveled around in this cloud during its transit from the sun, perhaps because of magnetic fields or electrostatic forces; or (*b*) the electrons are discharged from the Van Allen regions around the earth, in which event they would constitute part of the semipermanent flux of such electrons observed in the outer Van Allen region [*Van Allen,* 1959]; or (*c*) electrons are locally accelerated in the earth's magnetic field at the time of incidence of the solar cloud and are discharged down the lines of force as part of the auroral phenomenon.

In a recent publication [*Winckler, Peterson, Hoffman, and Arnoldy,* 1959], we have considered the detailed correlation between the X-ray bursts, the magnetic records, the auroral all-sky camera photographs, and other types of information for the great storm of February 10–11, 1958.

We will now consider another event in a similar way, namely, the very strong aurora of September 22–23, 1957. This was a time of extremely high solar activity, probably representing the peak in the sunspot numbers for the present solar cycle. The number of flares of all sizes recorded each day was so great that it is very difficult to correlate the storm with a specific flare. However, the magnetic records from Fredericksburg Observatory show that a typical strong storm with sudden commencement occurred coincidently with the observed aurora (see Fig. 15).

The sudden commencement occurred on September 23 at approximately 0235 UT. There was a very sharp positive excursion followed by

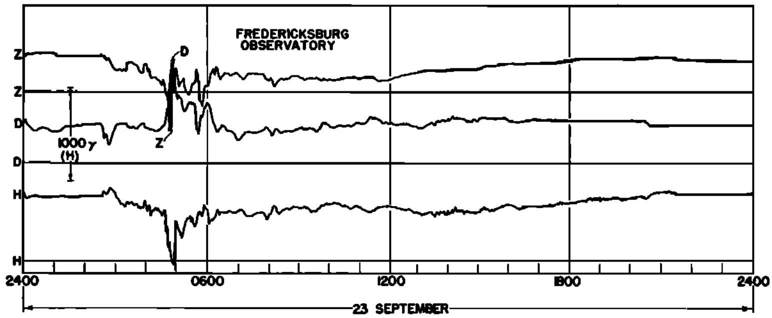

Fig. 15. Fredericksburg Observatory record for the strong magnetic storm of September 23, 1957. The sudden commencement occurred at approximately 0240 UT on September 23. After a very short positive phase, the storm exhibited large bay disturbances. Disturbances on this and other magnetic records show correlation with the balloon X rays for this event.

a negative region at the beginning of the storm. After a disturbed period, a large disturbance which developed into a negative bay began at 0438 UT on September 23. The bay disturbance ended by 0630 UT on September 23, and then, after a long disturbed period, the main phase of the storm ended by 2400 UT on September 23.

The balloon flight IGY-18, the record of which is shown in Figure 16, was launched about 0600 UT on September 23. It was observed that great auroral activity had been present for several hours before launch, and this is undoubtedly associated with the large disturbance shown on the Fredericksburg magnetogram. The balloon reached high altitude at about 0745 UT, and, as can be seen in Figure 16, X-ray bursts of considerable magnitude developed immediately. In the legend for the figure, the various auroral effects observed at Minneapolis close to the balloon are described. The most prominent feature, however, is an extremely large burst

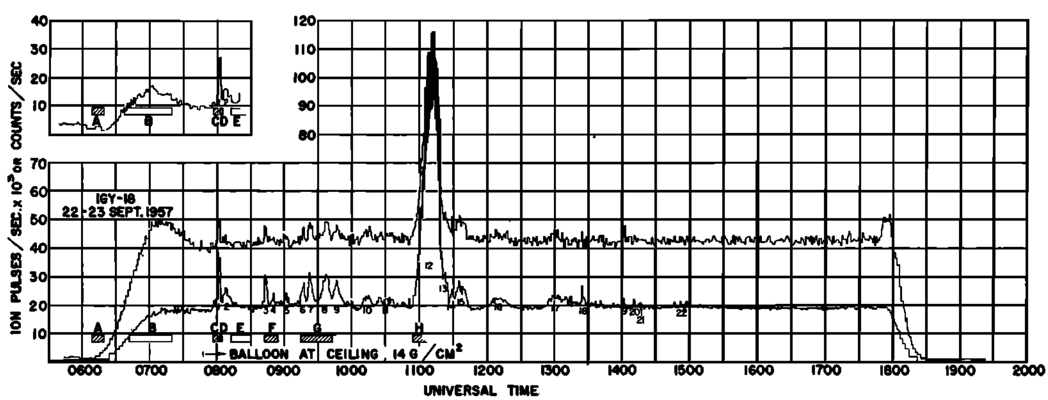

Fig. 16. Ion chamber (bottom), single counter (top), and photon counter (upper left, separate curve) response during the intense auroral storm of September 22–23, 1957. The balloon was launched about midnight CST during a lull in auroral activity, which had been very high in the earlier evening. The letters refer to observed auroral phenomena as follows: *A*, flaming auroral rays reaching zenith from all points of compass; red color. *B*, curtains in north but activity generally decreasing overhead. *B–C* (0735 UT), arcs in narrow bands extending across zenith and almost to horizon in east and west directions; north dark; no rays. *C*, extremely strong ray buildup from all directions; intense red patches at 30° elevation in west. *D*, red patches intense again after decrease. *E*, flaming rays; no red; activity decreased. *F*, strong rays in northwest; red color; strong flaming in west; general activity increasing. *G*, major ray buildup in west, north, and east, with corona; red color reappeared at 0945 UT; following *G*, general intensity decreased with flaming rays. *H*, very strong ray structure at 30° elevation in east with intense red color; visible against predawn sky light.

of X rays which began at about 1050 UT and in which the response to X rays was about 5 times above the cosmic-ray background. This excursion constitutes the largest increase observed in our series of balloon flights during the IGY. It lasted for approximately 30 minutes. On the Fredericksburg magnetogram, there is no definite correlating feature, which probably implies that the auroral phenomenon did not progress as far south as Fredericksburg at that time. Other stations in the auroral zone and below show a large bay disturbance at this time [*Akasofu,* 1959].

The large burst occurred just before dawn, local time, so that it is difficult to find all-sky camera records that show the aurora. However, a good record was found from a station at Choteau, Montana, which is on exactly the same geomagnetic latitude as Minneapolis. A series from the Choteau station close to the time of the beginning of the burst is shown in Figure 17. A remarkably intense phenomenon makes its appearance at that time and is evidently one loop of a very large rayed arc which is sliding in longitude from west to east and moving almost directly across the station at Choteau. It passes the zenith at 1048 UT. In Figure 18 is shown an enlarged view of the frame in which the rayed arc is over head. The rayed arc is accompanied by other arcs to the south and by considerable ray structure which extends far around to the north, almost closing the loop. From the sequence of photographs in Figure 17, it is possible to measure the velocity across the station if the height is assumed. Using the known geometry of the all-sky camera [*Elvey,* 1957], the result of the measurement is shown in Figure 19, assuming both 100- and 120-km heights.

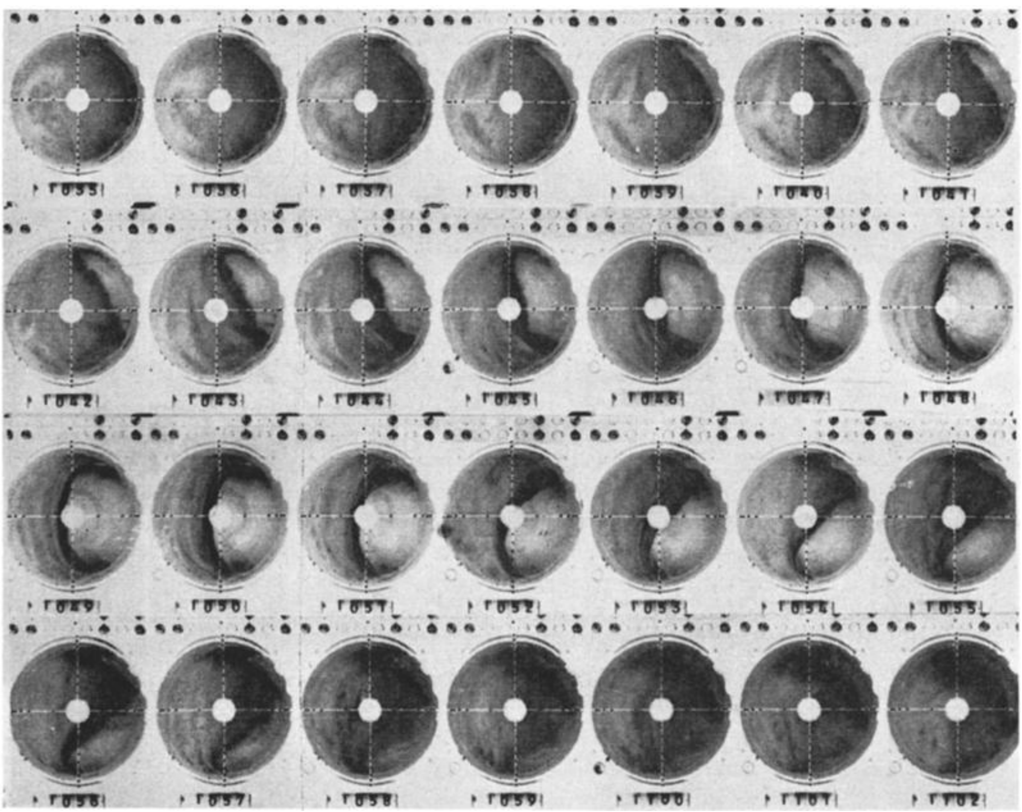

Fig. 17. Auroral all-sky camera records from Choteau, Montana, on September 23, 1957. The intense rayed band which moves across the station in these pictures is associated in time with the great X-ray burst observed at Minneapolis and is undoubtedly a part of the same auroral feature, which existed over a considerable range of longitudes at this time.

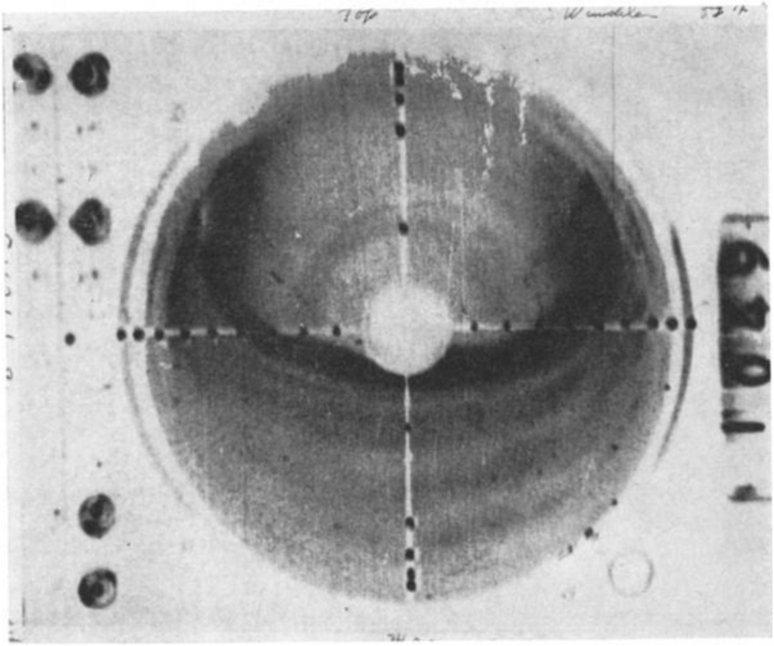

Fig. 18. Detail of the intense rayed band as observed over Choteau, Montana. The very intense band is accompanied by a succession of other, less intense arcs and by considerable ray structure which extends far around to the north.

The velocity obtained from this measurement is 0.5 km/sec. It seems certain that the intense X-ray burst observed at 1050 UT on the balloon near Minneapolis is associated with the auroral phenomenon shown in the Choteau records. The great intensity of the X-ray burst is consistent with the great luminous intensity of the concentrated rayed arc seen in Figure 18.

Under certain assumptions it becomes possible to compute the current of primary auroral electrons producing the X rays observed at balloon heights. We present here a brief outline along the lines of a previous discussion. The primary electron current is given by the expression

$$J = \frac{(dE/dx)_{\text{collision}}}{(dE/dx)_{\text{radiation}}} \times \frac{CI}{\text{energy/electron}} \times e \qquad (8)$$

where I is the observed X-ray energy flux, e is the electronic charge, and the constant C depends on the geometry. For a uniform bombardment over the sky $C = 2$, as half the X-ray energy is propagated upward. For an auroral arc the situation might be approximated by a line source of X rays extending a large distance in longitude and located at approximately 100-km altitude. The electron current would be a sheet aligned along the magnetic field, extending downward to the 100-km level, where the electrons stop. In this case $C = 2\pi h/w$, where h = (100 km − balloon height) = 70 km approximately, and W is the thickness or width of the electron stream in the north-south direction. For the ratio of collision loss to radiation loss we may use the relation given, for example, by *Fermi* [1950]:

$$(dE/dx)_{\text{collision}}/(dE/dx)_{\text{radiation}} = 800/ZE \qquad (9)$$

where Z is the atomic number of stopping material and E is the electron energy in Mev. The observed X-ray energy flux is computed from the ion-chamber rate according to the expression

$$I = \frac{R_n \cdot Q_n \cdot W}{e \cdot \mu \cdot M} \cdot K \quad \text{ev/cm}^2\text{/sec} \qquad (10)$$

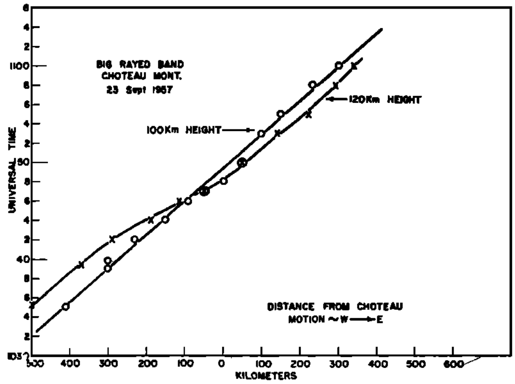

Fig. 19. Result of position measurements in the west-east direction over Choteau, Montana, of the center of the very intense rayed arc on September 23, 1957. The measurements are scaled from the all-sky camera records, and positions are given for two different heights of the auroral feature.

where R_n is the normalized ion-chamber rate in pulses per second, Q_n the normalized charge per pulse of the chamber, W the energy in electron volts required to form an ion pair in argon gas, e the electronic charge, μ the absorption constant in cm^2/g for X rays of the measured energy in argon, M the argon mass in grams, and K a correction for the energy in the form of X rays produced in the high atmosphere but not reaching the balloon level. This correction may be computed assuming a bremsstrahlung spectrum of X rays from the electrons coming to rest by ionization loss. As discussed previously, K has a value of approximately 10 [*Winckler, Peterson, Hoffman, and Arnoldy*, 1959].

Assuming $E = 100$ kev, and using known values for μ, Q_n, and M, we obtain the expressions

$$J = C \times R_n \times 3.0 \times 10^{-11} \ \text{amp/cm}^2$$
or
$$J = C \times R_n \times 1.9 \times 10^{8} \ \text{electrons/cm}^2\text{/sec} \qquad (11)$$

For uniform bombardment over the top of the atmosphere where $C = 2$ we obtain

$$J = R_n 6.0 \times 10^{-11} \ \text{amp/cm}^2$$
or
$$J = R_n 3.8 \times 10^{8} \ \text{electrons/cm}^2\text{/sec} \qquad (12)$$

For arc forms where $C = 2\pi h/w$ we obtain for 100-km aurora of thickness W cm in latitude

$$J = R_n(1.3 \times 10^{-6})/W \ \text{amp/cm}^2\text{/cm}$$
or
$$J = R_n(8.3 \times 10^{15})/W \ \text{electrons/cm}^2\text{/cm} \qquad (13)$$

The large increase at 1050 UT on September 23 produced a peak normalized ion-chamber rate of $R_n = 0.1$/sec. From Figure 18 we estimate the thickness of the rayed arc to be not more than 10 km. The resulting electron flux is $J = 8 \times 10^9/\text{cm}^2 \cdot \text{sec}$. This appears to be a value comparable with fluxes reported in the outer trapped radiation zone of the earth [*Van Allen*, 1959], where typical values are 10^{10}–$10^{11}/\text{cm}^2 \cdot$ sec. The aurora of September 13, 1957 (Fig. 14), was observed at great depth with an insensitive instrument. The *inferred* flux at high altitude in that event exceeded the September 23 event by 50 times.

5. *Measurement of solar γ rays and radioactive layers in the atmosphere.* In this section we shall discuss briefly two observations of quite different phenomena that are unique in that they were observed with the ion chambers and counters only over a very short time interval but became significant when correlated with other geophysical effects.

The first such event was a transitory increase —for an interval of only 18 seconds—in the counting rate of the ion chamber and Geiger counter observed on flight IGY-M on March 20, 1958, flown over the island of Cuba. The increases were significant above the low and rather steady background of the cosmic radiation at the latitude of Cuba. They were found to coincide precisely with a very intense radio burst observed on 3 cm and on 21 cm by the radio astronomy group at Meudon. They also coincided with the maximum phase of a class II flare. The event has been analyzed in its entirety [*Peterson and Winckler*, 1959] as being due to a burst of high-energy X rays or γ rays coming from the sun and probably generated there by electrons accelerated in the flare and producing bremsstrahlung in the photosphere of the sun. It was concluded that 9.4×10^{33} electrons producing the bremsstrahlung on the sun were required to account for the observed burst. If the number of electrons required to produce synchrotron radiation is estimated, assuming that the radio observation is due to this source, the number of electrons of similar energy is 2.5 $\times 10^{30}$. The discrepancy of 10^{2} is not difficult to explain in terms of the opacity of the solar photosphere to the electromagnetic radiation. The event is self-consistent with the above interpretation but has one very puzzling feature, namely that the source of the radio waves observed by Denisse at Meudon [*Denisse*, 1959] was observed to be very large. The size was such that the effects would have had to spread across the solar disk with the velocity of light and produce the electromagnetic radiation in the radio-frequency spectrum from the whole region simultaneously. This region is about one-third the size of the solar disk. It appears that this observation of γ rays from outside the earth is the only one so far recorded of such a phenomenon. No other observation of solar γ rays has been made during the IGY period, although a number of balloon flights were at high altitude during strong solar flares. Increases associated with flares have been shown to be due to particle effects or have been otherwise accounted for.

The second observation occurred on balloon flight IGY-27 on March 21, 1958; it stems from an increase in both the ion chamber and the counter observed while the balloon was rising through the lower atmosphere at a pressure of about 350 mb (see Fig. 2 above for the instrumental soundings for this flight). The increases were almost certainly due to a strong radiation layer in the atmosphere. Another case tentatively assigned to a radioactive cloud layer was observed on flight IGY-54, on October 31, 1958. A detailed study has been made of these two events [*Mantis and Winckler*, 1960]. It was concluded that on the March 21, 1958, event the increases in the instruments were due to γ rays of approximately 1-Mev energy and having a specific activity of 0.8×10^{-4} disintegration per second per cm^3 of air at 30,000 feet. The layer containing the activity was located in the jet stream, and the trajectory could be followed backward with a time delay of about 5 days to a probable source in Siberia. In analyzing the event, the decay of the fission fragments and the loss of intensity by diffusion were estimated. It should be noted that the radioactive layer was not observed on the descent of either of the balloons, although the descent occurred only a few hundred miles from the launch point. No other event intense enough to be detected was observed in the 83 IGY balloon flights on this program. The direct detection of radioactive debris in situ in the atmosphere is unusual. The fact that it is possible to make such measurements suggests that with more sensitive techniques the direct sounding measurement of radioactivity might be a useful tool for studying the distribution of radioactive material and drawing inferences about the large-scale circulation of the atmosphere.

Acknowledgments. A large number of people in the School of Physics, University of Minnesota, have contributed in a major way to the successful carrying out of this program. Besides those who have on occasion been joint authors of the papers analyzing detailed events, which are referred to above, credit should be given to the enthusiastic and loyal group of undergraduate physics and electrical engineering students who took part in the flight operations and contributed to the analysis of the data. Rudolph Thorness made major contributions in the design of the instrumentation, Robert Howard and Raymond Maas in the design of the electronic components, and William Huch in the design of the balloons and the techniques in conducting the launchings. James Stoddart successfully recovered many of the loads by airplane chase. We are appreciative of the support of the National Science Foundation operating under the U. S. National Committee for the IGY for the grant which set this project in operation, and also of the loyal and understanding support of the Office of Naval Research.

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