# Primary Cosmic-Ray and Solar Protons*

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A study of the low-energy portion of the primary cosmic-ray proton spectrum has been made in August and September, 1960. We detected a significant flux of primary protons with energies below 500 Mev, which previously had been considered absent. This result is of importance to astrophysical considerations as it imposes restraints upon possible modulation mechanisms should these particles be of galactic origin. The alternate possibility, namely of solar origin of these particles is also discussed. The observations were made in three high altitude balloon flights at geomagnetic latitudes $\lambda \geq 73°$ N. The results show that the low energy proton spectrum observed on quiet days may be represented by $dJ/dE = 2.3\times10^4 \times E^{-2}$ protons/m$^2$ sec-sr-Mev for $78 \leq E \leq 200$ Mev and flattens between 200 and 350 Mev. On September 8, 1960, the observed proton flux between 70 and 350 Mev was several times larger than on quiet days. These protons are believed to have been produced by a class 3 flare on September 3, 1960. Their energy spectrum has been measured.

## 1. INTRODUCTION

KNOWLEDGE of the primary cosmic-ray proton spectrum at low energies (K.E.<500 Mev) is essential to decide among various modulation mechanisms for the primary radiation which have been proposed in the past years. It also provides information about the origin of cosmic radiation and the physical properties of interplanetary and interstellar space. The importance of investigations in this field has been discussed in several comprehensive publications.[1–3] In particular there is the question whether in the vicinity of the earth any low-energy protons are present in the primary radiation aside from infrequently injected solar-flare particles. Previous observations indicated their absence at times near solar maximum, and conflicting evidence exists for their presence near solar minimum. In this paper we present the results of an investigation of the primary proton-energy spectrum below 1 Bev. In particular we raise the question, were there any low-energy primary protons present in 1960, two years after the last solar maximum, and if so, how are they affected by solar modulation?

Large variations in the cosmic radiation near the earth have been observed for several years. They have been identified as changes in intensity and energy spectrum of the primary radiation.[4] The mechanisms giving rise to these variations are solar controlled and operate within or near the solar system.[1,4,5] We are observing essentially two processes, which often operate at the same time:

(1) The modulation of the galactic cosmic-ray intensity by solar plasma and the associated magnetic fields in interplanetary space.

(2) The production of cosmic-ray particles in solar flares. One finds that large solar flares produce particle fluxes consisting mainly of protons with energies up to several hundred Mev[6] and in rare cases up to Bev's.[7] The solar flux is usually many orders of magnitude larger than the galactic cosmic-ray background. These solar particles are stored in interplanetary space for periods of days, during which time the observed cosmic-ray intensities slowly decline to the preflare level. Until now, there has been no evidence that the sun might also be a steady producer of particles, or that particles might be stored in the solar system for longer periods of time.

While there exists a large number of observations of solar flare produced protons, little is known about the low-energy galactic protons. Over the period of the last solar cycle, a survey of the changes in the primary galactic cosmic-ray spectrum was carried out by McDonald and Webber.[8–10] These authors observed decreasing fluxes for rigidities below 2 Bv for periods near solar maximum (1958) as well as near solar minimum (1954). Problems of albedo and the fact that the geomagnetic cutoff encountered in the observations was between 0.8 and 1.2 Bv, however, introduce uncertainties in the interpretation of their data in the low-energy region.

Observations made at high latitudes near solar maximum with integrating ion chambers,[1] using the absorption of particles in air for spectral information, also show no evidence for the presence of low-energy particles. However, these experiments would not detect small fluxes of primaries.

Near solar minimum all observers found a higher

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† A thesis submitted to the Department of Physics, the University of Chicago, Chicago, Illinois, in partial fulfillment of the requirements for the Ph.D. degree.
[1] H. V. Neher, Ann. Rev. Nuclear Sci. 8, 217 (1958).
[2] P. Morrison, E. P. Ney, J. A. Simpson, T. Gold and G. Cocconi, Suppl. Astrophys. J. 44, 369 (1960).
[3] *Progress in Elementary Particle and Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1957–60), Vols. I to IV.
[4] See, e.g., J. A. Simpson, Proc. Nat. Acad. Sci. 43, 42 (1957).
[5] P. Meyer and J. A. Simpson, Phys. Rev. 99, 1517 (1955).
[6] K. A. Anderson, R. Arnoldy, R. Hoffman, L. Peterson, and J. R. Winckler, J. Geophys. Research 64, 1133 (1959).
[7] P. Meyer, E. N. Parker, and J. A. Simpson, Phys. Rev. 104, 768 (1956).
[8] F. B. McDonald and W. Webber, Phys. Rev. 115, 194 (1959).
[9] F. B. McDonald, Phys. Rev. 116, 462 (1959).
[10] F. B. McDonald and W. Webber, J. Geophys. Research 65, 767 (1960).

cosmic-ray intensity than around 1958, as was to be expected from the inverse correlation with solar activity.[11] However, McDonald and Webber[8] again find a spectrum which decreases towards lower energies, while Neher[12] and Winckler and Anderson[13] from their altitude-intensity plots and studies of the latitude effect at balloon altitudes above 51° N find evidence for the presence of a substantial flux of low energy particles. If the observations in references 12 and 13 were due to primary protons, then the spectra found by McDonald and Webber could at those times definitely not be extrapolated to low energies, and instead of a decreasing spectrum one should actually find a rising spectrum towards lower energies.[8]

## 2. INSTRUMENTATION

### (A) The Detector System

We built a particle detector system which resolves mass, charge, and energy of a particle by a combined measurement of its ionization loss in a scintillation crystal and its range in a lead absorber.[14] (Figure 1 shows a cross section of the detector system.)

The "Telescope counter" and "Counter I" form a telescope with a geometry factor of 2.1 cm$^2$ sr. Only particles which give a coincidence between these two counters are analyzed. The lead absorber is subdivided into "range intervals" by scintillation counters. We measure the ionization loss of the particle in counter I, and determine its range from the number of range counters triggered in coincidence. For particles with range larger than the lead absorber of 121 g/cm$^2$, ($E>350$ Mev/nucleon), we determine in addition the ionization loss in "Counter II." The measurement of $dE/dx$ above and below the lead absorber makes it possible to determine the energy of particles from 350 to 450 Mev/nucleon.[15] The differential energy spectrum of particles with K.E.$>$450 Mev/nucleon cannot be determined by our system; in this region we only measure the integrated proton flux. In both counters I and II, $\frac{1}{4}$-in. thick NaI(Tl) crystals were used for the energy loss measurement.

The range detector geometry is surrounded on four sides by anticoincidence counters. They are designed to eliminate side showers, which might produce accidental coincidences unrelated to the vertical particle flux. However, they will also eliminate a fraction of the events due to vertically incident particles which make nuclear interactions in the lead absorber with secondary products. This effect has to be considered in the corrections for the vertical particle flux.

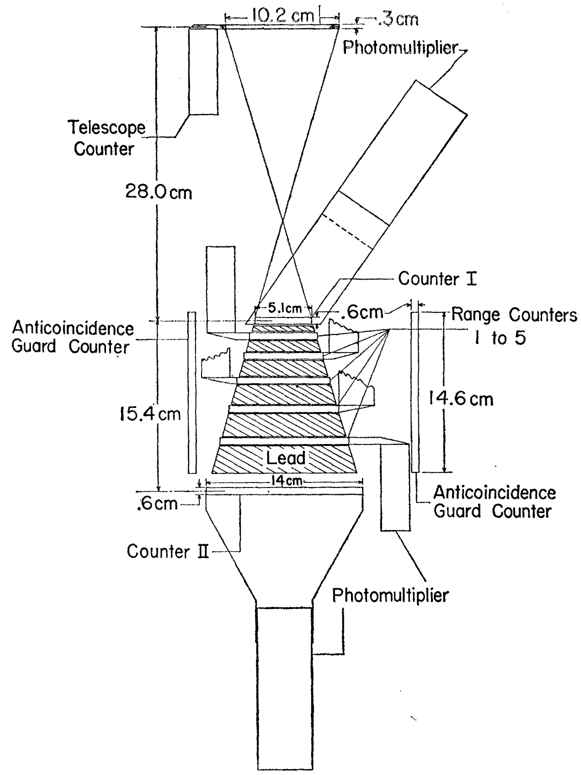


FIG. 1. Cross section of the detector system.

The detector characteristics can be summarized as follows:

(1) It separates the protons, alpha particles, mesons, electrons, and heavier particle components of cosmic radiation.

(2) It directly measures the differential energy spectrum of particles from 20 to about 450 Mev/nucleon.

(3) It measures the integral flux of particles with energies $E>450$ Mev/nucleon.

(4) It gives an energy spectrum up to 450 Mev/nucleon which is free from splash albedo particles (upward moving secondaries). It eliminates splash albedo electrons of all energies.

(5) It effectively eliminates accidental coincidences produced by side showers and similar effects.

### B. Airborne Analysis System

All observational data are analyzed and transformed into digital code in the payload during flight. The digitalized information is recorded on a 6-channel tape-recorder in the gondola, and also transmitted to a ground receiving and recording station via Pulse-Code-Modulation-FM on 6 subcarriers of a 73 Mc/sec transmitter. Figure 2 represents the airborne informa-

[11] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).
[12] H. V. Neher, Phys. Rev. **107**, 588 (1957).
[13] J. Winckler and K. Anderson, Phys. Rev. **108**, 148 (1957).
[14] The ionization loss and range identification technique has been used previously in proportional counter telescopes with lead absorber trays, e.g., G. J. Perlow, L. R. Davis, C. W. Kissinger, and J. D. Shipman, Jr., Phys. Rev. **88**, 321 (1952), and L. R. Davis, H. M. Caulk, and C. Y. Johnson, Phys. Rev. **101**, 800 (1956).
[15] This interval, however, has been included in the integral proton flux above 350 Mev in the present analysis, since detailed energy calibrations were not available.

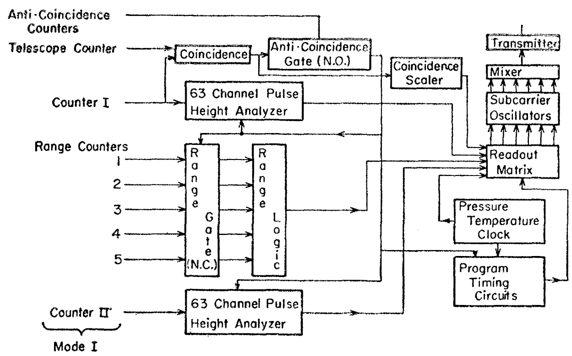


FIG. 2. Block diagram of airborne electronics.

tion analysis system. Its main elements are two 63-channel P. H. analyzers, the "Range-Logic," and a coincidence register. The two P. H. analyzers record the pulses from counters I and II, corresponding to the energy loss of a particle in these counters. The "Range-Logic" consists of a diode-matrix, which measures the depth a particle has penetrated in the absorber. The coincidence register records the total number of events which trigger the coincidence counter telescope. Every 7.5 minutes the system records and transmits digitalized pressure-altitude and equipment temperature for a nominal period of 15 sec. The pressure sensing instrument was an aneroid-type transducer. In addition, the readings of a Wallace-Tiernan pressure gauge are recorded by a 16-mm camera in 5-minute intervals. All electronic circuitry was completely transistorized and tested to operate between $-35°C$ and $+40°C$.

The equipment was kept at 1 atmosphere pressure in a cylindrical aluminum container with a 12-mil aluminum top window. The total amount of absorber above counter I was about 0.4 g/cm$^2$ air equivalent.

### (C) Data Analysis

The telemetered data were directly recorded on teletype paper tape. The digital computer "George" at Argonne National Laboratory was programmed for reducing these data. The energy spectra of the particles are obtained from the distribution of particle intensity vs range and energy loss for any desired interval of time using the known range-energy relations.[16,17] The equipment is calibrated before flight using relativistic $\mu$ mesons and the positions of the relativistic proton and alpha-particle peaks give inflight calibration checks.

The proper performance of the detector system and calibration procedures were verified by exposing the equipment to the external proton beam of the Chicago synchrocyclotron at various energies up to 300 Mev.

### (D) Corrections

#### (1) *Nuclear Interactions in the Lead Absorber*

Our technique of identifying an event by a combined measurement of the energy-loss and range of a particle is based on the assumption that the range of the particle is determined by ionization loss only. However, a fraction of particles will make nuclear interactions in the lead absorber. In this case, two possibilities are of interest for our data analysis.

(1) One of the secondaries produced in the interaction falls into the "acceptance angle" of the anticoincidence counters and has sufficient energy to penetrate the interlaying absorber between its origin and the anticoincidence counter. In this case, regardless how the other secondaries behave, the event will not be analyzed by the detection system. However, for all such events, a correction factor must be applied to the flux value of primaries.

(2) None of the secondaries produced triggers the anticoincidence. In this case, the event will be analyzed by the detector. However, the range information obtained will in general not be correlated to the initial energy loss of the primary which interacted. The measured range is determined by that secondary which penetrates farthest in the absorber. The observed energy spectrum has to be corrected for such events.

The probabilty for nuclear interaction of a proton was calculated as a function of depth in the lead absorber. We then determined for various energies of the incident particle (a) the probability that a secondary would trigger the anticoincidence and (b) the probable range of the most energetic secondary for the fraction of cases where no anticoincidence occurs.

To arrive at numerical results we used an interaction mean free path for protons in lead of 160 g/cm$^2$ and the empirical data of Camerini *et al.*[18,19] for the spectra and angular distribution of the secondaries produced in an

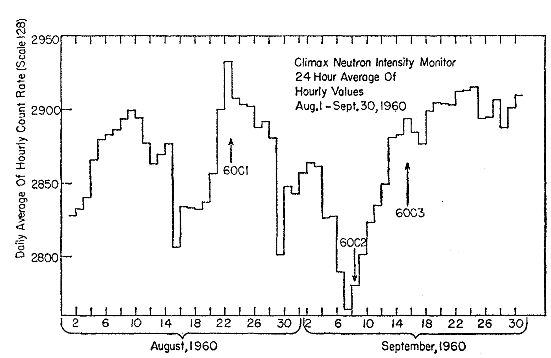


FIG. 3. Daily averages of Climax neutron monitor data during period of balloon measurements.

[16] *Kosmische Strahlung*, edited by W. Heisenberg (Springer-Verlag, Berlin, 1953), pp. 462, 570.

[17] M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, 1954 (unpublished).

[18] U. Camerini, P. H. Fowler, W. O. Lock, and H. Muirhead, Phil. Mag. **41**, 413 (1950).

[19] U. Camerini, J. H. Davies, P. H. Fowler, C. Franzinetti, H. Muirhead, W. O. Lock, D. H. Perkins, and G. Yekutieli, Phil. Mag. **42**, 1241 (1951).

TABLE I. Contribution to the count rate in different range intervals by secondaries from various production layers above the equipment and corrections for interactions in the lead absorber.

| Range interval | Corrections for nuclear interactions in the absorber | Secondaries under $x$ g/cm² air equivalent $x=0.4$ | $x=1.4$ | $x=2.4$ | $x=3.4$ | $x=4.4$ |
|---|---|---|---|---|---|---|
| $R$ = g/cm² Pb | (%) | particles/m² sec sr | | | | |
| $R \leq 10.5$ | − 1 | 3.0 | 8.7 | 12.7 | 15.9 | 18.0 |
| $10.5 \leq R \leq 22.9$ | − 2 | 1.4 | 4.0 | 6.1 | 8.3 | 10.4 |
| $22.9 \leq R \leq 40.3$ | − 3 | 0.9 | 2.9 | 4.6 | 6.1 | 7.6 |
| $40.3 \leq R \leq 61.7$ | + 7 | 0.4 | 1.6 | 2.6 | 3.6 | 4.6 |
| $61.7 \leq R \leq 87.1$ | +12 | 0.4 | 1.3 | 2.1 | 2.9 | 3.6 |
| $87.1 \leq R \leq 122.1$ | +22 | 0.3 | 0.9 | 1.4 | 2.0 | 2.6 |
| $R \geq 122.1$ | +37 | 4.3 | 15.0 | 25.7 | 36.5 | 47.2 |

interaction. The magnitude of this correction depends on the geometry of the equipment and the shape of the cosmic ray energy spectrum. In Table I, column 2 we give, as an example, values for the balloon flight that required the largest corrections.

### (2) *Secondaries Produced in the Atmosphere*

On the basis of empirical data[18–20] we derived corrections for the contribution of secondaries to the measured proton flux at 3 to 5 g/cm² atmospheric depth. We used the production rate of stars with various prong numbers as a function of atmospheric depth obtained by Lord[20] in 1949, when the solar cycle was at a similar phase as in our measurements. With an interaction mean free path for protons, $\lambda(\text{emulsion}) = 1.4\ \lambda(\text{air})$, we derived the average number of stars produced per gram of air and the multiplicity of their secondaries. We applied the results of Camerini *et al.*[18,19] for the energy spectra and angular distributions of secondaries and calculated their contribution to the observed count rate in our detector system. Table I lists the contribution of secondaries, which were produced in the gondola material above the telescope (0.4 g/cm² air equivalent) and in various thicknesses of air absorber above the detectors. These results are in good agreement with extrapolations of altitude-intensity curves, obtained during ascent of the balloon, as discussed in Sec. 4(A).

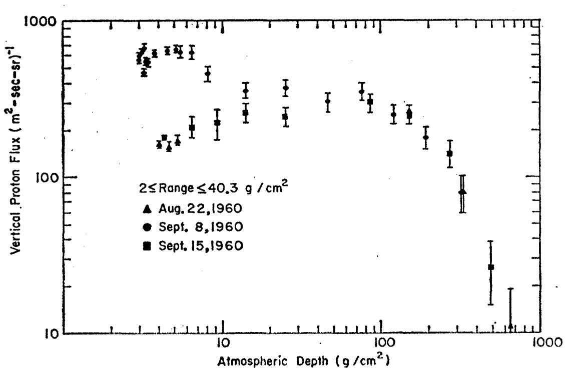


FIG. 4. Vertical proton flux vs atmospheric depth for protons with range in Pb between 2 and 40.3 g/cm².

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

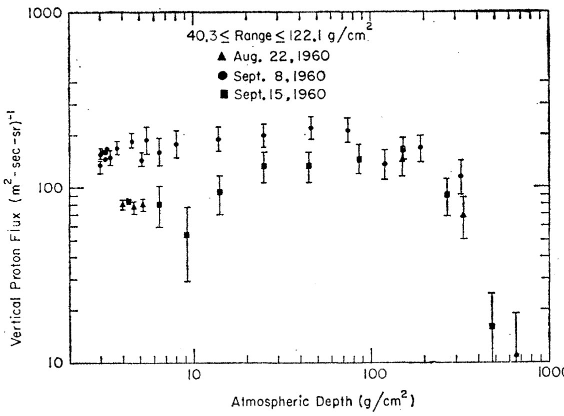


FIG. 5. Vertical proton flux vs atmospheric depth for protons with range in Pb between 40.3 and 122.1 g/cm².

### 3. BALLOON FLIGHTS

The observational data of this paper are based on three Skyhook balloon flights. The flights were performed on August 22, September 8, and September 15, 1960, with floating altitudes between 3 and 5 g/cm² of air. The balloons remained at constant altitudes for about 8 to 10 hours in each flight. The launch-site was Fort Churchill, Manitoba, Canada, at 72.8° N geomagnetic latitude with a vertical geomagnetic cutoff of 0.11 Bv (~6 Mev for protons) according to Quenby and Webber.[21] Fort Churchill was chosen for these observations because of its low-geomagnetic cutoff, which allows particles in the energy range of interest for this experiment to reach the earth. The residual air absorber above the detector (3–5 g/cm²) introduced an "atmospheric cutoff"; only primary protons of energy greater than about 70 Mev could reach the detector. All balloons drifted towards higher geomagnetic latitudes and at no time during the flights could geomagnetic cutoff effects have influenced the observations. All flights were satisfactory and are included in the present analysis. (No data were recorded between 10:00 and 14:00 UT on August 22, 1960.)

In Fig. 3 the total cosmic-ray intensity measured by the Climax neutron monitor is plotted as a function of time for the period of the balloon observations. The arrows indicate the days on which balloon flights were made. For the entire period of observation, only one solar flare (September 3, 00:40, class 3, type IV radio emission) is known to have produced high-energy solar protons.[22] No solar-flare proton event was observed in the months of July and August, 1960. The riometer records also showed no significant events during July and August, 1960.[23]

[21] F. Quenby and W. Webber, Phil. Mag. 4, 90 (1959).
[22] J. R. Winckler, P. D. Bhavsar, A. J. Masley, and T. C. May, Phys. Rev. Letters 6, 488 (1961).
[23] We wish to thank H. Leinbach for making this information available to us.

## 4. RESULTS

### (A) Proton Flux at 73° N Geomagnetic Latitude

The interactions of primaries (and secondaries) with air nuclei produce a substantial number of singly charged secondaries with energies ranging over the entire spectrum. Some of the secondaries move in an upward direction and form the "splash albedo." A fraction of the splash albedo in the Southern hemisphere returns along the geomagnetic field lines to the earth's atmosphere in the Northern hemisphere and forms the "albedo primaries."[24] The rigidity of these particles must be smaller than the local geomagnetic cutoff.

The separation of secondaries, splash albedo, and albedo primaries cannot be accomplished by the particle detector alone. Thus in planning balloon flights care was taken to keep the contribution of nonprimaries at a minimum. In particular, the flights took place at a geomagnetic latitude of 73° N where the cutoff for protons is smaller than 10 Mev. This means that we do not expect to see albedo primaries with energies larger than 10 Mev. Since our detector did not register primary particles with less than 70 Mev, albedo primaries are not detected. We pointed out in Sec. 2(A) that splash albedo particles cannot contribute to the observed flux below energies of 450 Mev/nucleon (slow splash albedo). It has been shown[8] that fast splash albedo particles consist almost entirely of electrons. Our detector system also eliminates those. We therefore can disregard albedo altogether.

However, we shall have to correct for secondary protons produced in the 3 to 5 g/cm$^2$ of air above the detector. We solved this problem by two independent methods. In Sec. 2(D.2) we described the method of calculating the expected contribution of secondaries to the count rate in the various energy intervals. A second method of correcting for the contribution of secondaries is based on the altitude dependence of the vertical flux of incident particles and its extrapolation to the top of the atmosphere. Figures 4–6 show the altitude dependence for various range intervals. The presence of an enhanced flux of low-energy protons above the transition maximum on September 8, 1960, can be seen clearly in both low-energy intervals (Figs. 4 and 5). On this date the correction due to secondaries is very small, since the flux of higher energy protons (range>122 g/cm$^2$ Pb), which are mainly responsible for the production of secondaries, showed no noticeable increase over quiet days (Fig. 6). We have a complete altitude-intensity curve for the flight on September 15, which fell on a quiet day. For this flight we can demonstrate an excellent agreement between the calculated corrections for secondaries and an extrapolation of the altitude intensity curves to the top of the atmosphere (0 g/cm$^2$). In Fig. 7 we have replotted the high-altitude portion of Figs. 4–6 for September 15 on a logarithmic flux vs linear pressure scale, including the correction for nuclear interactions. The value for the flux at 4.3 g/cm$^2$ atmospheric depth was obtained with great statistical accuracy. If we subtract the calculated contributions of secondaries as listed in Table I, we obtain an extrapolation to 0 g/cm$^2$ as represented by the open points in Fig. 7, which are connected by a dashed line. An extrapolation of this line to greater atmospheric depth (full line) shows excellent agreement with the altitude-intensity data obtained during the ascent of the equipment. Thus we are justified to use this extrapolation procedure for deriving the primary proton flux at the top of the atmosphere. Due to the high altitudes reached by the detector, the corrections for atmospheric secondaries are small and cannot materially influence the interpretation of the observations. The same correction procedure was applied for all energy intervals included in this analysis.

Table II gives the measured and corrected flux values for protons on the three dates of observation. It clearly shows, contrary to expectations based on previous results of other observers,[8–10] the existence of a significant flux of low-energy primary protons in the range 70–350 Mev. The presence of protons below 70 Mev

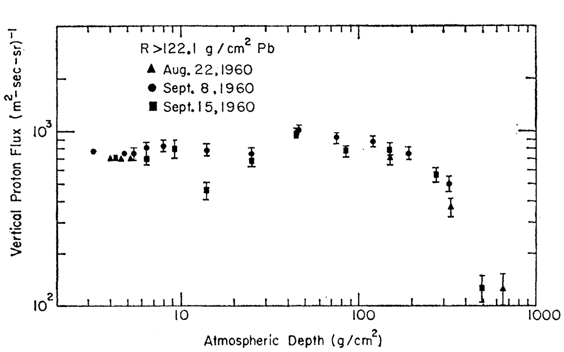


FIG. 6. Vertical proton flux vs atmospheric depth for protons with range in Pb larger than 122.1 g/cm$^2$.

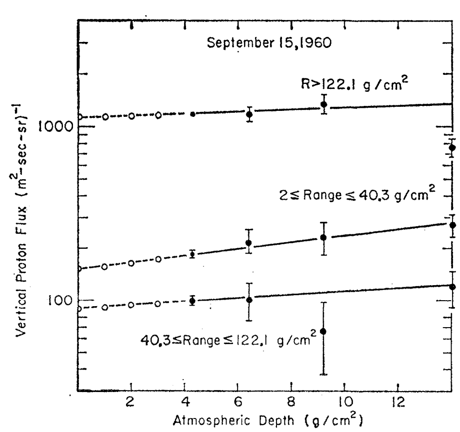


FIG. 7. Extrapolations of proton fluxes to the top of the atmosphere. (The open circles are based on calculations.)

[24] S. B. Treiman, Phys. Rev. 91, 957 (1953).

TABLE II. Proton flux measurements on August 22, September 8, and September 15, 1960, for various energy intervals (averaged over total time at altitude).

| Kinetic energy of primary protons at 0 g/cm² | $E_0 \leq E \leq 187$ Mev | | $187 \leq E \leq 350$ Mev | | $E > 350$ Mev | |
|---|---|---|---|---|---|---|
| Proton range in Pb at detector | $2 \leq R \leq 40$ g/cm² | | $40 \leq R \leq 122$ g/cm² | | $R > 122$ g/cm² | |
| | Measured flux[a] | Corrected flux[b] | Measured flux[a] | Corrected flux[b] | Measured flux[a] | Corrected flux[b] |
| Date of observation | protons/m² sec-sr | | protons/m² sec-sr | | protons/m² sec-sr | |
| August 22, 1960; $E_0=78$ Mev | 165±5 | 134± 7 | 79±4 | 83±6 | 704±11 | 1076±130 |
| September 8, 1960; $E_0=70$ Mev | 594±9 | 546±11 | 158±4 | 179±9 | 731±11 | 1129±135 |
| September 15, 1960; $E_0=78$ Mev | 191±5 | 150± 8 | 87±3 | 92±7 | 742±11 | 1138±140 |

[a] Errors given are statistical.
[b] Errors given are statistical plus systematic, correction includes nuclear interaction in lead absorber and contribution from atmospheric secondaries.

cannot be established from this work since the atmospheric cutoff prevents us from observing such primaries.

There exists evidence for the presence of substantial fluxes of low-energy protons at times near solar minimum.[12,13] No previous measurements of other observers, however, lead us to expect such particles near solar maximum, at which time our observations took place. Unfortunately, none of the detectors flown in earlier years showed as high directionality and unambiguity for the detection of low-energy protons as our detector. We cannot clearly decide, therefore, whether low-energy protons were actually absent in earlier observations at or near solar maximum, or whether they were simply not detected. In order to learn more about these newly discovered primary protons, it is interesting to study their variation with time.

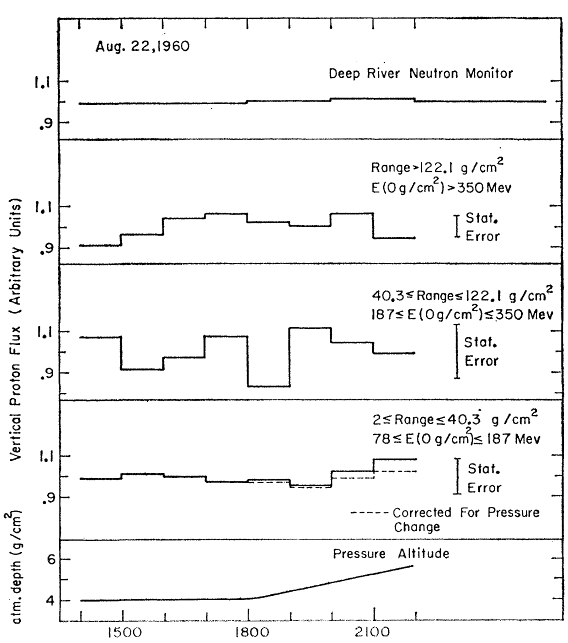


FIG. 8. Proton flux, neutron monitor intensity and balloon altitude vs time on August 22, 1960.

## (B) Time Variations in the Primary Proton Flux

Table II gives an indication of time variations within the period of one month. The low energy flux values on August 22, 1960, and September 15, 1960, were of comparable magnitude, while on September 8, 1960, a large increase was observed in the two low-energy intervals listed, but no comparable variation could be seen in the higher energy interval. There seems to be little doubt that the additional low-energy protons on September 8 originated in the class 3 solar flare of September 3, 1960, which produced a large number of solar protons.[22,25] It has been demonstrated[26,27] that

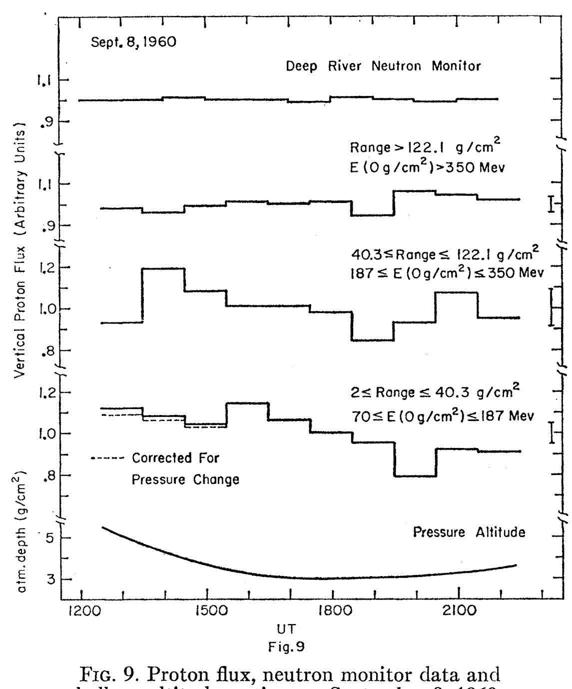


FIG. 9. Proton flux, neutron monitor data and balloon altitude vs time on September 8, 1960.

[25] L. R. Davis, C. E. Fichtel, D. E. Guss, and K. W. Ogilvie, Phys. Rev. Letters 6, 492 (1961).
[26] K. Anderson and D. Enemark, J. Geophys. Research 65, 2657 (1960).
[27] A. N. Charakhian, V. F. Tulinov, and T. N. Charakhian, *Proceedings of the First International Conference of Space Research* (North-Holland Publishing Company, Amsterdam, 1960), pp. 649.

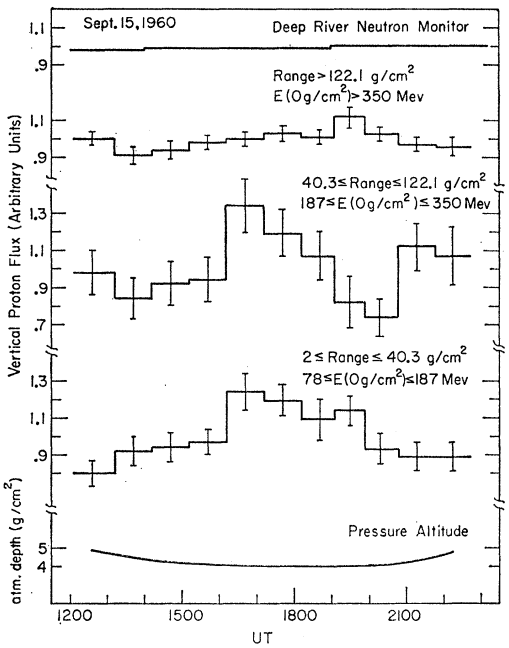


FIG. 10. Proton flux, neutron monitor data, and balloon altitude vs time on September 15, 1960.

solar protons arrive for a period of several days after the visible period of a flare. Anderson and Enemark[26] have observed solar protons of about 100 Mev energy as late as 10 days after a flare.

Figures 8–10 have been plotted for the study of possible diurnal variations in intensity. Each figure lists the hourly averages normalized to the total flight mean value of these energy intervals, into which we have grouped the observed fluxes. For comparison we also have included the intensity variations observed at the sea-level Deep River neutron monitor[28] which is sensitive essentially to the flux of particles with energies larger than 1 Bev. The graphs include the thickness of air absorber, under which the measurements were made. The possible effects due to secondaries from pressure variations are indicated by dashed lines. It is interesting to note that the lack of correlation between intensity and pressure changes, especially on September 15, is an additional verification of our earlier arguments, which proved that the observed low-energy particles are primaries and not due to the production of secondaries in the air above the detector.

Within the limits of statistics, we can detect no significant short-time intensity variation of August 22 in any of the plotted intervals. The results from September 15, where the observed average intensities were similar to August 22, again show no large variations for the neutron monitor data and the high energy protons ($E>350$ Mev) observed at 4 g/cm² of air. However, both the lower energy intervals show a peak about 17:00 UT (11:00 local time). This peak is real, but we consider it premature at present to draw any conclusions from this single observation. The results from September 8 show a relatively constant neutron monitor rate. The observations near the top of the atmosphere show a slight increase over the 10-hour interval of observations for protons with energy $E>350$ Mev. Both lower energy intervals show a decrease in the same time period. This effect will be discussed in Sec. 4(D) together with the flare particle energy spectrum.

### (C) Energy Spectra of Protons

Detailed data during the ascent of the balloons could be obtained on the flights on September 8 and 15 only. We have plotted the observed differential energy spectra for various altitudes above and below the transition maximum (Figs. 11, 12). These spectra contain contributions from primaries and secondary protons and show how the spectrum changes with altitude. At 150 g/cm² atmospheric depth we expect to observe only secondary protons in the energy range considered here. At this depth a peak at about 150 Mev is observed which is in good agreement with theories about the development of the proton component of the secondary flux in the atmosphere.[29] At higher altitudes the contribution of primaries becomes

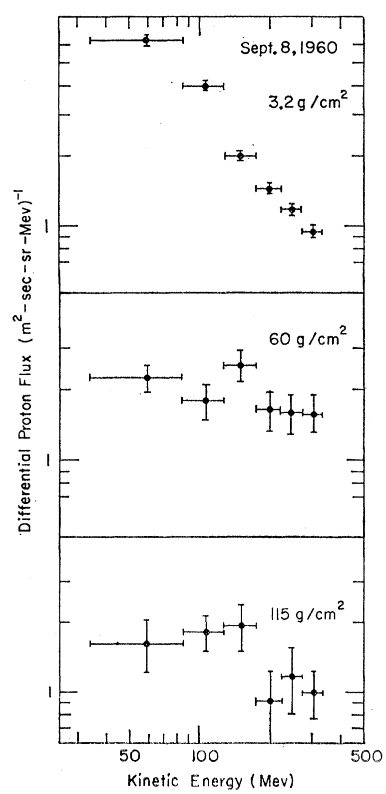


FIG. 11. Proton-energy spectra observed in the atmosphere on September 8, 1960, at various altitudes.

[28] The author wishes to thank H. Carmichael and T. Steljes for making the neutron monitor data available to us.

[29] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1956), pp. 486.

noticeable and the spectrum steepens. This effect is very marked in the September 8 flight, where the low-energy flux was enhanced by a factor of 2 to 3 over September 15.

Figures 13 and 14 give the differential energy spectra of the primary protons at 0 g/cm$^2$, which were derived from the data in Figs. 11 and 12. They are corrected for secondaries and interactions in the lead absorber. The spectrum observed on September 8, when solar protons were present, will be discussed separately in Sec. 4(D).

The energy spectra on August 22 and September 15 are very similar. They were measured on "quiet" days, when no unusual solar or geomagnetic activity[30] was taking place. No solar proton "events" are known to have occurred in the 8-week period prior to August 22, 1960. The spectra clearly cannot be described by a simple power law over their entire range, but the section below 200 Mev may be approximated by $dJ/dE = KE^{-\gamma}$ protons/m$^2$ sec-sr-Mev with $\gamma \approx 2$, $K \simeq 2.3\times 10^4$, and $E$ measured in Mev. The change in slope above 200 Mev is not due to statistics and must be considered real. Additional evidence for this flattening of the spectrum comes from the proton flux observed for energies larger than 350 Mev. From earlier work[31,32] it is known that the differential energy spectrum above 500 Mev can be described by $dJ/dE = K/(1+E)^\gamma$ with $\gamma$ ranging from 2 to 2.5 ($E$ measured in Bev). If one assumes such a spectrum, i.e., $dJ/dE = 1530/(1+E)^2$ protons/m$^2$ sec-sr-Bev for $E > 600$ Mev, all particles with energy $E > 350$ Mev (see Table I) can be accommodated and their differential spectrum matched to the observed spectrum below 350 Mev, if one invokes a flat differential energy spectrum ($dJ/dE = 0.6$ protons/m$^2$ sec-sr-Mev) in the interval from 350 to 600 Mev (dashed line in Fig. 14). It is certainly not possible to extrapolate the spectrum observed below 200 Mev to higher energies without a change in slope and at the same time account for the integral particle flux above 200 Mev.

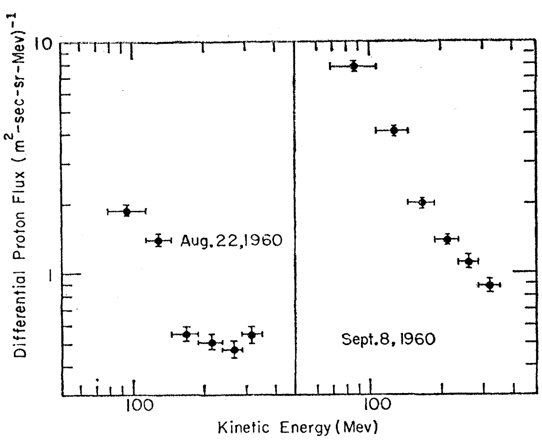


FIG. 13. Primary proton energy spectra at 0 g/cm$^2$ on August 22, and September 8, 1960.

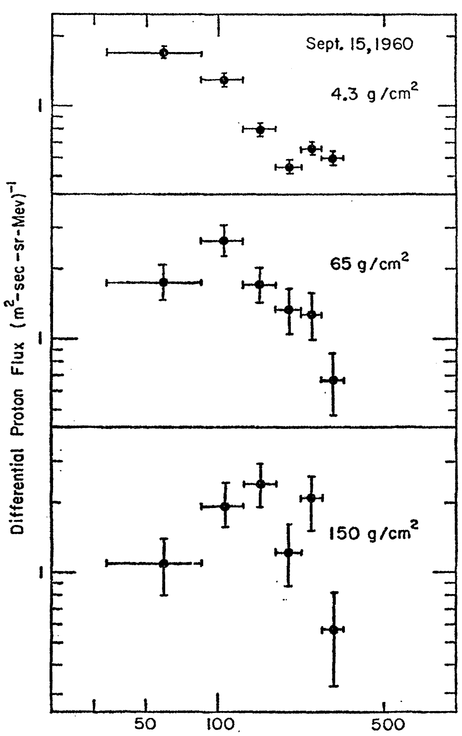


FIG. 12. Proton-energy spectra observed in the atmosphere on September 15, 1960, at various altitudes.

For comparison with earlier observations of McDonald and Webber,[9] we have plotted the September 15, 1960, spectrum on a rigidity scale (Fig. 15). The dashed lines in Fig. 15 indicate typical differential rigidity spectra observed by McDonald and Webber near solar minimum (1954) and solar maximum (1958). Long term intensity variations as recorded by neutron monitor stations[33] (Fig. 16) suggest that the differential rigidity spectrum for protons above 1 Bv in 1960 should lie between the 1955 and 1959 curves of McDonald and Webber in Fig. 15. Using the same line of argument as above for the energy spectrum, this is actually the case, if one assumes a flat or slightly peaked spectrum between 855 Mv and about 2 Bv, which matches our observed rigidity spectrum at 885 Mv and, at about 2 Bv, goes over into a differential spectrum of the form $dJ/dR = KR^{-2.25}$, as found by McDonald[34] for this rigidity region. Consequently, our particle flux above 885 Mv is consistent with earlier data. Extrapolation

[30] Solar Geophysical data, U. S. Department of Commerce, CRPL-F194B, CRPL-F195B, 1960 (unpublished).

[31] B. Rossi, Suppl. Nuovo cimento **2**, 275 (1955).
[32] V. L. Ginsburg, *Progress in Elementary Particle and Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1960), Vol. IV, p. 344.
[33] C. Y. Fan, P. Meyer, and J. A. Simpson, Phys. Rev. Letters **5**, 272 (1960).
[34] F. B. McDonald, Phys. Rev. **104**, 1723 (1956).

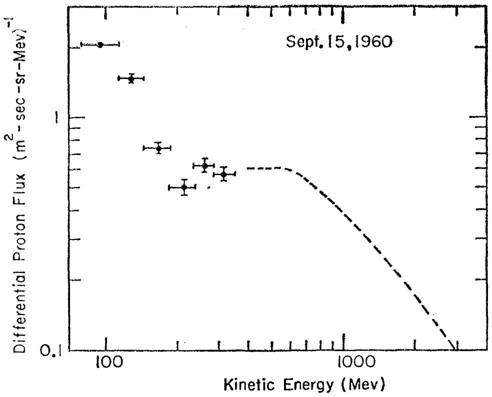


FIG. 14. Primary proton-energy spectrum at 0 g/cm² on September 15, 1960. Dashed line: tentative extrapolation to higher energies, based on the integral flux for $E>350$ Mev.

of the McDonald and Webber spectra towards rigidities below 600 Mv yield spectra which decline towards lower rigidities, while our observations show a rising intensity. Since the flights of McDonald and Webber were performed at geomagnetic latitudes of 54° N with a much higher geomagnetic cutoff than in our observations at 73° N, we consider it premature to draw any conclusions from this discrepancy. The fact that these authors did not observe the low-rigidity primaries does not necessarily mean they were absent in the primary flux.

### (D) Solar Protons on September 8, 1960

The increased flux of low-energy protons, which we observed on September 8, 1960, near the top of the atmosphere at Fort Churchill, can reasonably be associated with the solar flare of September 3, 1960. This event has been studied by rocket[25] and balloon flights.[22] Winckler *et al.*[22] observed particles from the September 3 flare until September 6 at Fort Churchill. Measurements of the energy spectrum of the flare particles were made with the ion-chamber and Geiger counter telescope detector, using the atmosphere as a variable absorber on ascent of the balloon, and directly with emulsions and Geiger counters in the rocket flights. The results (reference 22, Fig. 3) indicate that the flare particle spectrum steepens with time during both the rise and fall of intensity. Typical proton differential energy spectra on September 3, 1960, derived from Fig. 3, reference 22, can be represented by power laws of the form $dJ/dE=KE^{-\gamma}$, where $\gamma\approx 4$, for $120\lesssim$ K.E. $\lesssim 320$ Mev at 12:00 UT (Balloon), $\gamma\approx 2.1$ for $20\lesssim$ K.E. $\lesssim 200$ Mev at 17:30 UT (Rocket), $\gamma\approx 4.5$, for $120\lesssim$ K.E. $\lesssim 320$ Mev at 24:00 UT (Balloon). No spectra for times later than 24 hours after the onset of the flare are given in reference 22. It is therefore of interest to study the low-energy proton spectrum, which we observed on September 8, 1960, 5 days after occurrence of the solar flare event. We should like to determine whether the inferred steepening of the spectrum continued through September 8.

In order to deduce the flare particle spectrum from the observed low-energy proton spectrum, the background of non-flare cosmic-ray protons has to be subtracted. Figure 3 shows that the observations of September 8 fell into the recovery period of a small Forbush decrease ($\sim 4\%$ at sea level), which started on September 4. Since ground-level neutron monitors are insensitive to the effects of primary protons below 400 Mev, they cannot be used to estimate the change of the low-energy cosmic-ray proton background during the Forbush decrease. However, we can impose restrictions upon the intensity and spectrum of solar protons, under specific assumptions. In the following we shall use a spectrum, which is an average for the 10 hours of observation on September 8.

There are 3 extreme cases that might be assumed to establish limits on the characteristics of the solar proton flux of September 8, 1960. Consider that (1) the background flux below 170 Mev was completely removed due to the Forbush decrease and all primary protons observed below 170 Mev are flare produced protons, or that (2) the cosmic ray "background" remained unchanged and is given by the August 22 or September 15 spectrum, or that (3) the solar proton spectrum is a power law $dJ/dE=KE^{-\gamma}$ with $\gamma\geq 3.5$ as suggested by other observers.[22]

In case (1) [Fig. 17(a)] the solar proton spectrum is given by $dJ/dE=15\times 10^4\times E^{-2.2}$ protons/m² sec-sr-Mev, which would require a background spectrum as indicated by the dashed curve (B). For comparison, the September 15 "quiet-day" spectrum is plotted in the graph. An extrapolation of the $E^{-2.2}$ spectrum to higher energies would result in a flare particle contribution of $J(E>350\text{ Mev})\approx 110$ protons/m² sec-sr to the flux above 350 Mev.

In case (2) [Fig. 17(b)] the difference between the September 8 and 15 spectra results in a spectrum of the

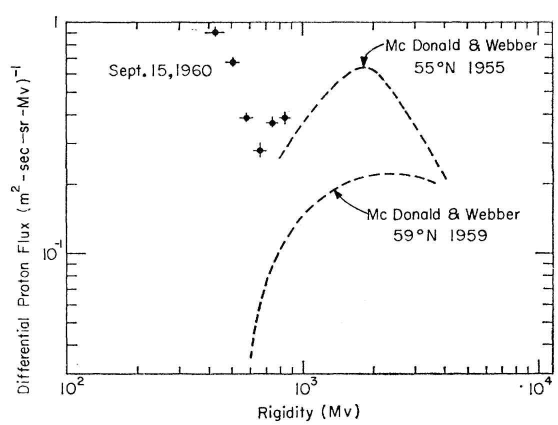


FIG. 15. Primary proton-rigidity spectrum at 0 g/cm² on September 15, 1960. Dashed lines: Typical spectra observed by McDonald and Webber.[10]

form $dJ/dE = 10.5\times10^4\times E^{-2.2}$ protons/m$^2$ sec-sr-Mev. The extrapolated spectrum contributed $J(E>350$ Mev$)\approx 77$ protons/m$^2$ sec-sr to the observed flux above 350 Mev.

In case (3) [Fig. 17(c)] we wish to test whether a solar proton power law spectrum $dJ/dE = KE^{-\gamma}$, with $\gamma \geq 3.5$ can be made to agree with the observations. We consider the most conservative case $\gamma = 3.5$, and normalize the flare spectrum at 80 Mev to the observed data. In this case the background intensity is given by curve B in Fig. [17(c)]. We find that the background intensity above 150 Mev is required to be higher than on a quiet day (September 15), which certainly is not the case, since our observations were made during a Forbush decrease. One should also note that the presence of solar protons below 80 Mev or a steeper slope of the flare particle spectrum towards higher energies would require an even higher background intensity.

We, therefore, can definitely eliminate case (3). The flare particle spectrum must have an exponent $\gamma$ less than 3.5 in the 70–350 Mev region on September 8, 1960; 5 days after the flare, in fact, it must be equal to $2.2\pm0.2$ unless one wishes to invoke an increased background intensity, which we consider unreasonable.

If one subtracts the contribution of solar protons from the observed total flux above 350 Mev, one finds for case (1) a 9.8% and for case (2) a 6.8% decrease with respect to the quiet day fluxes of August 22 or September 15. The Forbush decrease of 4% measured by ground-level neutron monitors on September 8 is not in conflict with either case (1) or (2). We conclude that the flare particle energy spectrum of September 8 follows a power law with exponent $\gamma = 2.2$ from 70 to 350 Mev. This slope is identical with the one measured on September 3 (17:30 UT) in rocket observations.

A systematic variation of the proton intensity was observed on September 8, 1960. Figure 18 shows this behavior for the two low-energy intervals discussed here. A straight-line least-squares fit to the observed

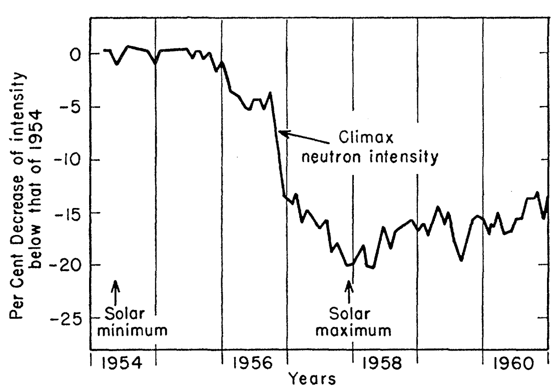


FIG. 16. Monthly averages of Climax neutron monitor intensity, 1954–1960.

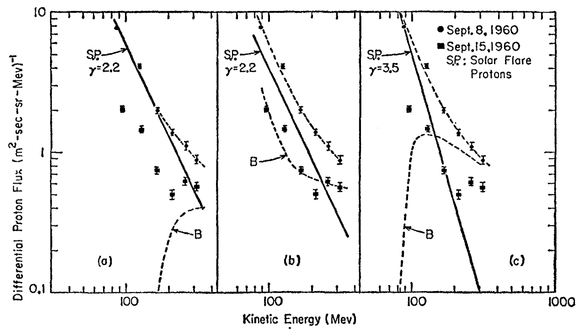


FIG. 17. Solar proton-energy spectrum at 0 g/cm$^2$ on September 8, 1960 under various assumptions [see Sec. 4(D)]. $\gamma$ is the exponent of the differential energy spectra.

data gives the following relations for the fluxes:

$$J(70\leq E\leq 185 \text{ Mev}) = 689 - 17.3(t-t_0),$$
$$J(185\leq E\leq 350 \text{ Mev}) = 168 - 1.8(t-t_0),$$
$$J(E>350 \text{ Mev}) = 1189 + 7.6(t-t_0),$$

where $J=$ (protons/m$^2$ sec-sr), $(t-t_0)=$ (hours), and $t_0 = 12{:}00$ UT September 8, 1960.

These relations seem to imply that on September 8 the intensity between 70 and 185 Mev decreases faster than the intensity between 185 and 350 Mev. However, we recall that these observations were made during the recovery period of a Forbush decrease, which is also demonstrated by the behavior of the intensity above 350 Mev. In the interval between 185 and 350 Mev, we might actually be observing a superposition of a decrease in solar proton intensity and an increase in the galactic proton intensity. Consequently, we cannot use the time dependence of the proton flux in the energy intervals studied here to draw quantitative conclusions concerning the property of the storage mechanism for solar protons.

## 5. SUMMARY AND CONCLUSIONS

Three Skyhook balloon flights were made from Fort Churchill, Manitoba, which has a calculated geomagnetic cutoff of about 0.1 Bv.[21] Average floating altitude of the balloons was 3 to 5 g/cm$^2$ atmospheric depth. Measurements obtained with our detector system, which records range and energy loss of a particle, provide accurate and reliable data about the primary proton flux and energy spectrum between 70 and 450 Mev. Two independent methods allow a clear separation of primary and secondary proton fluxes.

The results from these observations show the unexpected presence of a significant flux of low-energy protons down to energies of 70 Mev, where atmospheric cutoff sets in. On August 22 and September 15, 1960, which were "quiet days" with respect to solar and geomagnetic activity,[30] very similar low-energy primary proton spectra, showing increasing differential fluxes towards lower energies, were observed. For the results

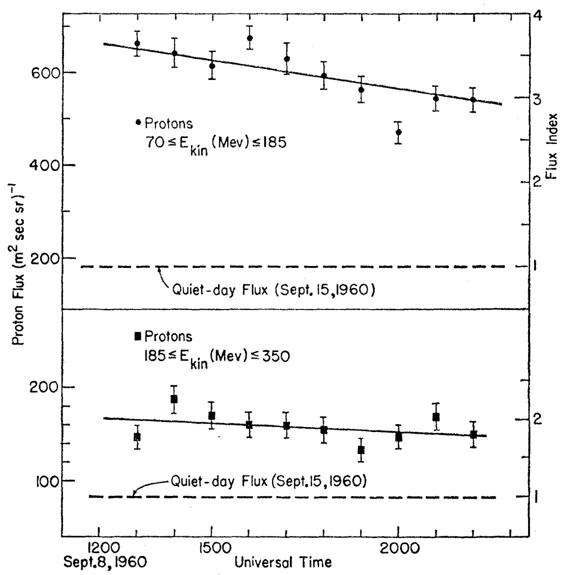


FIG. 18. Time variation of proton flux on September 8, 1960. The straight lines were obtained by least-squares fit.

of September 15, the differential energy spectrum between 78 and 200 Mev can be approximated by $dJ/dE = 2.3\times10^4\times E^{-2}$ protons/m² sec-sr-Mev. Between 200 and 350 Mev, $dJ/dE\sim$constant. On Sept. 15 a time variation of the primary proton flux below 350 Mev with a peak intensity around 11:00 local time was observed. During the same interval, no time variation in the particle flux above 350 Mev could be detected. No time variations were observed during the 8-hour period of observation on August 22.

The presence of a large number of primary protons of kinetic energy smaller than 350 Mev is at variance with conclusions based on previous observations at similar periods of the solar cycle[1] ($\sim$2 years after maximum), and we do not find an explanation on the basis of presently available theories.

On September 8, 1960, the primary proton flux below 350 Mev was increased by a factor of 2 or 3 over that of August 22 and September 15. These additional protons are believed to have their origin in a class 3 solar flare on September 3, 1960, which is known to have produced high-energy protons.[22,25] It was shown in Sec. 4(D) that the differential energy spectrum of these solar protons must have an exponent of $\gamma\approx2.2$, if a power law dependence of the form $dJ/dE=KE^{-\gamma}$ is assumed. This result differs from other observations,[22,26] which predict a much steeper power law spectrum for such a late stage (5th day) in the decay of the flare particle intensity. In fact, our spectrum is very similar in slope to the one found in rocket soundings about 17 hours after the flare, when the intensity was about 100 times higher. It is doubtful whether the Forbush decrease, which started on September 4, 1960, could have caused the relatively small exponent in the solar proton power law spectrum, which we observed on September 8. However, our knowledge of the mechanism, which produces a Forbush decrease is still very limited, so that such a possibility cannot definitely be excluded.

We pointed out earlier that the presence of the low-energy protons on quiet days cannot be explained on the basis of present theories. It is obvious from the low-cutoff value of 10 Mev that the observed protons cannot have been trapped like Van Allen particles prior to detection, just as they cannot have come along the line of force from the Southern hemisphere.

If the observed low-energy protons are of galactic origin, they do not represent the true galactic low-energy spectrum, but rather the spectrum after modulation by the mechanism which causes the 11-year cycle variation in cosmic radiation. The 11-year cycle has been studied by aircraft latitude surveys for the energy region of about 1 to 5 Bev,[35] up to 15 Bev with the Chicago neutron monitor network,[36] and to energies of about 1 Bev with a balloon borne neutron monitor.[37] It was found that the 11-year variation of the galactic cosmic-ray intensity is rigidity dependent, with the largest variations occurring at low rigidities. Results obtained with cosmic ray instruments on the Pioneer V space probe[33] indicate that the 11-year modulation mechanism is heliocentric and affects a volume which includes the entire earth orbit. Most of the theoretical models for the modulation of galactic cosmic-ray intensity involve a rigidity- or velocity-dependent mechanism. We shall discuss here only two extreme models, which were proposed by Parker in his discussion of the solar wind: (1) modulation by a stable spiral field about the sun[38]; (2) modulation, through disordered fields from instabilities in the spiral field beyond the orbit of earth.[39]

With $j_\infty(\eta)$=primary galactic proton flux before modulation, $j_0(\eta)$=galactic proton flux observed at the earth after modulation, $\eta$=kinetic energy, we find from reference 39 for case (2): $j_0(\eta)/j_\infty(\eta)\sim0$ for protons below about 400 Mev near solar maximum. Consequently, the finite proton flux in this energy interval, which we observed in 1960 near solar maximum, cannot be allowed in such a model. In case (1) we find from reference 38 for nonrelativistic energies: $j_0(\eta)/j_\infty(\eta)\propto 1-\kappa/w$, where $w$ is the velocity of the particle, $\kappa$=constant. For a 50% decrease of the differential particle flux at 1 Bev, as observed by McDonald and Webber[8] between solar minimum and solar maximum, $\kappa\sim0.5c$ ($c$=velocity of light). Using this value of $\kappa$ for lower energies, we find $(j_0/j_\infty)$(200 Mev)$\sim$0.1, and $(j_0/j_\infty)$(100 Mev)$\sim$0, which again is at variance with our observations in 1960. A value of $\kappa=0.1c$, which seems

[35] P. Meyer and J. Simpson, Phys. Rev. **106**, 568 (1957).
[36] J. A. Simpson (private communication).
[37] K. B. Fenton, P. Meyer, and J. A. Simpson (unpublished results).
[38] E. N. Parker, Astrophys. J. **133**, 1014 (1961).
[39] E. N. Parker, Phys. Rev. **110**, 1445 (1958).

to be typical for Forbush decreases, would give a much smaller intensity decrease: $(j_0/j_\infty)(100\text{ Mev})\sim 0.75$. We therefore conclude that under case (2), with disordered magnetic fields beyond the orbit of earth, the observed low-energy proton flux in 1960 could not be of galactic origin. However, for sufficiently small $\kappa$, with case (1) of a stable spiral field, the observation of low-energy galactic proton fluxes as seen in 1960 would be possible.

Finally, suppose that the low-energy protons are of solar origin. It has been shown[40] that stars like the sun cannot account for the production of the observed galactic cosmic-ray flux. Solar flares, however, are known to frequently produce large numbers of low-energy cosmic-ray particles, as discussed in Sec. 4(D). The flare produced solar protons are stored in the inner solar system and their intensity is observed to decrease over periods of days. It has been generally assumed that the sun produces these particles only on distinct occasions, mainly in connection with class 3 or class 3+ flares associated with a type IV radio outburst, and that after the return of the low-energy cosmic-ray intensity to the preflare level, no more solar protons were present. However, the sun is known to frequently produce smaller flares, and it is possible that in these events protons are accelerated to $\sim$100-Mev energies in small numbers. The frequent occurrence of flares smaller that class 3 ($\sim$6/day class 1, $\sim$0.4/day class 2 during July, August, September, 1960) combined with the typical decay period of several days for stored particles could very well produce a more or less constant low-energy solar proton background during the periods of enhanced solar activity. In order to explain the observed "quiet-day" cosmic-ray intensity in the region of 80 to 350 Mev by solar production, the following average energy output by the sun in form of cosmic-ray energy would be required:

$$P \geq \mathcal{E}/\tau \approx (4\pi/3) r_E^3 (J\bar{E}/\tau w),$$

where $r_E = 1$ A.U. (astronomical unit), $J$ = particle flux with average energy $\bar{E}$ and velocity $w$, and $\tau$ = storage time of flare particles.

With $\tau = 10$ days, which agrees with experiments, an average energy output in form of cosmic rays of the order of $10^{20}$ ergs/sec would be required for the solar origin of the observed low-energy proton flux. This number is small in terms of solar energy, in fact the energy released in the form of high-energy particles during the February 23, 1956, solar flare corresponds to about $2\times 10^{22}$ ergs/sec, if averaged over a five-year time interval.[7,40]

At present we do not possess sufficient evidence to decide conclusively in favor of either of the possibilities discussed. The assumption of solar origin would appear the simpler, however. The primary cosmic-ray spectrum, which we observed in 1960, then would consist of low-energy solar protons superimposed on the galactic spectrum, which due to modulation, lacks low-energy protons.

However, further observations at other times during the 11-year cycle of solar activity will be necessary before any final decision can be made.

[40] E. N. Parker, Phys. Rev. **107**, 830 (1957).

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