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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-3B-20. Solar Cosmic Ray Event of September 3, 1960

P. D. BHAVSAR
University of Minnesota, Minneapolis, Minnesota, U.S.A.

Simultaneous balloon observations from two different latitudes were made during this solar cosmic ray event. A very remarkable feature of delayed propagation of solar cosmic rays through interplanetary space was studied. This delay was caused by the passage of solar cosmic rays through magnetic plasma clouds from previous flares. The delay was energy-dependent and could be easily seen from the time variations of the solar proton energy spectrum and intensity variations at two locations. The spectrum became steep, as the time passed, because of the late arrival of the low energy particles. Most of the time during the event, the intensity of solar cosmic rays at Minneapolis was lower than that at Churchill because of the higher geomagnetic cutoff at Minneapolis. This intensity became comparable at both the stations during the main phase of the magnetic storms, indicating that the geomagnetic cutoff at Minneapolis is removed during the main phase.

§1. Introduction

During the first week of September 1960 the sun was very active and produced several flares on the visible disc. One of these flares produced solar cosmic rays, which were observed on earth, at sea level by neutron monitors, and at high altitudes by balloon borne instruments and rockets. During this period, the cosmic ray group of the University of Minnesota flew several simultaneous balloons from Minneapolis, Minnesota, U. S. A., ($\lambda = 55.1°$) and Fort Churchill, Manitoba, Canada ($\lambda = 68.7°$). The detectors used were ion chambers, single Geiger counters and telescopes, nuclear emulsions, and scintillation counters. In what follows, results obtained from the analysis of ion chamber, Geiger counter and telescope data will be presented.

In Table I we give a summary of the sequence of solar-terrestrial events, before, during, and after the cosmic ray flare. Out of several flares during this period, only major flares of importance 3 are listed. The first of them took place on September 2 at 0706 UT with solar coordinates N 19°, W 25°. The second flare took place about 16 hours after the first one, at about the same location on the sun. The third flare, accompanied by a type IV radio emission, took place at 0040 UT on September 3 when the 2nd flare was still in progress. The solar coordinates of this flare were N 17°, E 90°, that is, it was in a region which was just appearing on the east limb of the sun. This flare was very intense, and was observed in the visible region of the spectrum. Because this was the only flare which had a type IV radio emission, it is believed to be the source of the solar cosmic rays. Solar plasma clouds from the first two flares described above reached the earth on September 4 and produced magnetic storm sudden commence-

Table I. Solar-terrestrial time table

Date, time (U. T.)	Event	Comment on tentative identification
Sept. 2, 0706	Class 3 flare	Solar coordinates N19 W25; source of magnetic cloud; S. C. and Forbush decrease.
Sept. 2, 2234	Class 3 flare	Solar coordinates N21 W31; source of apparent nonmagnetic cloud but strong magnetic storm; no Type IV radio emission.
Sept. 3, 0040	Class 3 flare	Solar coordinates N17 E90; source of cosmic rays; accompanied by Type IV.
Sept. 3, 0112	Class 3 flare	Cosmic-ray flare maximum; x-ray burst (local).
Sept. 4, 0230	S. C.	Begin magnetic storm from 0706 flare Sept. 2.
Sept. 4, 0230	Forbush decrease	Indicates magnetic character of solar cloud.
Sept. 4, 1830	S. C.	Begin magnetic storm from 2230 flare Sept. 2; *no* Forbush effect.

ments (SC) at 0230 UT and 1830 UT, also 16 hours apart. A Forbush decrease was observed by the sea level detectors beginning about 0230 UT on September 4, but no Forbush decrease was observed at or after the second SC at 1830 UT. This fact helps us to speculate about the characteristics of the plasma clouds from the first two flares. We believe that the plasma cloud from the first flare was magnetic in character, which produced the Forbush decrease, while the cloud from the second flare was nonmagnetic.

In Fig. 1 we show the situation in interplanetary space applicable at the time when the cosmic ray flare was in progress at 0100 UT on September 3. The solar cloud from the 0706 UT flare on September 2 was in transit near the sun. This is a very naive

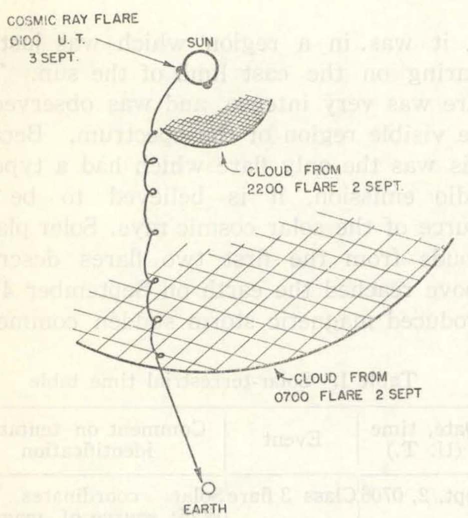

Fig. 1. Disturbances from flares in the region approximately 30° W of central meridian were in transit at the time of the cosmic ray flare. Here plasma clouds from two major flares are shown. Cosmic-ray flare was on the east limb and particles from it had to diffuse and propagate into these clouds to reach the earth.

picture of the situation, which must be very complicated in reality as this same region had produced several smaller flares before and during this period. To reach the earth, particles from the cosmic ray flare had to diffuse into and propagate through these plasma clouds.

§ 2. Experimental Results

From the Geiger counter observations during the ascent of the balloons, and from two simultaneous balloon flights at different latitudes, we studied the spectrum of the solar cosmic ray particles and its time variations. Nuclear emulsion results (*Freier*, private communication) had shown that the major contributing particles were protons. If the proton spectrum is obeying a power law of the type $N(>E) = CE^{-\gamma}$, then it could be easily shown[1] that the rate versus atmospheric depth plot on a log-log scale would be a straight line, provided no geomagnetic cutoff restricts the arrival of the full intensity. In Fig. 2, two such typical plots, one for a Minneapolis balloon flight, and one for a Churchill balloon flight are shown. As seen,

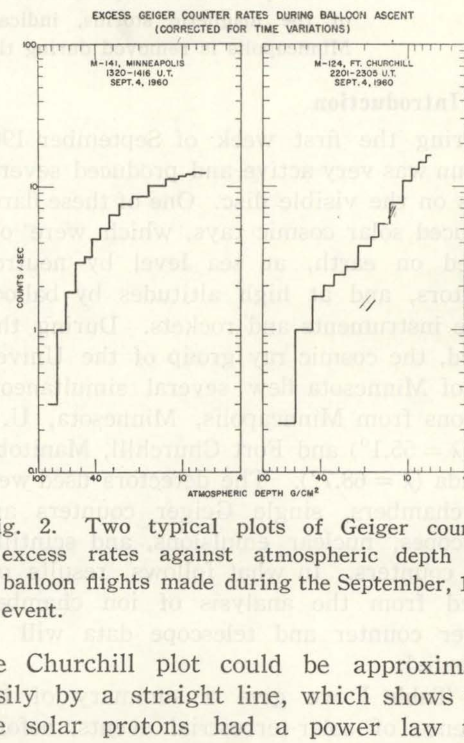

Fig. 2. Two typical plots of Geiger counter excess rates against atmospheric depth for balloon flights made during the September, 1960 event.

the Churchill plot could be approximated easily by a straight line, which shows that the solar protons had a power law type spectrum in space. The plot for the Minneapolis flight does not show this character but bends over, which suggests the absence of low energy particles at Minneapolis. All other Minneapolis balloon ascent data showed this character. This character is understandable as the magnetic field was not much disturbed during these periods, and therefore the magnetic cutoffs were operative which prevented protons below the cutoff to arrive at Minneapolis. The geomagnetic cutoff at Churchill being very low, the minimum energy particles that could be detected are determined by the balloon depth. By assuming that the solar proton spectrum in space is determined by the Churchill rate-ascent plot, and the cutoff at Minneapolis is around 0.72 Bv (250 Mev proton KE), the calculated intensity versus depth plot at Minneapolis approximately fits the observed plot. This value of the geomagnetic cutoff at Minneapolis is in fairly good agreement with the value quoted by *McDonald* and *Webber*,(1959)[2].

With this information about the effective geomagnetic cutoff value at Minneapolis and Geiger counter data from two different locations spectra of solar protons in space were determined, and are shown in Fig. 3. In the left section of the figure are shown the spectra during the growth of intensity at balloon altitudes, and in the right section during the initial decay. Two rocket ascents were made at Churchill by the NASA Solar Beam Research Group[3] at 1410 and 1730 UT on September 3, 1960. Their results are also included in Fig. 3. In Table 2, the same spectra and a few more are tabulated. How each one was obtained is also mentioned in the table. As one could easity see, the spectrum steepens with time through both the rise and fall of intensity during the first part of the event. This, we believe, is due to the larger delay in the propagation of lower energy particles in the interplanetary space.

With the above information about the solar cosmic ray spectrum during different times of the event, and assuming that the changes took place uniformly and gradually, we corrected the single Geiger counter rates at both the stations and reduced them to a constant atmospheric depth for the study of the time variations of the solar cosmic ray intensity. This was necessary as the rates of balloon instruments for solar cosmic rays are very sensitive to altitude changes, and the balloons did not float at constant altitude. These corrected rates are shown in the top section

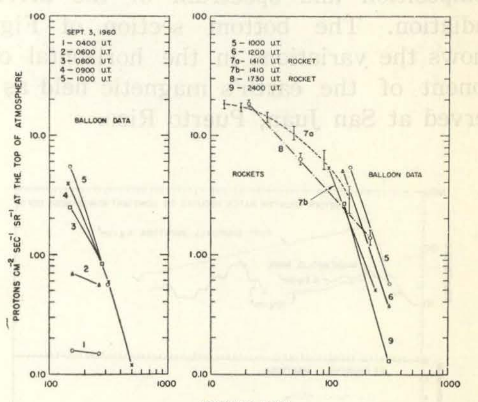

Fig. 3. Left: Spectra during growth of event from simultaneous balloon measurements at Churchill and Minneapolis. Right: Spectra during initial decay of event from balloon and rocket data. (Rocket results, *Davis* et al[3])

Table II. Solar Proton Spectrum in Space at Different Times of the Event.

Time UT	Solar Proton Spectrum E=Kinetic energy in Mev N(>E)/cm². sec. sr.	Applicable in the energy interval (Mev)	Method
0400, Sept. 3	$0.2\times10^{4}E^{-0.4}$	150 to 320	Mpls and Churchill balloon data
0800, Sept. 3	$1.3\times10^{4}E^{-1.7}$	150 to 320	Mpls and Churchill balloon data
0900, Sept. 3	$1.9\times10^{5}E^{-2.2}$ $3.4\times10^{8}E^{-3.5}$	135 to 320 >320	Mpls balloon ascent combined with Churchill balloon data
1000, Sept. 3	$1.9\times10^{7}E^{-3}$	150 to 320	Mpls and Churchill balloon data
1200, Sept. 3	$6.8\times10^{6}E^{-2.9}$	130 to 320	Mpls and Churchill balloon data
1408, Sept. 3	$6.4\times10^{5}E^{-2.5}$	100 to 250	Mpls and Churchill balloon data
0000, Sept. 4	$4.4\times10^{7}E^{-3.4}$	130 to 320	Mpls and Churchill balloon data
1400, Sept. 4	$3.1\times10^{4}E^{-2.1}$ $9.3\times10^{13}E^{-6}$	82 to 270 >270	Mpls and Churchill ascent data combined
2230, Sept. 4	$3.6\times10^{4}E^{-6.3}$ $6.6\times10^{12}E^{-5.7}$	90 to 270 >270	Chruchill balloon ascent

of Fig. 4. Between about 0200 and 2300 UT on September 4, there was no balloon flight up at Churchill; however, the character of the rates before and after this period indicated a steadily decaying intensity. Therefore, we have linked this gap with a dotted line which shows the expected intensity at Churchill. In the same diagram we have also plotted, in the central section, the mean ionization per count expressen relative to the minimum ionization. The changes in mean ionization, when studied together with intensity changes, tell us whether the changes are pure intensity changes or are changes in the composition and spectrum of the arriving radiation. The bottom section of Fig. 4 shows the variations in the horizontal component of the earth's magnetic field as observed at San Juan, Puerto Rico.

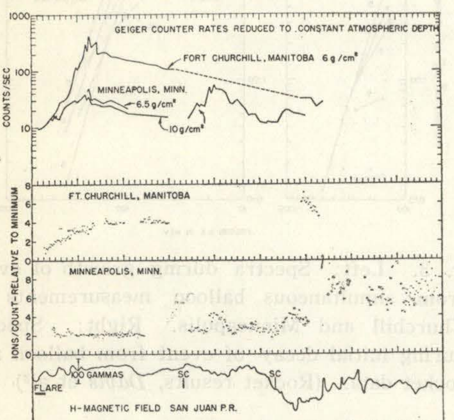

Fig. 4. Top: Geiger counter rates during the event at Churchill and Minneapolis corrected to constant atmospheric depths. Center: Ions /count ratio expressed relative to minimum ionization. Bottom: Earth's horizontal field variations as recorded at San Juan, Puerto Rico.

§ 3. Discussions

Two important characteristics are very well documented by the results shown in Fig. 3 and 4.

(1) Delayed propagation of solar cosmic rays through the interplanetary space: As shown, the counting rates at Churchill and at Minneapolis rose slowly after the flare time. A maximum is shown on Minneapolis rate at about 0940 UT, after which there is a decrease with a smaller second peak at 1000 UT. Churchill intensity also shows a similar character but it has its 1000 UT peak larger than the 0940 UT peak. This fact could be interpreted as Minneapolis rates reached their maximum value earlier than Churchill. The Deep River neutron monitor (data obtained by courtesy of H. Carmichael) recorded maximum intensity between about 0800 and 0900 UT, even earlier than Minneapolis balloon rate maximum. This means that the time of delay of the maximum cosmic ray intensity at earth measured from the time of the flare is smallest for the high energy detector like neutron monitor while it is largest for the lowest energy detectors like balloon instruments at Churchill. Steepening of the spectra with time as shown in Fig. 3 shows the same effect on the propagation times of the particles of different energies that the low energy particles arrived relatively later than the high energy ones.

Solar cosmic rays are supposed to be injected in space during the progress of the flare which is of the order of an hour or less. This delay in arrival must be due to the presence of a region in between the sun and earth which either stores and then releases the solar cosmic rays in a time dependent on the energy of the particles, or particles diffuse through this region with an energy dependent mean free path. Such delays, or dispersion as it is called, even for very high energy solar cosmic rays (10^9–10^{10} ev) have been discussed by *Lust* and *Simpson*, (1957)[4]; however, the delay observed in the present case is more than an order of magnitude larger than what was observed for high energies.

McCracken and *Palmeira*, (1960)[5] have studied a delay of similar nature as observed by neutron monitors for the July 17, 1959 solar cosmic ray event. However, unlike the present case, during that event the delaying magnetic fields were supposed to have come out from the same region of the sun where the cosmic ray flare took place. It seems that this difference is not important for the delayed propagation of solar cosmic rays since during that even also the maximum neutron intensity was recorded about 8 hours after the flare, while Minneapolis balloons showed the maximum after about 14 hours.

This difference, of whether the magnetic cloud restricting the motion of the solar protons in space originated in the same region as the cosmic ray flare or not may have an effect on the spectrum and intensity of solar cosmic rays however. The region which produced the magnetic cloud associated with 0707 UT flare on September 2, was very active and had produced many more smaller flares earlier. A small magnetic storm was in progress on earth at the time of the cosmic ray flare and there is reason to believe that the plasma clouds with magnetic fields were spread out in space between the earth and the sun from this active region at the time of the cosmic ray flare. The cosmic ray flare took place very far from the region of production of these magnetic clouds. Under such circumstances, the solar cosmic rays will have to be diffused in the cloud, which then will flatten the spectrum and because of the reflection at boundaries we may not see the full intensity. The low intensity of the present event and comparatively flat spectrum may be the direct cause of such a mechanism.

If the cosmic ray flare takes place in the same region which produced the plasma clouds previously, the particles will not have any difficulty in getting injected in the cloud and only the delay in propagation will be caused by the magnetic field and its irregularities in it. One should expect the full intensity to be delayed for some time, but when the full intensity is observed the spectrum observed also will not be much different from the steep production spectrum as observed previously for such events.

(2) Geomagnetic cutoff changes at Minneapolis: One also observes in Fig. 4 that the solar cosmic ray intensity at Minneapolis is lower that at Churchill during most of the time of the event. This is understandable because the Minneapolis geomagnetic cutoff is much higher than what it is at Churchill. However, the intensity at Minneapolis shows two large increases between about 0400-1500 UT and after 1930 UT on September 4. These times are coincident with the main phase of the two magnetic storms which followed SC rt 0230 and 1830 UT. We believe that this is one more case of cutoff change at Minneapolis. This is inferred from the fact that the mean ionization at Minneapolis goes up during both these increases, indicating that there are more low energy particles present during these times. That Minneapolis intensity is comparable to Churchill intensity during these periods is also proof that the cutoffs are removed and full intensity is allowed at Minneapolis which was normally restricted.

That our above interpretation is correct is also supported by the results obtained from the Wilson cloud chamber flown by Dr. James Earl of the University of Minnesota (private communication) during one of these periods. His balloon reached ceiling at about 1800 UT on September 4, and the solar proton spectrum derived from the cloud chamber photographs showed a close similarity to the spectrum inferred from the earlier monitor flight M-141 ascent at Minneapolis shown in Fig. 2. After about 1930 UT the cloud chamber pictures showed that low energy protons of energy below about 250 Mev started coming in abundance which were almost absent previously.

Nuclear emulsion observations of Freier are in broad agreement with the about mentioned interpretation of the cutoff and its changes; however, they show that the cutoff at Minneapolis was not very sharply defined during this period. This could not be studied with results of the instruments we are discussing at present. This event also had many other interesting features of strong aurora and x-ray bursts. This will be discussed elsewhere in more detail.

§ 4. Acknowledgements

The above observations were made in collaboration with Prof. J. R. Winckler, Mr. T. C. May and Mr. A.J. Masley. Balloon operations at Churchill at this time were carried out by Mr. Ralph Fuchs and Mr. John Anderson of the University of Minnesota. This work was sponsored by the National Aeronautics and Space Administration.

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Discussion

McCracken, K. G.: Dr. Gold has suggested that the radiation may be trapped in a magnetic configuration above the flare on the east limb, and then gradually diffusing across to the foot of the line of force connecting the earth. We can exclude this possibility, since it precits an anisotropic flux of cosmic radiation at the earth, but this was not observed.

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II-3B-21. A Survey of Polar Cap Absorption Events (Solar Proton Events) in the Period 1952 through 1960

D. K. BAILEY

National Bureau of Standards, Boulder, Colorado, U.S.A.

AND

J. M. HARRINGTON

Page Communication Engineers, Inc. Washington, D.C., U.S.A.

From a detailed survey of signal-strength recordings from several high-latitude VHF ionospheric scatter paths it has been possible to detect and classify some 44 PCA's in the uninterrupted period from 1952 through 1960. It has also been possible to estimate the onset time and duration of each event. Some eight of these events have been accompanied by ground-level increases in cosmic-ray intensity and are thus describable as solar cosmic-ray events. Most of the 44 events have been followed by significant magnetic storms some 15 to 30 hours after the onset of the ionospheric absorption over the polar cap. Of these, seven have exhibited the phenomenon of breakdown of Störmer cutoffs shortly after the onset of the magnetic storm, by the admission to lower magnetic latitudes, typically 60°N, of solar protons of normally excluded energies.

Strong solar-cycle dependence in the occurrence of PCA's is found. Furthermore it is suggested that particle storage, apparently always present during times of high solar activity, is not well developed in sunspot minimum years, with the result that the few PCA's then are of relatively shot duration and localized in the polar cap.

The first clearly recognized polar cap absorption (PCA) event occurred on 23 February 1956. It produced marked effects on the signal intensities of the VHF ionospheric "forward" scatter radio communication links operating, at that time, between points in Labrador, Greenland, and Iceland. This particular event has been intensively studied by one of us and accounts of the observational material, positions of the pathmidpoints, operating frequencies and path lengths are available[1].

Beginning with the event of 23 February 1956 the continuous signal intensity record-