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II-4-15. Flux and Energy Spectra of Primary Cosmic Ray Protons from 70 to 400 Mev*,**

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A study of the low energy portion of the primary cosmic ray proton spectrum was made in August and September 1960. The observations took place in three high altitude balloon flights at geomagnetic latitudes $\lambda \geq 73°$N. We detected a significant flux of primary protons with energies below 500 Mev, which previously had been considered absent. Fluxes and energy spectra of these particles are given and their possible origins are discussed.

It has been known for a number of years that the modulation mechanisms which affect the flux of primary cosmic ray particles in the vicinity of the earth show their largest influence in the low energy region of the spectrum. These changes in the primary energy spectrum, *i.e.* as a function of the solar cycle phase, have led to the formulation of a number of theories which try to account for the modulation phenomena.

It is clear that detailed measurements of the low energy primary particles would be most useful in studying the nature of the modulation mechanisms and for that reason we investigated the proton energy spectrum in the region of 70 to 400 Mev.+

The observations were carried out in August and September 1960 from Ft. Churchill, Manitoba at a geomagnetic latitude of about 73° N. According to Quenby and Webber[1] the geomagnetic cutoff for primary protons at Fort Churchill is about 6 Mev. The instruments were flown with balloons at 3 to 5 g/cm^2 atmospheric depth. The lowest energy of primary protons, which could be observed, was given by the atmospheric cutoff and amounted to about 70 Mev.

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** This paper was read by P. Meyer.

+ For a more detailed description of this experiment see: Rochus Vogt, "Primary Cosmic Ray and Solar Protons," Phys. Rev. (in press)

The energy spectrum of the vertically incident primary particles was obtained through a simultaneous measurement of their energy loss in a NaI crystal and their range in a lead absorber. Fig. 1 shows a cross-section of the detector system. The telescope geometry of 2.1 cm^2 sterad is defined by the "Telescope-counter" and "Counter 1". Only particles which give a coincidence between these two counters are analyzed. The lead

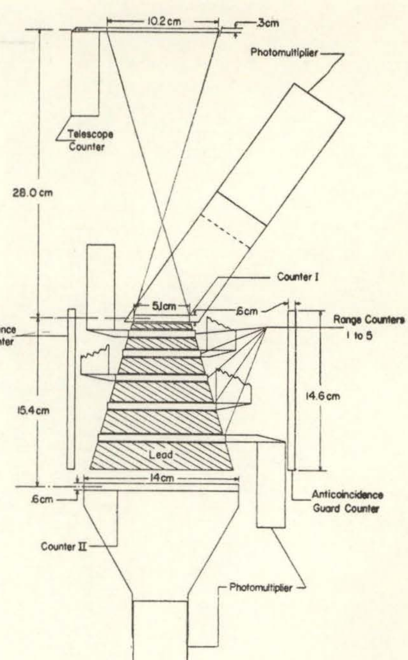

Fig. 1. Cross section of the detector system.

absorber is subdivided into "range intervals" by scintillation counters. We measure the ionization loss of the particle in Counter 1, 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/cm², (E>350 Mev/nucleon), we determine in addition the ionization loss in "Counter II."

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. Important features of the detector system are: 1. Separation of protons from other components through characteristic range-energy loss relations. 2. Determination of the energy spectrum of vertically incident protons up to 450 Mev without contribution from splash albedo.

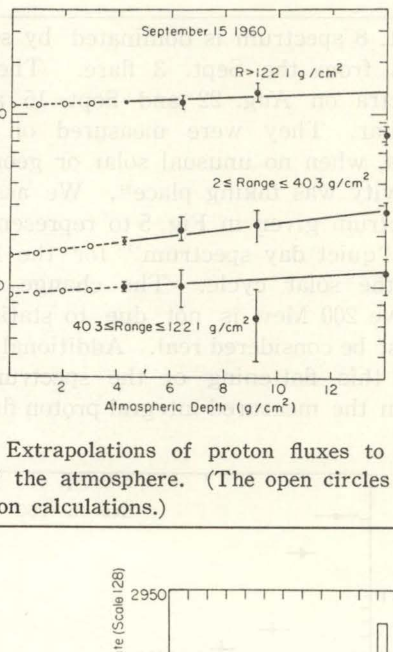

Fig. 2. Extrapolations of proton fluxes to the top of the atmosphere. (The open circles are based on calculations.)

At the latitude of our observations no return albedo can contribute to the proton flux measured in our detector, and corrections have to be applied only for the secondaries produced above the detector and for the fraction of particles which make nuclear interactions in the lead. Such corrections were obtained from calculations based on empirical data from nuclear emulsion observations (Camerini *et. al.*[2,3], Lord[4]). Due to the high altitudes attained in the flights, the corrections for secondaries are small and can in no way materially influence the interpretation of the results. Fig. 2 shows as an example the extrapolation to the top of the atmosphere of the vertically incident proton fluxes for various energy intervals. The open circles were obtained by calculation. The dashed lines connecting these points are extended into the region where the altitude dependence was measured, and we find very good argument between calculations and measurement. Table I lists the measured and corrected flux values of vertically incident protons at the top of the atmosphere for various energy intervals. Fig. 3 gives the Climax neutron monitor data for the period when our measurements took place. The Sept. 8, 1960 flight fell into the Forbush decrease which followed the Sept. 3, 1960 flare. Although the intensity of high energy primaries was depressed on this day, as shown by the neutron monitor observations, the flux

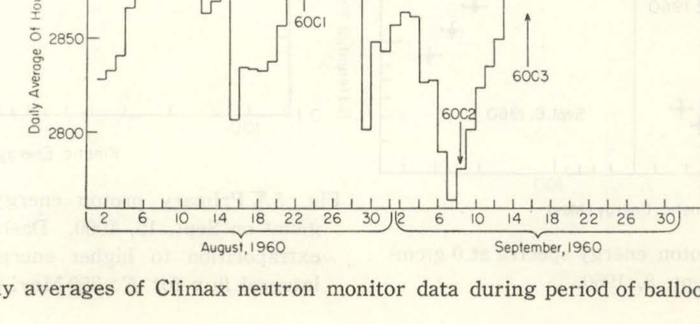

Fig. 3. Daily averages of Climax neutron monitor data during period of balloon measurements.

Table I. Proton flux measurements on Aug. 22, Sept. 8 and Sept. 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	
Date of observation	Measured flux*	Corrected flux**	Measured flux*	Corrected flux**	Measured flux*	Corrected flux**
	protons/m²-sec-sterad		protons/m²-sec-stered		protons/m²-sec-sterad	
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

* Errors given are statistical.

** Errors given are statistical plus systematic, correction includes nuclear interaction in lead absorbar and contribution from atmospheric secondaries.

of protons between 70 and 400 Mev was enhanced by a factor 2 to 3 due to the storage of solar injected flare particles. On August 22 and September 15, 1960 the proton flux and energy spectra were almost identical. We detected (see Table I) a substantial flux of low energy protons, contrary to expectations based on the results of other observers[5,6,7,8] for periods close to the maximum of the solar cycle. Figs. 4 and 5 give the differential energy spectra of the primary protons at 0 g/cm². They are corrected for secondaries and nuclear interactions. The Sept. 8 spectrum is dominated by solar protons from the Sept. 3 flare. The energy spectra on Aug. 22 and Sept. 15 are very similar. They were measured on "quiet" days, when no unusual solar or geomagnetic activity was taking place[9]. We assume the spectrum given in Fig. 5 to represent a typical "quiet day spectrum" for the 1960 part of the solar cycle. The change in shape above 200 Mev is not due to statistics and must be considered real. Additional evidence for this flattening of the spectrum comes from the measured integral proton flux above

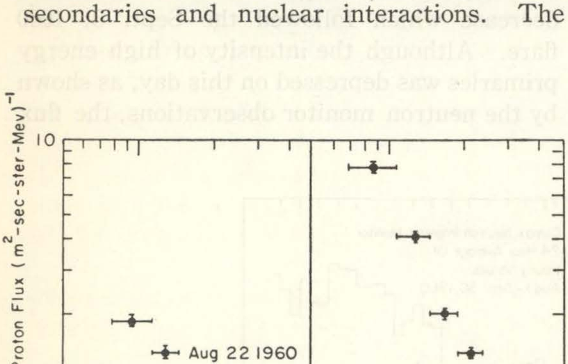

Fig. 4. Primary proton energy spectra at 0 g/cm² on Aug. 22 and Sept. 8, 1960.

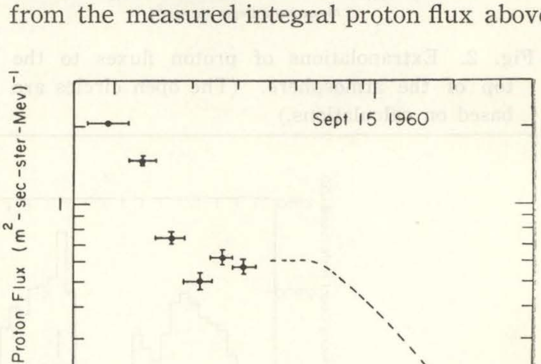

Fig. 5. Primary proton energy spectrum at 0 g/cm² on Sept. 15, 1960. Dashed line: tentative extrapolation to higher energies, based on the integral flux for $E > 350$ Mev.

350 Mev. In order to accommodate this flux within the known spectrum for higher energies[10] one arrives at the shape indicated by the dashed line. Details of the form of the spectrum between 350 Mev and 1 Bev are, of course, not known.

These results are surprising in view of the evidence obtained in earlier experiments by other observers. Measurements made by Neher[8] near solar minimum with ionization chambers indicated the presence of a flux of low energy primaries. No experiment, however, led us to expect their presence at times near solar maximum, when our observations took place. The primary spectra deduced by McDonald and Webber[5,6,7] indicate a decreasing intensity towards lower energies at all phases of the solar cycle. Fig. 6 gives a comparison between their spectra and our data. Neutron monitor results suggest that the differential rigidity spectrum for protons above 1 BV rigidity should be between the 1955 and 1959 curves of McDonald and Webber. Our measured particle flux above 880MV is consistent with such an assumption. However, at rigidities below 600 MV these authors find spectra which decline towards lower energies, while our observations show a rising intensity. One should bear in mind, however, that the measurements of McDonald and Webber were made at much lower geomagnetic latitudes (54° N) than ours and that the problem of geomagnetic cutoff is by no means completely understood. We feel, therefore, that the McDonald and Webber experiment does not necessarily exclude the possibility that low energy primaries might

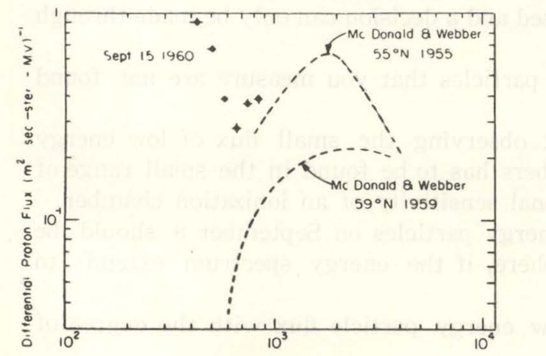

Fig. 6. Primary proton rigidity spectrum at 0 g/cm² on Sept. 15, 1960. Dashed lines: typical spectra observed by McDonald and Webber.[7]

have been present at times during their observations.

If one assumes the observed low energy protons to be of galactic origin, subject to solar cycle modulation, one encounters difficulties with present theories for the modulation mechanism. Modulation by disordered fields from instabilities in the spiral field of the sun beyond the orbit of earth[11] excludes all protons below about 400 Mev near solar maximum. A finite galactic proton flux in the energy region of our observations can therefore not be allowed in such a model. Parker's recently proposed model[12] which for non-relativistic energies yields a flux ratio $(J_0/J_\infty)\sim 1-k/w$ (J_0=flux observed at earth, J_∞=galactic flux, w=particle velocity) would, with a suitably chosen constant k ($k\sim 0.1\,c$) permit the arrival of a substantial fraction of low energy galactic primaries. With $k\approx 0.5\,c$, as determined from the 50% reduction of the particle flux at 1 Bev at solar maximum[5], the arrival of the measured low energy proton flux again would not be permitted.

As an alternative, we may propose that the low energy proton flux, which was observed on "quiet" days, has a solar origin. This would require frequent emission of particles in the 100 Mev region by the sun, possibly by small flares. The very similar flux and energy spectra observed on August 22 and September 15 then must be regarded as fortuitous. With a storage time of about 10 days for solar flare particles, an average energy output of about 10^{20} ergs/sec in form of energetic protons by the sun would be required, if the flux and spectrum, which we observed, lasts for long periods of time. This amount of energy is small in terms of solar output and could be easily produced by the sun.

At present, we do not have sufficient evidence to decide between solar and galactic origin. A number of further observations, carried out by us in July and August 1961 should help to clarify the situation.

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Discussion

Gall, R.: Some return albedo might also exist: (not the albedo coming from the other hemisphere, but the one leaving and coming back to the observation point).

Meyer, P.: It is unlikely that this type of return albedo flux was measured because 1) only a narrow angle around zenith was accepted by the telescope and 2) the observed spectrum is quite different from a secondary particle spectrum.

Ehmert, A.: We have a similar experience concerning such low energy radiation. A series of balloon measurements with single Geiger counters over Lindau in 1959 approved that on most cases a strong linear correlation was found between the particle number at any pressure level and the neutron number at the ground station at the same time.

So at any time the intensity at any level can be predicted so far it belongs to galactic cosmic radiation. But during a deep Forbush decrease in July 1959 an excess radiation was recorded at pressures below 100 mm Hg. The absorption of this radiation indicates a proton energy of 400 Mev. It is important that our cut-off is normally much higher.

In our case, mentioned above, there was no short time variation of this extra radiation during the ascent, but the other day it was vanished.

Meyer: The low energy particle increase mentioned by Prof. Ehmert appears to have the features of one of the solar events with breakdown of the geomagnetic cut-off.

With respect to the experiment reported here it should be noted that flux and energy spectrum of protons between 70 and 350 Mev remained unchanged for measurements almost apart.

Waddington, C. J.: It can be noticed that both your "quiet time" flights were just after the occurrence of a small Forbush decrease. There could be some storage of particle.

Meyer: It is certainly possible that the low energy protons are of solar origin at all times. This alternative has been discussed and a decision can only be made through further experiments.

Neher, H.V.: It is surprising that these particles that you measure are not found in balloon latitude surveys above the knee.

Meyer: I believe that the reason for not observing the small flux of low energy protons with balloon borne ionization chambers has to be found in the small range of the protons combined with the omnidirectional sensitivity of an ionization chamber.

Kondō, I.: I think the increase of low energy particles on September 8 should be observed as Aurora or Blackout in ionosphere, if the energy spectrum extends to lower energy with same slope.

Is there any correlation between these low energy particle flux with the degree of ionization in ionosphere?

Meyer: P.C.A. has been observed at Fort-Churchill following the September 3 flare. I believe that it persisted through September 6 but I do not remember the data of September 8.