② AEROSPACE MEDICINE
Formerly THE JOURNAL OF AVIATION MEDICINE
Official Publication of the Aerospace Medical Association

VOLUME 32 OCTOBER, 1961 NUMBER 10

Symposium on Aerospace Radiobiology

I. Solar Influences on the Radiation Field in Space

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IN THE last three years, progress in the understanding of the production of cosmic rays by the sun has been rapid. This is because the period of high solar activity provided a large variety of events to study and many new types of measurements were developed. At the present time we have data obtained on the solar cosmic rays at high altitude with nuclear emulsions both in balloons and in rockets, Wilson cloud chambers carried in balloons, many types of counting instruments at various latitudes and longitudes, and, in a number of cases, with counters in an earth satellite. The cosmic rays have also been measured in space 5,000,000 km from earth with a space probe.

Although most of the solar cosmic ray particles have been identified as protons, analysis of nuclear emulsions exposed under proper conditions has shown α-particles and heavy nuclei up to $Z = 16$ in the solar beams. The propagation from the sun to the earth has shown many complex features associated with magnetic fields in space. These magnetic fields have now been directly observed with space probes. The association between the propagation of the solar cosmic rays from the sun to the earth, and the modulation by the solar-produced magnetic fields of the galactic cosmic radiation is now much better understood.

Despite the abundance of solar data and the knowledge of the composition and energy spectrum of the cosmic rays, the details of the acceleration mechanism on the sun remain obscure.

This paper will supplement and bring up-to-date information about solar cosmic rays given at an earlier symposium.[1] In this paper we will summarize certain kinds of knowledge about a series of fourteen solar cosmic ray events. These events are selected because direct measurements have been made on the primary particles with balloons or rockets. The list of fourteen includes most of the larger events of the period from 1958 through 1960. Complete lists of the occurrence of all events, numbering about forty of all sizes, which were determined by polar cap ionospheric effects are available elsewhere.[2-4] The present list of events is given in Table I. We propose to discuss the following features for this symposium: (1) Energy spectra and composition of the solar cosmic rays; (2) The time variations and the resulting implications about propagation from sun to earth.

ENERGY SPECTRA

The available integral energy spectra of the series of events are given in Figure 1. These

This work was supported by the National Science Foundation, the National Aeronautics and Space Administration, and the Office of Naval Research.

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Presented at the 32nd annual meeting of the Aerospace Medical Association, Chicago, Illinois, April 25, 1961.

spectra are for protons, which are known to be the principal component of the solar cosmic ray events. The numbers refer to Table I, where details of the source of the spectra are

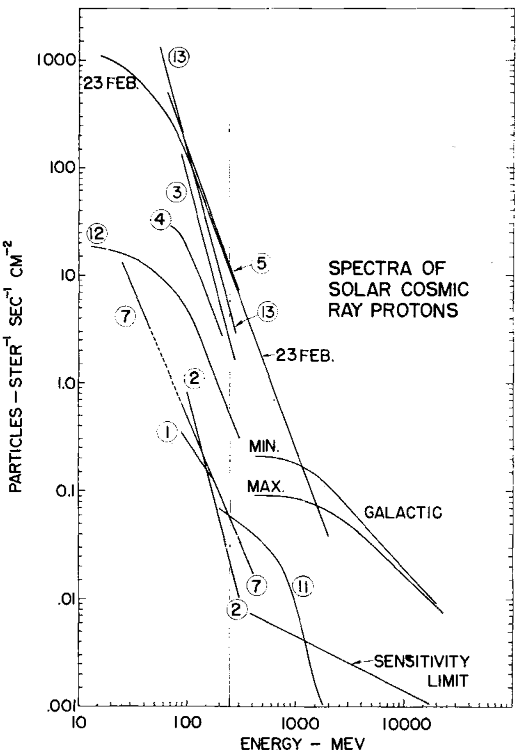

Fig. 1. Energy spectra of solar cosmic ray protons. (See Table I).

given. These spectra are measured under various circumstances with balloons, rockets and satellites. Because the spectra are determined either at high latitude, or at low latitude when the geomagnetic cutoffs were very low, they may be assumed to represent the spectra in space near the earth at the times given in Table I. As will be discussed later (for example, event No. 12 on September 3, 1960), the energy dispersion in the propagation from sun to earth may modify the spectra considerably, especially in the low energy region. These spectra are thus not necessarily the source spectra, except possibly in the high energy regions. Because the spectra are measured at various times with respect to the flares which are the source of the particles, the relative intensities are not necessarily in the proper order for the events. This feature will become clearer in the next section on the time history of the events, and in Figure 2. Nevertheless, it can be seen in Figure 1 that the intensities vary over wide limits from event to event and that, in general, the spectra are much steeper than the galactic cosmic ray spectra. Some of these events, namely No. 11 (May 4, 1960), No. 12 (September 3, 1960), No. 13 (November 12, 1960), No. 14 (November 15, 1960), and February 23, 1956, were

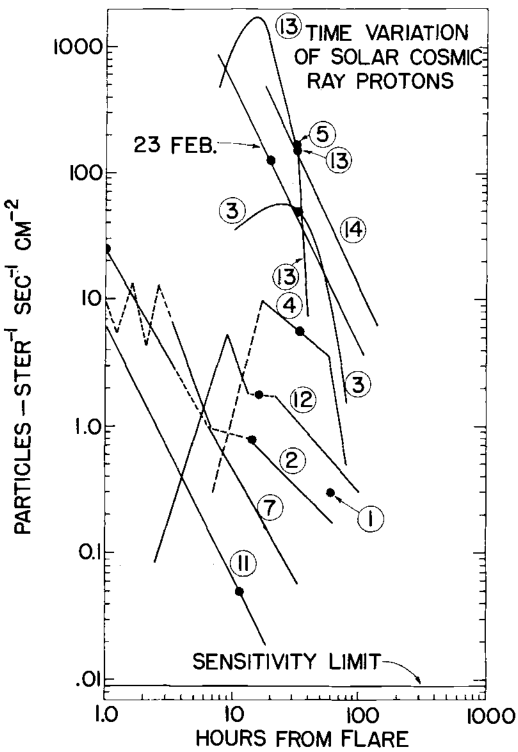

Fig. 2. Time variation of typical solar cosmic ray protons. The data refer to the total flux above approximately 100 Mev. The solid points designate times at which the spectra in Figure 1 were measured.

detected by sea level monitors. Due to the uncertain neutron yield function in the 1-Bev and lower region, the sea level data cannot be used at present to extend these spectra to intermediate energies, i.e., above 400 Mev where balloon data end. Since the detection of these

TABLE I. SOLAR COSMIC RAY ENERGY SPECTRA

Event No.	Flare Date, Time UT	Spectra Measurement Date, Time UT	ΔT Hrs.	N(>E)=CEγ (Mev) Eqn. of Spectra		Literature Source	Notes
				C	γ		
(1)	23 Mar 1958 0950	26 Mar 1300-1800	78	7.2×10^{5}	2.7	(a)(c)	Flare assignment tentative. First P.C.A. on 25 Mar at time of S.C. indicating cosmic rays contained in magnetic solar cloud. Spectra from nuclear emulsions at Mpls.
(2)	22 Aug 1958 1417	23 Aug 0500	15	8.0×10^{7}	4	(b)	Spectra from counters on ascent at Ft. Churchill.
(3)	10 May 1959 2055	12 May 0500	32	2.5×10^{9}	6	(c)(d)	Spectra from counters on ascent. Emulsions give $\gamma=5$ as average.
(4)	10 July 1959 0210	11 July 1800-1600	30-38 av. 34	—	—	(e)	Spectra falls off at low energies. Not a simple power law. Exponential fit is good. See Figure 2.
(5)	14 July 1959 0325	15 July 1030	31	1.1×10^{8}	2.9	(f)	Spectra from counters on ascent. Approximate agreement with emulsions averaged from 0900-1430 UT 15 July.
(6)	16 July 1959 2114					(f)	Produced sea level effect.
(7)	1 Apr 1960 0843	1 Apr 0945	1		2.4	(g)(h)(i)	Spectrum from balloon and satellite counters—measured simultaneously.
(8)	5 Apr 1960	5-6 Apr				(h)(i)	Spectrum probably similar to (7). Seen only by satellite and space probe.
(9)	28 Apr 1960 0130					(g)	Spectra not measured for these events.
(10)	29 Apr 1960 0107					(g)	Spectra not measured for these events.
(11)	4 May 1960 1020	4 May 1700-2500	7-15 11 av.	—	—	(j)	Not a power law spectrum. Has exponential form.
(12)	3 Sept 1960 0040	3 Sept 1400	13			(k)(l)	Region 10<E<100 Mev from rocket. 100<E<300 balloons at two latitudes.
(13)	12 Nov 1960 1322	13 Nov 2000	31			(m)	Emulsion spectra. Short balloon exposure.
(14)	15 Nov 1960						

Literature Source:

(a) "Balloon Observations of Solar Cosmic Rays on March 26, 1959," P. S. Freier, E. P. Ney, and J. R. Winckler, *J. of Geophys. Research*, 64, 685-688, 1959.

(b) "Observations of Low-Energy Solar Cosmic Rays from the Flare of 22 August, 1958," K. A. Anderson, R. Arnoldy, R. Hoffman, L. Peterson, and J. R. Winckler, *J. of Geophys. Research*, 64, 1133-1147, 1959.

(c) "Protons from the Sun on May 12, 1959," E. P. Ney, J. R. Winckler, and P. S. Freier, *Phys. Rev. Letters*, 3, 183-185, 1959.

(d) "Low Energy Solar Cosmic Rays and the Geomagnetic Storm of May 12, 1959," J. R. Winckler, and P. D. Bhavsar, *J. of Geophys. Research*, 65, 2637-2655, 1960.

(e) P. S. Freier and E. P. Ney (Private Communication).

(f) "The Time Variations of Solar Cosmic Rays during July 1959 at Minneapolis," J. R. Winckler, P. D. Bhavsar, and L. Peterson *J. of Geophys. Research*, 66, 995-1022, 1961.

(g) A. J. Masley[10].

(h) J. A. Van Allen and Wei Ching Liu[11].

(i) R. L. Arnoldy, R. Hoffman and J. R. Winckler[12].

(j) "The High-Energy Cosmic-Ray Flare of May 4, 1960. Part I. High-Altitude Ionization and Counter Measurements," J. R. Winckler, A. J. Masley and T. C. May. "Part II. Emulsion Measurements," S. Biswas and P. S. Freier, *J. of Geophys Research*, 66, 1023-1033, 1961.

(k) J. R. Winckler, P. D. Bhavsar, A. J. Masley and T. C. May[6].

(l) L. R. Davis, C. E. Fichtel, D. E. Guss and K. W. Ogilvie[7].

(m) E. P. Ney and W. Stein[13].

events by neutron monitors depends sensitively on the solar cosmic ray flux in the galactic range of energies, a small decrease in slope of the balloon spectra in Figure 1 may result in a "high energy" flare event. High energy events thus do not seem unique in any way, but represent less frequent cases of spectra dropping off somewhat less rapidly with increasing energy.

The line marked sensitivity limit refers to a balloon ion chamber[5] at approximately 7 g/cm^2 atmospheric depth, and represents a change equivalent to 5 per cent of the galactic background rate. If excess radiation is present above this level of intensity, its detection becomes highly probable as an increase in the balloon ionization rate at high latitude.

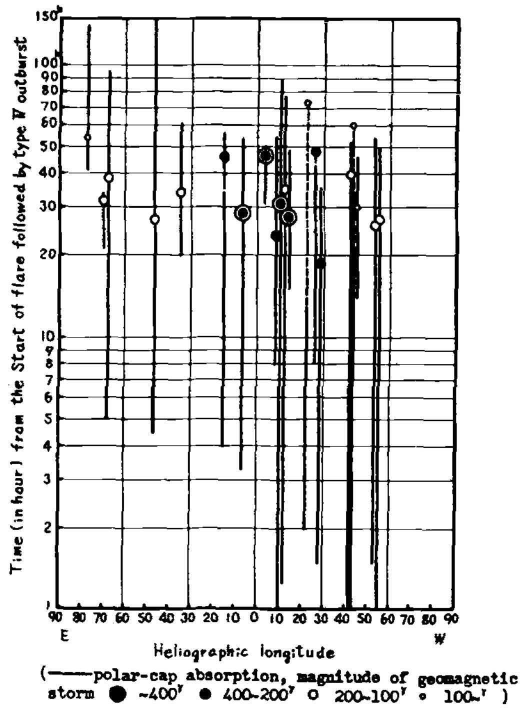

Fig. 3. Starting and ending times of polar blackouts signifying the arrival of 5-25 Mev solar flare protons at earth. (Shown by vertical lines). (From Obayashi[2]).

The vertical line at 250 Mev represents the "normal" geomagnetic cutoff as measured at Minneapolis by several investigators.[6] These cutoffs are determined by measuring directly in emulsions and energy-sensitive counters the lower energy limit of protons or α-particles of galactic or solar origin. The lower limit is taken to be the point in the energy spectrum below which the number of observed particles drops rapidly to zero. Because of the possible connection between changes in the geomagnetic cutoffs for cosmic rays and the postulated ring current during the main phase of magnetic storms,[7] it becomes important to establish the correct cutoffs during both normal and disturbed periods. This problem, which is important from the standpoint of the geomagnetic theory of cosmic radiation, will be discussed elsewhere.

TIME VARIATIONS

The time variations collected in Figure 2 will now be discussed. These data are mainly from high latitude results and should represent the free space intensity near the earth. This figure is an estimate of the changes in the integral intensity above 100 Mev, as a function of time from the start of the flare. The black points are the times at which the various spectra in Figure 1 are measured. The curves of Figure 2 have been normalized at 100 Mev using these spectra. In some cases the intensity above 100 Mev is not known at all within a few hours of the flare but decays in a regular fashion at later times, e.g., February 23, 1956. Observations back to within one hour of the time of the flare for Cases 7 and 11 show a continual decay following approximately the power law $I = I_0 T^{-\alpha}$, where I_0 is the intensity at one hour from the flare and $\alpha \approx 2$. A number of cases show striking delays in which the intensity rises to a maximum ten to fifteen hours after the flare, and then sharply drops away. In general, the fast-rising and regularly-decaying events originate in flares on the center or western part of the solar disc. The delayed events arise from flares on the central or eastern hemisphere. For the very low energy particles causing polar blackouts, which lie in the 5-25 Mev range where a larger number of events is available for study, a systematic effect with flare position seems to occur. Figure 3, due to Obayashi,[2] shows such an effect. For the 100-Mev and higher energies, and for the relatively few events studied here, the condition of space between the sun and the earth, as determined by the few days of solar activity previous to the cosmic ray flare, seems to be the most important factor. A few examples will now be discussed in detail.

A very interesting event in the slow-rising class occurred on September 3, 1960.[6] Observations were made during and after the flare by simultaneous balloon flights at Ft. Churchill, Manitoba, Canada, and Minneapolis. The event was also observed with low intensity at sea level in high latitudes. The time variation of this event is given as curve (12) in Figure 2. The details of some of the balloon and sea level magnetic cutoff of 250 Mev. The two-point spectra evaluated for these stations at various times are shown in Figure 5, where we note that the spectrum grows and steepens with time, then

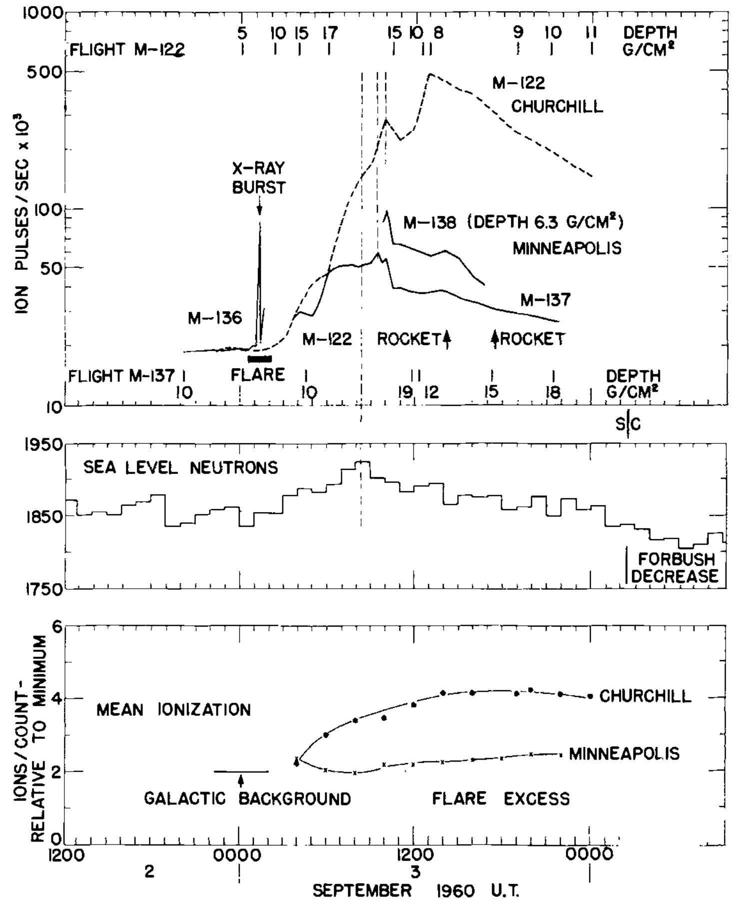

Fig. 4. High altitude and sea level observations during a greatly delayed solar event on September 3, 1960. The x-ray burst accompanies the flare maximum.

measurements are shown in Figure 4. Here we see the flare (note x-ray burst coincident with flare maximum) which occurred on the extreme east limb, followed by the slow increase of cosmic rays at all stations. The relatively larger delay in the low-energy protons near 100 Mev is shown by the slow increase in mean ionizing power of the particles at Ft. Churchill where the cutoff is limited by the air at 100 Mev. The low-energy delay is also shown by comparing Ft. Churchill with Minneapolis, with a geo- falls away. Emulsion spectra from sounding rockets[7] confirm these results and for the first time extend the spectrum down to 10 Mev. For this event the large energy dispersion seems related to the existence prior to the cosmic ray flare of solar clouds from earlier flares in another solar region (Fig. 6). At least one of these clouds contained magnetic fields as shown by the ensuing Forbush decrease of galactic primaries.

The July 1959 events all showed delayed rise times (Fig. 2, event 4). The interval between flare and maximum intensity decreased as the three major events proceeded.[8]

The November 12, 1960 cosmic ray flare is of somewhat similar character. The early time was observed simultaneously with balloons,[10] an earth satellite,[11] and a space probe.[12] The time decay of intensity was particularly well shown in space 5,000,000 km from earth. The space history of 100-Mev particles is shown in curve (13), Figure 2. For higher energy particles, definite evidence for containment in a solar-produced magnetic field in space has been shown by Steljes and his associates.[9] Their concept of the interplanetary fields leading to this effect is given in Figure 7.

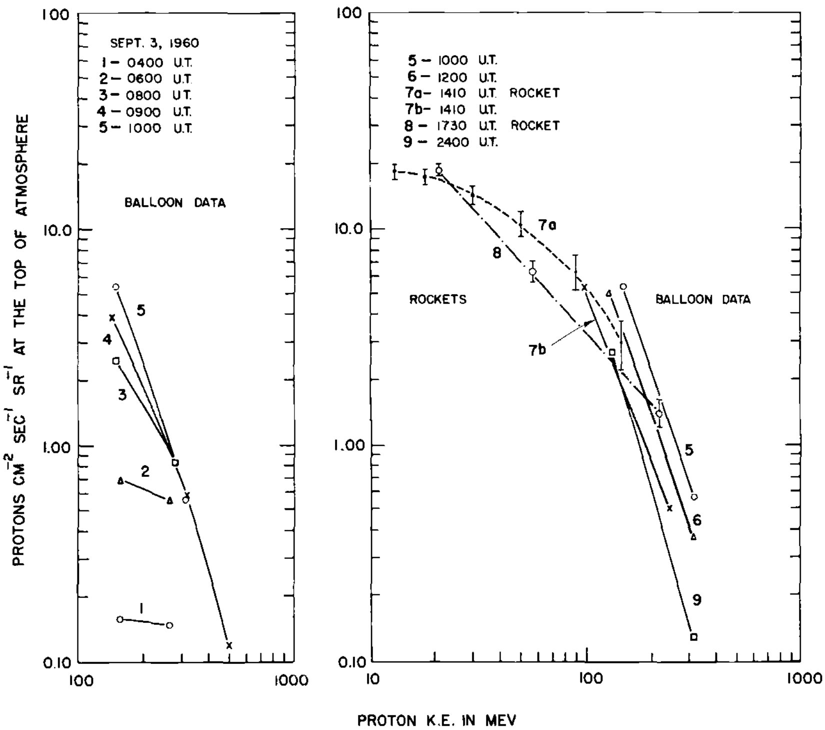

Fig. 5. Spectra of solar cosmic rays at various times following a flare. This event occurred on the solar east limb and is an example of a greatly delayed propagation. Note that low energy particles arrive last.

Very direct transfer of 100-Mev protons from flares on solar central meridian is shown by the August 22, 1958 and April 1, 1960 events [Fig. 2, curves (2) and (7)]. The April 1 flare began shortly after a strong terrestrial magnetic storm and Forbush decrease had occurred. These processes evidently established a direct connection between the solar flare region and the earth along magnetic field lines. The April 1 event probe results early in the event gave evidence for an anisotropic behavior of the solar cosmic rays, probably due to alignment with the free space magnetic fields.

COMPOSITION

The application of nuclear emulsions to the solar cosmic ray problem has now shown the existence of both α-particles and heavier nuclei. Ney et al[13] and Freier and Biswas[14] have measured α-particles at both Ft. Churchill and Minneapolis accompanying the protons. As pointed out by Ney, the heavier Z components can be resolved best when "normal" cutoffs are operative which greatly reduces the total proton flux relative to α's. The spectral cutoff is then

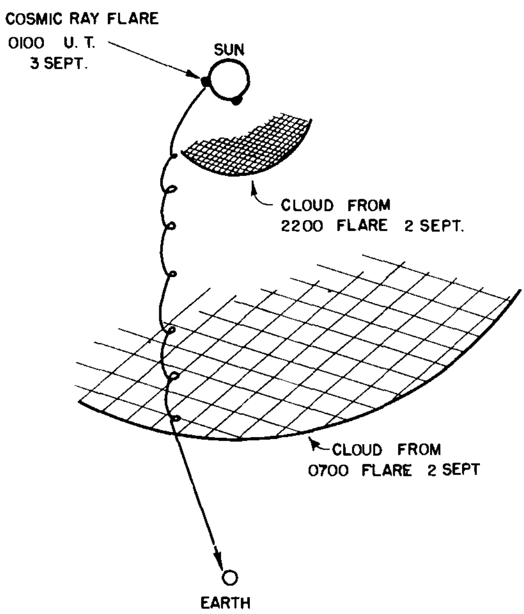

Fig. 6. Estimate of conditions in space during the September 3 event. Solar cosmic rays from the 0100 UT flare on solar east limb had to propagate through or around the clouds from previous flares in a solar region near central meridian.

particles in the atmosphere decreases rapidly with increasing Z, the detection of $Z>2$ nuclei was made possible by nuclear emulsions recovered from sounding rockets at Ft. Churchill by Davis et al[7] for the events of September 3, 1960 and November 12-15, 1960. Tentative values of protons and higher Z components from recent measurements are summarized in Table II. The ratios of protons to α's is highly variable between events, and appears to change during a single event. A considerable number of other measurements will be available when the emulsion analyses are completed.

If more exact knowledge of the relative abundances of the light elements in the solar chromosphere were available, some further details of the flare high energy processes might emerge. Or conversely, if some model of an acceleration process is considered, the cosmic ray abundances may provide the best means of determining the relative proportion of light elements in the sun. Some measure of the accuracy or significance of this procedure from these events is conveyed by Table II.

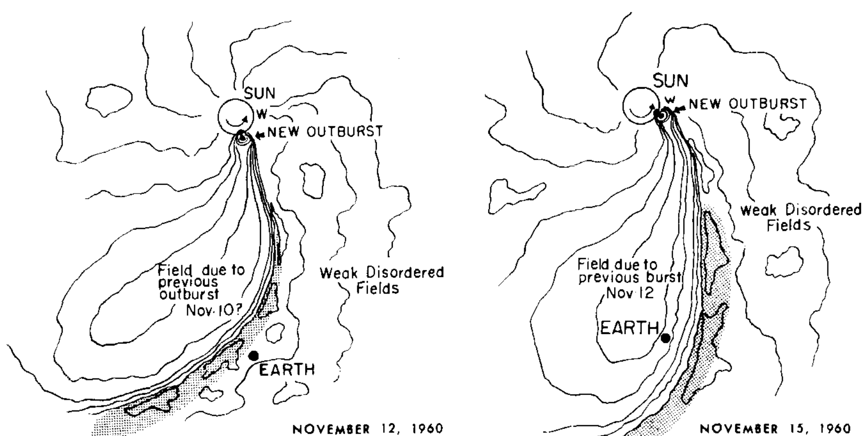

Fig. 7. A guess at the magnetic fields between sun and earth for the November 12, 1960, and November 15, 1960, events. (From Steljes et al[9]).

limited for both components by the minimum Störmer magnetic rigidity and not by the atmospheric range relation, which overwhelmingly favors protons.

Because for the same rigidity the range of the

SOURCE

The events discussed here (Table I) all originate in very large solar flares. In considering the cosmic ray acceleration mechanism, one may be led to believe that only very large flares can reach into the 100-Mev or Bev range of particle energies. Observations with Pioneer V space probe, however, show that many small flares in an active region produce weak bursts of solar protons between 20 and 100 Mev in energy.[12] These smaller bursts can be correlated with changes in the minimum reflection frequency of the polar ionosphere (Obayashi, private communication) showing the terrestrial bombardment by these particles. It is generally accepted that the conversion of magnetic energy into other forms is the source of the energetic particles, and that this process probably occurs during the explosive phase of the flare as revealed by the light curve, for example for H_α emission. Recent measurements also indicate that the amount of energy liberated in energetic particles may be as large as the observed visual energy from a flare.

TABLE II. PRELIMINARY MEASUREMENTS OF HEAVY NUCLEI IN SOLAR COSMIC RAYS

Event		Rigidity Range BV	Flux/m²:sec:ster			Ratio: Z=1 / Z=n	Reference No.
Date	Time		Protons	α's	6<Z<13		
3 Sept 1960	0930-1700	.87-1.32	3400	106	—	32±4	(14)
3 Sept 1960	1408	.57	23,000		23	1000±300	(7)
4 Sept 1960	1650-2320	.77-1.31	900	50	—	18±5	(14)
15 Nov 1960	1000-1200	.8 -1.2			—	1.5	(13)

In conclusion, it should be pointed out that the number of large flares per year which may produce events of the type analyzed here is at present dropping rapidly as the solar cycle wanes. The probability of adding significantly to our knowledge of these events by further experiments is very poor until activity again increases, about 1966-67 and thereafter.

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