ROCKET OBSERVATIONS OF SOLAR PROTONS ON SEPTEMBER 3, 1960

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It is now well established that high-energy nuclei arrive at the earth following some major solar flares. These solar particle beams have been observed using ground-level monitors, balloon-borne counters, and nuclear emulsions, and counters in satellites and space probes.

To obtain a more detailed picture of the character of solar particle beams in the range of energies between 2 Mev and 250 Mev, sounding rockets were used to carry charged-particle detectors well above the earth's atmosphere during several of these events. The rockets were launched from Fort Churchill, Manitoba, Canada, geomagnetic coordinates 60.7°N, 324.4°E where the magnetic field of the earth does not prevent the entry of low-energy particles. A typical flight trajectory for the Nike-Cajun sounding rocket is shown in Fig. 1. The rockets carried a Geiger counter, scintillation detector, nuclear emulsions, and a magnetometer to provide rocket aspect as a function of time.

Beginning on June 6, 1960, a 24-hour-a-day stand-by for a solar particle beam was begun at the Rocket Research Facility at Fort Churchill. Arrangements had been made with several solar observatories and riometer stations to send immediate notification of a major solar flare or polar cap absorption event. When the experiment was concluded at the end of November, ten firings had been made into four solar particle beams, and four other firings for comparison purposes had been made during quiet periods and periods of auroral absorption.

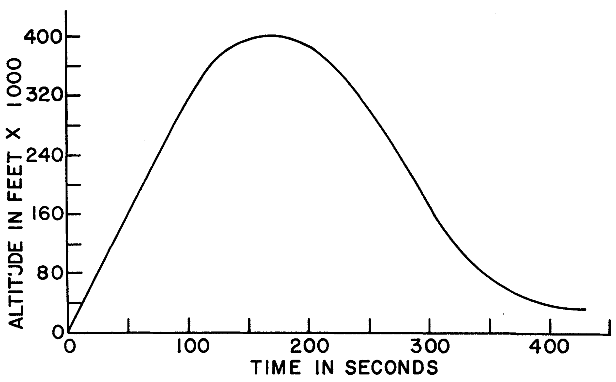

FIG. 1. SBE Nike-Cajun trajectory.

During the solar particle event, which began on September 3, 1960, at 2100 U.T., and is generally credited to a flare of magnitude 3 (solar coordinates 20°N, 87°E) occurring at 0040 U.T. on September 3, two rockets were shot. The exact firing times are given in Table I. Reduction and interpretation of the scintillation counter results for these two firings is not complete, but the Geiger counter results and emulsion results are reduced and will be presented here. The counter data were reduced by Davis and Ogilvie, and the emulsion data by Guss and Fichtel. The results are presented together because they refer to the same event and the same conclusions can be drawn from both.

The Geiger counter used was an Anton 302, placed so that its axis was parallel to the axis of the rocket, and mounted close to its wall on one side. The solid angle to the front, of almost 2 steradians, was shielded by the equivalent of 0.65 g/cm^2 of aluminum, and that to the rear by a variable but larger amount. Outside the atmosphere, the regular precessional motion of the rocket places a variable amount of absorber between the protons and the sensitive volume. Assuming an isotropic distribution in the upper hemisphere, two points on the integral energy spectrum of the particles may be obtained from

Table I. Rocket firing data.

Rocket designation	Firing time	Performance	Emulsions recovered
NASA 1019	1408 U.T.	Max altitude 130 km	yes
NASA 1020	1730 U.T.	Max altitude 130 km	no

the counting rates observed with the Geiger counter pointing first upwards and then down. The angular distribution of Geiger counter rate is consistent with the assumption of isotropy in the upper hemisphere. The only particles we have considered approaching the apparatus from below, are those which mirror so close under it that their range allows them to make the journey back up again. This correction increases the effective solid angle by about 10%. Another flux value may be found by summing up contributions to the solid angle, when the apparatus is at a depth of approximately 10 g on the way up. The appropriate energy is found by weighting the contribution of each sector by the reciprocal of the proton energy which can just penetrate to it.

The flux values in Table II show that in the energy region 22 to 67 Mev, the flux was the same at 1730 U.T. as at 1408 U.T., but a reduction had taken place in the 200-Mev region. This is in general agreement with the sea-level neutron monitor observations at Deep River, Ontario, which was showing an increased rate at the time of the first rocket firing.

The emulsion section of the payload consisted of a 1-in. by 4-in. diameter cylindrical stack of 600-micron thick Ilford G-5 nuclear emulsions, with the plane of the emulsions perpendicular to the rocket axis. The stack was shielded from the ambient radiation by 0.175 g/cm^2 of aluminum and 0.013 g/cm^2 of reflective aluminum foil and Mylar.

To obtain the proton energy spectrum, the emulsions were scanned so that all tracks from protons with kinetic energies between 13 Mev and 250 Mev within a given solid angle would be recorded. The proton energies were determined from range measurements in the energy interval between 13 Mev and 90 Mev and from grain density measurements in the energy interval between 90 Mev and 250 Mev. In the latter interval, it is not possible to determine the direction of motion of the particles, and a penetration correction must be made for those particles which cross the scan line by first traversing the emulsion.

The analysis of the Geiger counter data from this flight is consistent with the assumption that the solar beam particles were isotropic over slightly more than the upper hemisphere and zero over the remainder of the lower hemisphere and this was assumed in obtaining the unidirectional fluxes from the emulsion data.

With the above assumption, the observed spectrum was corrected in the following way for ascent, descent, and the ionization loss in the atmosphere of mirrored particles to yield the integral spectrum under zero atmosphere. The observed differential spectrum was corrected for background and approximately corrected for penetration. An integral spectrum was then formed by normalizing to the flux at 250 Mev observed by Winckler et al.[1] at the same time at balloon altitudes. Because of the relatively small flux of protons with energies greater than 250 Mev, a change of the integral flux at that point would not appreciably alter the shape of the integral spectrum at lower energies, as may be seen from Fig. 2. The resulting spectrum was taken as a first approximation to the integral spectrum at the top of the atmosphere. Using this, the spectra at various absorber depths were computed, and the contributions, including penetration, at each absorber depth, were added to give a spectrum which was compared to the observed spectrum. From this comparison, a better estimate of the spectrum at zero atmosphere was made and the procedure repeated until agreement was reached.

The integral energy spectrum (a) and the differential energy spectrum (b) for protons at zero atmosphere found from the emulsion data, are

Table II. Proton flux measurements during polar cap absorption on September 3, 1960.

Energy (Mev)	Integral flux (particles/cm^2 sec sr)	Time (U.T.)	Ft. Churchill riometer absorption at 30 Mc/sec
22	18.5 ±1	1408	1.4
67	7.3 ±0.5		
177	3.8 ±1.0		
22	19.7 ±1	1730	1.4
67	6.5 ±1		
220	1.3 ±0.6		

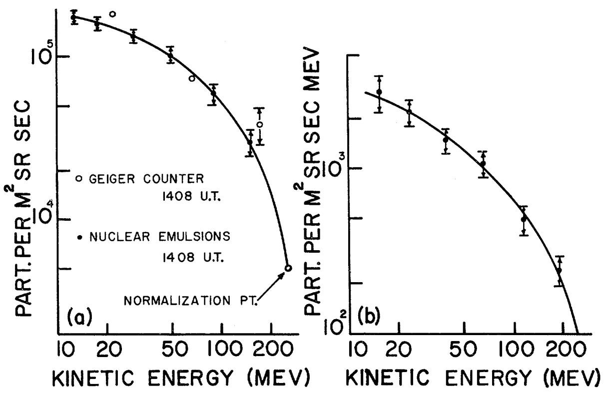

FIG. 2. Proton energy spectrum from solar particle beam of September 3, 1960. (a) Integral spectrum; (b) differential spectrum. NASA rocket 1019.

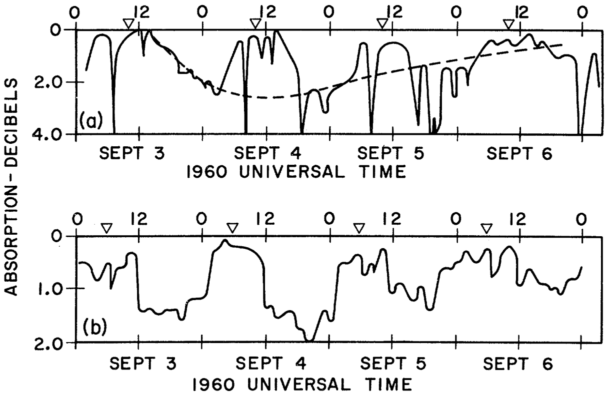

FIG. 3. Riometer absorption produced by the solar particle beam of September 3, 1960. (a) 27.6-Mc/sec riometer at College, Alaska; (b) 30-Mc/sec riometer at Fort Churchill, Canada.

shown in Fig. 2. The errors on the emulsion points include the uncertainty of the ascent correction as well as the statistical uncertainty associated with each point. The slope of the energy spectrum in the 13-Mev to 50-Mev region is very much smaller than that at higher energies. Although there are no previous experimental data in this low-energy region to indicate what slope is expected, this result is consistent with the discussion to be given below. We also show the points obtained at the same time by means of the Geiger counter. These were calculated completely independently of the emulsion flux values and spectral slope, and represent good agreement with them.

Figure 3 shows the absorption detected on the riometers at Fort Churchill[2] and at College, Alaska,[3] for the September 3 event. (Little and Leinbach[4] discuss riometers and the nighttime recovery effect due to recombination of ions in the atmosphere.) Although the event was only a moderate one in the low-energy region for which riometers are most sensitive, it was detected by the neutron monitor at Deep River, so a relatively large high-energy component was present, at least early in the event. From Fig. 3, one sees that the low-energy flux was characterized by a slow rise time to maximum intensity and a very long period where the riometer absorption was near maximum at about 2 db. Winckler *et al.*[1] have pointed out that these facts, combined with their own results and solar observations, strongly suggest a rigidity- or energy-dependent diffusion mechanism whereby low-energy particles reach the earth less efficiently in the early part of the event, so the flux of protons in the tens of kinetic energy range would be depressed more than those in the 100-Mev or greater range. The emulsion and Geiger counter spectra are consistent with this.

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[1] J. R. Winckler, P. D. Bhavsar, A. J. Masely, and T. C. May, preceding Letter [Phys. Rev. Letters **6**, 488 (1961)].

[2] Courtesy of Defence Research Telecommunications Establishment, Shirley Bay, Ontario, Canada.

[3] Courtesy of H. Leinbach, University of Alaska, College, Alaska.

[4] C. G. Little and H. Leinbach, Proc. Inst. Radio Engrs. **46**, 334 (1958).