DELAYED PROPAGATION OF SOLAR COSMIC RAYS ON SEPTEMBER 3, 1960*

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We should like to describe observations of a solar cosmic-ray increase which is remarkable for the large delay time in the arrival of the particles. Furthermore, the delays are energy dependent and are probably produced by a partially known sequence of events in interplanetary space. The present case is of particular interest because the delays extended to high energies detectable by balloons and by ground-level monitoring instruments and because the event was well documented by balloons at several latitudes during and after the flare and by rocket flights.[1]

In Table I we describe the sequence of solar-terrestrial events before, during, and after the cosmic-ray flare. Although there were several smaller flares during this period, only major flares of importance 3 are listed in the table. The flare at 0040 U.T. on September 3 was the only flare which was accompanied by a Type IV radio emission and, therefore, we believe that it was the source of the solar cosmic rays. This flare was in a region just appearing on the east limb of the sun, but was preceded by several large flares in a region on the face of the disk. An artist's conception of the situation in interplanetary space is shown in Fig. 1. This figure applies at the time of the cosmic-ray flare. The solar cloud from the 0706 U.T. flare on September 2 was in transit near the earth, while the cloud from the 2234 U.T. flare on September 2 had just left the sun. Judging by the Forbush decrease in galactic cosmic rays, which began at 0230 U.T. on September 4, the first cloud was magnetic in character. The second cloud did not produce a Forbush decrease but did produce a very strong geomagnetic storm on the earth. Note from the table that the delay between the first and second magnetic storms is the same as the delay between the flares which we have tentatively assigned as their sources.

The cosmic-ray data summarized in Fig. 2 result from high-altitude balloons flown at Fort Churchill, Manitoba, Canada, and at Minneapolis, and from the ground-level neutron monitor at

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 0700 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.

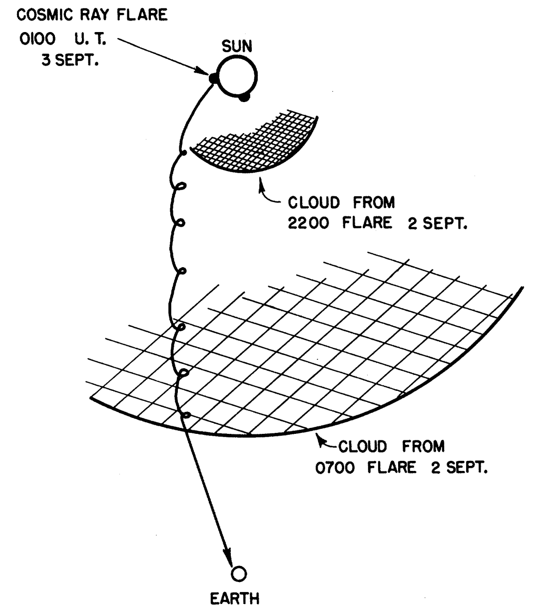

FIG. 1. Disturbances from two flares in the region approximately 30°W of central meridian were in transit at the time of the cosmic-ray flare. Particles from the cosmic-ray flare on the east limb were propagated through or around the magnetic cloud from the 0700 flare.

Deep River, Ontario, Canada.[2] The balloon instrumentation included integrating ionization chambers, Geiger counters, coincidence telescopes, and nuclear emulsions. The results of these instruments have been examined in detail and clearly show that all of the rate increases in Fig. 2 result from the solar cosmic-ray particles with the exception of the flare-coincident x-ray burst. The data are consistent with these particles being principally protons similar in some respects to other cases of solar flare protons observed with balloons.[3] For simplicity, in Fig. 2, we show only the ionization chamber records. The cosmic-ray flare is marked on the balloon records in Minneapolis by a large x-ray burst coincident with flare maximum. No x rays were observed at Fort Churchill, however. We conclude that this x-ray burst was the result of electrons precipitated from the geomagnetic field during the flare, and was not the direct solar bremsstrahlung which has been observed several times recently.[4] Following the flare, the cosmic-ray particles slowly increased in rate at all locations. Because the rates of the balloon instruments for solar cosmic rays are sensitive to altitude, a balloon depth schedule is included above and below the top section of Fig. 2 for the appropriate balloon flights. Two simultaneous flights are shown at Minneapolis at different depths. Since geomagnetic conditions were quiet during this period, we can with fair confidence assume that the geomagnetic cutoff at Minneapolis was operative and was about 250 Mev.[5] The energy cutoff at Fort Churchill is determined by the balloon depth, which varied between 5 and 15 g/cm^2 atmospheric depth during the flight. The corresponding energies are 75 Mev and 125 Mev. The characteristic energy of the sea-level neutron monitor is estimated to be between 500 and 600 Mev.

Two effects are seen to be operative. First of all, the time delay of the maximum cosmic-ray intensity at earth measured from the time of the flare is smallest for the high-energy detector and largest for the lowest energy detector at Churchill. The times at which the intensity maxima occurred on the neutron monitor, Minneapolis balloon, and Churchill balloon are marked by vertical lines on Fig. 2. Second, the low-energy particle intensity increases with time with respect to the high-energy particles. Since the Churchill balloon is continuously sensitive down to about 125 Mev or less, the changing character of the spectrum can be examined by plotting the ratio of ionization rate to counting rate for the Churchill flight. This is shown in the lower portion of Fig. 2. The I/I_{min} ratio at Churchill increases with time from a value like that for galactic cosmic rays (2 times minimum) to a value of about 4.2 times minimum ionization, showing the relative increase of low-energy particles. The ratio at Minneapolis, however, first decreases and then follows a slight increase with time, but maintains a value consistent with a spectrum of protons cut off below 250 Mev. Also shown on Fig. 2 is the time of the sudden commencement caused by the Class 3 flare at 0700 U.T. on September 2, and the beginning of the Forbush decrease shown by the sea-level neutron monitor. Two rocket ascents were made at Fort Churchill by the NASA Solar Beam Research Group.[1] These flights were made in the decay phase of the radiation as seen by the balloon flights.

From the balloon counter data at Churchill and Minneapolis, and from the Churchill rockets, we have attempted to construct the spectra in space at various times during the event. In the left section of Fig. 3 is shown the growth of intensity, and in the right section the initial decay. These spectra agree reasonably well with the mean ion-

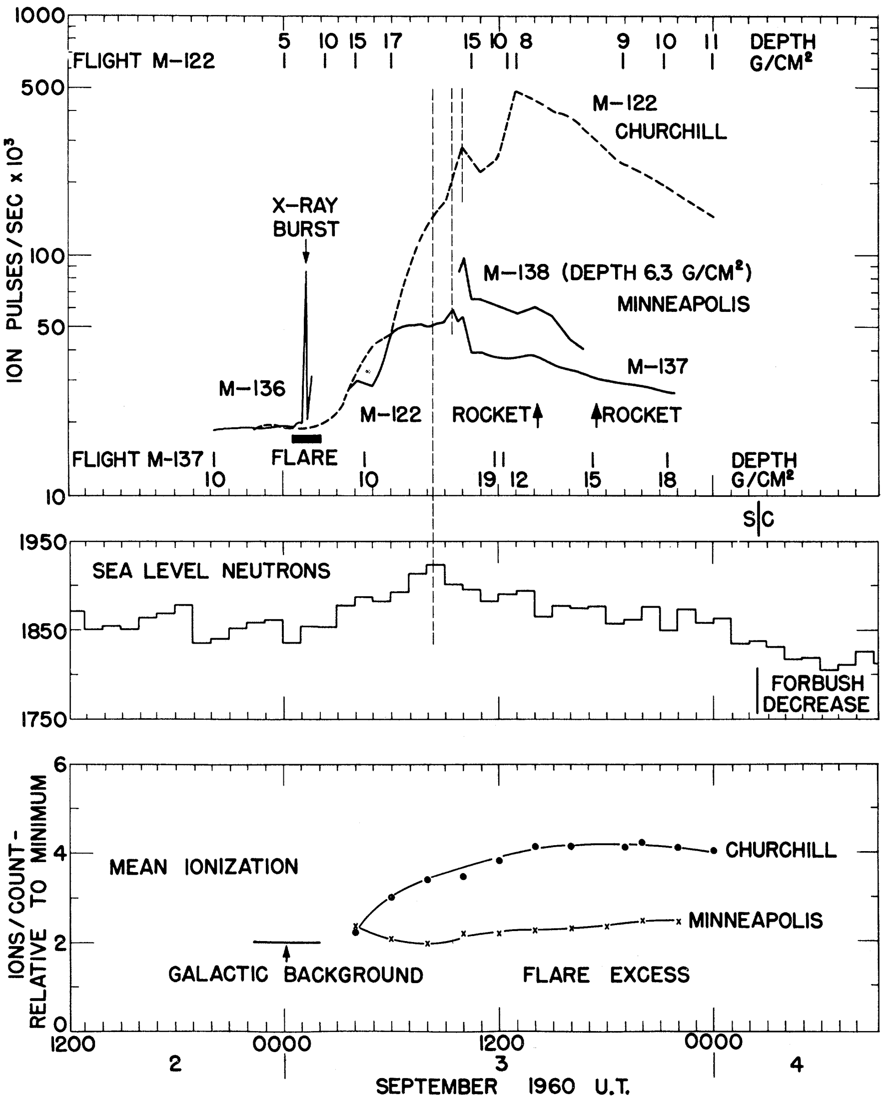

FIG. 2. Upper: total ionization rates at Fort Churchill and Minneapolis in the initial period when normal geomagnetic cutoffs were in effect. Center: flare increase seen on sea-level neutrons (courtesy Carmichael and Steljes). Lower: mean ionization showing growth of particles below 250 Mev with time at Fort Churchill.

ization measurements at Churchill in Fig. 2. Qualitatively, the spectrum steepens with time through both the rise and the fall of intensity. If we assume that the solar cosmic rays are injected into the solar system in a time of one hour or less during the flare, then the observed spectral changes can only be due to the energy dispersion between the sun and the earth. This dispersion increases the transit times twentyfold or more over the direct time of flight. We assume that this dispersion effect is associated with the unusual configuration of solar plasma and magnetic fields between the sun and the earth. The flare cosmic rays would be forced to travel through or around this region. It would indeed be difficult to relate in a detailed manner the spatial phenomena to the appearance of the spectra shown. However, the time dependence of the spectra is like that which would be obtained from a diffusion law with an energy-dependent mean free path. It seems quite possible that a kind of pseudodiffusion might take place in which the radius of curvature of the proton was a characteristic length in the diffusion process. Another kind of process which might produce an energy dispersion of this kind is the precession of particles in a nonuniform magnetic field, analogous to the precession of the Van Allen particles around the dipole field of the earth.

Although the polar ionospheric effects due to the very low-energy solar cosmic rays frequently show a delay,[6,7] balloon detectors have

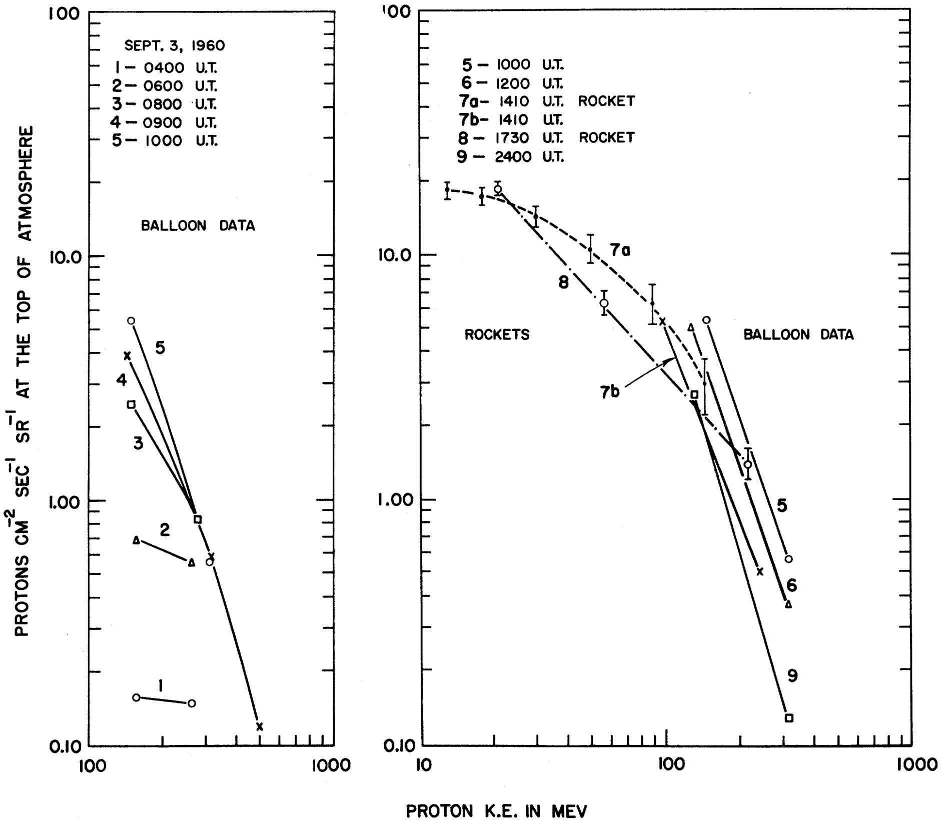

FIG. 3. Left: spectra during growth of event from simultaneous balloon measurements at Fort Churchill and Minneapolis. Right: spectra during initial decay of event from balloon and rocket data. (Rocket results from Fichtel, Davis, and Ogilvie, NASA Solar Beam Group.)

shown the prompt arrival of low-energy (100-Mev) particles. An event on August 22, 1958, reported earlier,[8] was observed by similar balloon equipment at Churchill and Minneapolis which measured the full intensity with a delay comparable to the direct transit time from the sun of 100-Mev protons. The August 22 event originated on the solar central meridian, at a time when no known recent solar events had disturbed the earth-sun region.

Many further balloon flights were made during this event at both Churchill and Minneapolis, and these will be described in more detail in a later communication. When the magnetic field became disturbed on September 4 and subsequently, it was again observed that the normal Störmer cutoffs at Minneapolis were altered and that very low-energy particles were admitted. In fact, at this time the flux values were the same at Churchill and Minneapolis, showing that the low-energy limit was determined by the atmospheric cutoff and not by the geomagnetic field. The event decayed slowly and was observed until September 6 by the Churchill balloon flights.

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[2] Data obtained courtesy of H. Carmichael through World Data Center A for Cosmic Rays.

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