

STUDIES OF SOLAR PROTONS WITH EXPLORERS XII AND XIV

D. A. BRYANT,* T. L. CLINE, U. D. DESAI,† AND F. B. McDONALD

Goddard Space Flight Center, Greenbelt, Maryland

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ABSTRACT

Four solar proton events observed by Explorers XII and XIV in 1961 and 1962 are discussed. These events are directly associated with solar activity and, in three cases, are followed either by secondary events delayed by about 2 days or by recurrent events on succeeding solar rotations. It is shown that the rate of propagation of solar protons is, in some of the primary events, linearly dependent on particle velocity. For example, the time taken to reach maximum intensity is inversely proportional to velocity. It follows that the mode of propagation (as measured by the distance traveled in reaching the Earth, for example) is independent of velocity. This result makes possible a separation of source characteristics from propagation effects. In each event which shows a velocity dependence, the maximum intensity is reached long after the rectilinear travel time. We conclude from this that propagation involves an important degree of scattering and that the degree of scattering is independent of energy over the observed range of 1.4 to 500 MeV. The energy spectrum at the time of escape from the Sun, the "source spectrum," is determined in each event which shows a velocity dependence. In each case it is a power law in kinetic energy from a few MeV to several hundred MeV. All events show periodic fluctuations in intensity, which are simultaneous at all energies and have a period of from 1 to 1.5 hours depending on the event. The lack of dispersion indicates the existence of a periodic structure either in the solar wind or in the region between the magnetosphere and the Earth's shock front.

I. INTRODUCTION

During the last solar cycle it has become apparent that large solar flares are often accompanied by the acceleration of protons and other nuclei to energies sometimes exceeding tens of BeV. Over a five-year period centered around the last solar maximum about sixty of these events were observed. Solar-proton events have been studied by many techniques. Ionization chambers, mu-meson telescopes, and neutron monitors at sea level provide indirect information at energies above a few BeV. With high-altitude balloons, measurements down to about 80 MeV are possible. Rocket measurements have no inherent low-energy threshold but are limited to brief samples of an event. Studies by radio techniques of the ionization produced in the D-layer are sensitive to energies down to about 10 MeV but have little energy resolution. Satellite studies can combine the advantages of the other techniques: they can provide almost continuous coverage with good energy and time resolution and with no inherent energy threshold, yielding a higher probability of detection of solar-proton events than can be provided by the other methods. Finally, a satellite with a sufficiently eccentric orbit can provide measurements of solar protons free of interaction with the Earth's magnetic field and free of disturbances by the Earth's trapped radiation.

The satellites Explorer XII and Explorer XIV carried cosmic-ray instruments with response for solar protons of energy as low as 1.4 MeV. They were active from August 16 to December 5, 1961, and from October 2, 1962, to August 1, 1963, respectively. We discuss here several findings resulting from the study of the major solar proton events observed with these satellites during 1961 and 1962. Anomalous features of certain other events will be treated in later papers.

* Now at D S I.R. Radio Research Station, Slough, Bucks, England.

† Now at Physical Research Laboratory, Navrangpura, Ahmedabad, India.

II. THE APPARATUS

Explorers XII and XIV were essentially identical satellites with similar orbits. The apogee of Explorer XII was about 13 Earth radii and that of Explorer XIV about 16 Earth radii; thus, for more than half the time in each orbit they were beyond the outer edge of the magnetosphere which varied from about 7 to over 12 Earth radii. Gaps about 8 hours wide appear in the data as a result of discarding the observations made during the passes of the satellite through the magnetosphere. Various characteristics of the satellites are listed in Table 1.

The detectors used for solar proton measurements in Explorers XII and XIV provided differential energy measurements from 1.4 to 500 MeV and an integral measurement at about 600 MEV. There were three detectors: a scintillation-counter telescope, a Geiger-counter telescope, and a single scintillation counter. The scintillation-counter telescope with a 32-channel pulse-height analyzer provided the differential-energy measurements for energies above 50 MeV and the integral measurement at 600 MeV. The Geiger-counter telescope used in the single mode and in the coincidence mode gave integral

TABLE 1
SATELLITE CHARACTERISTICS

Parameter	Explorer XII	Explorer XIV
Dates of operation	Aug. 16–Dec 5, 1961	Oct. 2, 1962—Aug 1, 1963
Orbital period	26 5 hr	36 5 hr
Apogee, geocentric	83600 km	104800 km
Initial G perigee	6700 km	6700 km
Sun-apogee angle from Earth	$\approx 0^\circ$ min. to $\approx 110^\circ$ max.	$\approx 70^\circ$ to 180° and back to $\approx 0^\circ$
Initial spin period	2 2 sec	5 sec
Direction of spin axis	+47° right ascension; –27° declination	Uncertain due to precession

measurements at 30 and 100 MeV. Low-energy measurements were made with the single scintillation counter and an 8-channel integral pulse-height analyzer. The axis of the Geiger-counter telescope was oriented parallel to the satellite's spin axis and the other detectors were normal to it. A summary of the dynamic range and resolution of each of the detectors is given in Table 2. Corrections were applied to all the data for particles penetrating the detector shielding and for particles clipping the edges of the scintillators; only when these corrections were small were the data used for analysis. The detectors are described more fully in a previous publication (Bryant, Cline, Desai, and McDonald 1962).

III. THE EVENTS

In this paper we confine our attention to the solar proton events following the flares of September 10, September 28, and November 10, 1961, and the flare of October 23, 1962. Some details of these flares and the plage regions producing them are given in Table 3. The table also contains comments on the flares (H. Dodson Prince and R. Hedeman, private communication) and on the accompanying Type IV radio emission (A. Maxwell, J. Warwick, private communications). Some of the flares were followed by delayed effects, and these are also listed. Effects delayed by the 2-day transit of enhanced plasma and effects delayed by the 27-day rotation of the Sun are listed separately.

Figure 1 is a calendar of events observed by Explorers XII and XIV. Primary events

and delayed events are indicated separately. The cosmic-ray intensity measured by a sea-level neutron monitor (courtesy H. Carmichael, private communication) is shown for comparison. There was no evidence either for any other smaller discrete events or for any separate, long-term increases over the general background level. The intensity of protons of an arbitrarily chosen energy interval, centered at 87 MeV, is plotted for all five primary events in Figure 2 in order to show the widely varying behavior of the events. The event of September 7, 1961, which is not clearly linked to any known flare, will be discussed in a later paper.

TABLE 2
DETECTOR CHARACTERISTICS

	DETECTOR		
	Plastic-Scintillator Telescope	Geiger-Counter Telescope	CsI Crystal
Proton energy range	> 55 MeV	> 30 MeV	1.4 to 22 MeV
Information recorded	32 differential channels	Coincidence mode: Single mode:	8 integral levels
Energy intervals processed	Energy Interval (MeV)	Mean Energies (MeV)	Energy Lower Limits
	55 to 118 118 to 150 150 to 200 200 to 255 255 to 335 335 to 500	87 135 175 228 295 418 (Above 600)	≈ 30 MeV ≈ 100 MeV (Sensitivity is a function of energy)
Geometric factor (cm ² ster)	13.4	150 12.7	2.85
	(Corrections take into account variation of geometric factor with energy)		
Time resolution	5 min of storage each 7 min	1.6 sec of storage each mode during 5 out of 7 min	1.6 sec of storage each level for 5 out of 7 min
Direction of detector axis	Normal to spin axis	Parallel to spin axis	Normal to spin axis

IV. THE EVENT OF SEPTEMBER 28, 1961

The solar proton event of September 28, 1961, was initiated by a class 3 flare 29° east of central meridian. Table 3 shows the pertinent solar and geophysical data. Some aspects of the event were considered in an earlier paper (Bryant *et al.*, 1962).

Intensity versus time profiles of various energy components of the event are shown in Figure 3. Time is measured in hours from 2208 U.T., the time of emission at the Sun of a brief X-ray burst observed by Anderson and Winckler (1962) from 2216 to 2217 U.T. For the first few hours points are plotted at intervals of about 7 min, and later points are hourly averages. The energy parameter is the mean energy of each interval as outlined in Table 2. It is clear that the time taken to reach maximum intensity in-

creases with decreasing energy. The data are less complete at the lower energies because at first the correction due to high-energy particles which penetrate the shielding of the low-energy particle detector is large, and because the satellite entered the trapped-radiation zone soon after the first effect became small.

There is a departure from a smooth decay at about 48 hours. At that time an increase took place in the intensity of low-energy particles which was associated with the arrival of a solar plasma stream that produced a sudden-commencement geomagnetic storm and a Forbush decrease. This occurrence is described in detail in the earlier paper, but for the sake of completeness it is briefly described here. The details of this increase, omitted in Figure 3, are shown for some energy intervals in Figure 4 on a linear time scale. The increase starts at about 1930 U.T. just before the sudden commencement of a magnetic

TABLE 3
DETAILS OF THE FLARES

	EVENT			
	Sept 10, 1961	Sept 28, 1961	Nov 10, 1961	Oct 23, 1962
<i>Plage:</i>				
Number	6212	6235	6264	6581
Rotation order	2	3	4	2
Earlier, later	6197, 6235	6212,		6563,
Flares produced	69	15	9 after Nov. 5	.
<i>Flare:</i>				
Class	>1+	3	>1+	2
Position	W 87, N.12	E.29, N 13	W.90, N 19	W 70, N 03
H α (UT):				
Start	1950	2202	1434	1642
Max	2020	2223	1444	1708
Stop	2054	2530	1450	1745
Type IV onset (U.T.)	1937	2212	1445	1656
<i>Comments (optical and radio observations [U T])</i>	A very large, bright flare Loops at 2017, throughout 2025-2055 Considerable Type II	A very large, bright flare Type III bursts earlier on Sept 27 Type III G and Type II	Accompanied by unusual loop activity Limb prominence at 1430; loops for many hours with max. at 1555 Type III G and Type II	Occurs where there are no spots Type III G at 1649 and later Type II
<i>2-day delayed effects:</i>				
Cosmic ray decreases	Sept 11-14	Sept. 30-Oct 5	None	None
Low-energy particles	Sept 12 max	Sept. 30 max.	None	None
Geomagnetic activity	Sept 11, 1606 U.T.	Sept. 30, 2108 U.T.	None	None
<i>Recurrent effects:</i>				
Cosmic-ray decreases	None (central meridian passage on Sept. 28-30)	Oct. 28-Nov. 1	Dec 1-Dec. 4	None
Low-energy particles		Oct. 27 max.	Dec. 1 max.	None
Geomagnetic activity		Oct 26, 1940 U.T. Oct 28, 0820 U.T.	Dec. 1-Dec. 4	None

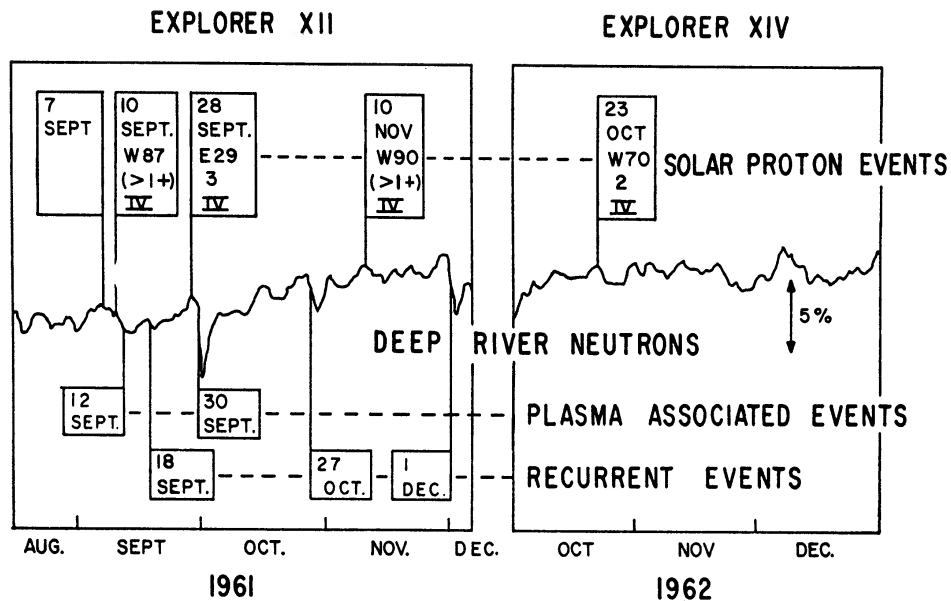


FIG. 1.—A calendar of solar proton events observed with Explorers XII and XIV during 1961 and 1962. The occurrence of each primary event is indicated above the cosmic-ray neutron intensity plots with a flag which displays the solar longitude and classification of the parent flare and the existence of associated Type IV radio bursts. Occurrences of both varieties of delayed proton events are also indicated; a plasma-associated event occurs with a delay of 2 days and a recurrent event takes place when a long-lived solar streamer passes central meridian on a succeeding solar rotation.

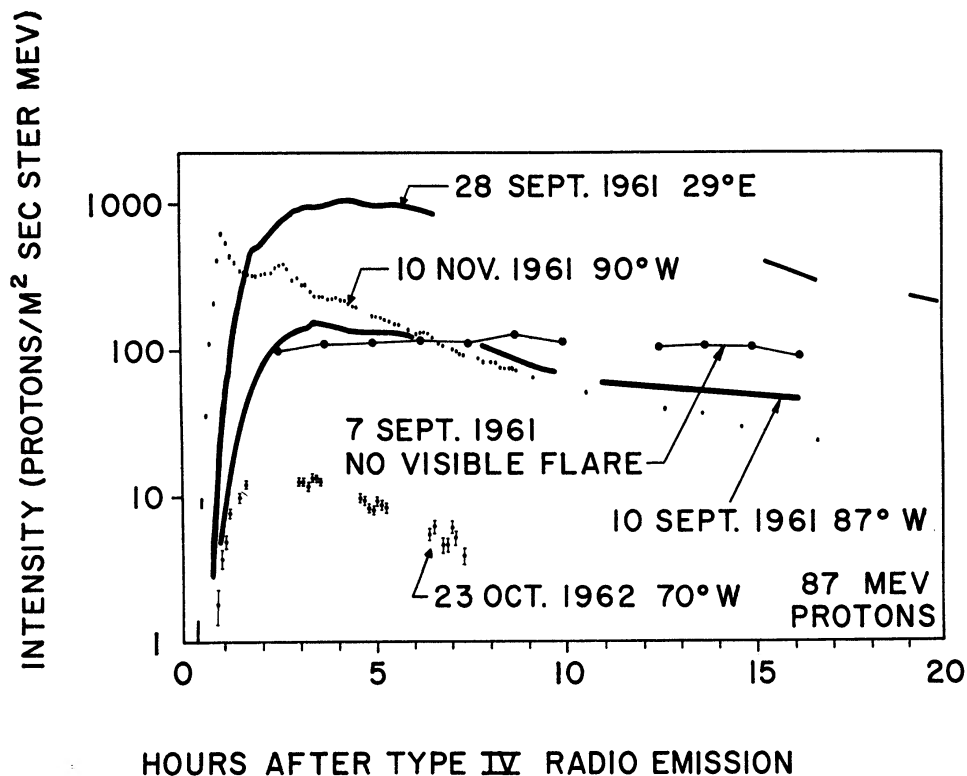


FIG. 2.—The intensities of 87-MeV protons during the five primary solar proton events observed with Explorers XII and XIV. Time is measured in each case from the Type IV emission. The profiles of only two events, those of September 28, 1961, and October 23, 1962, are seen to be quantitatively similar.

storm at 2108 U.T. The maximum intensity of protons of energy above 3 MeV is, during the increase, more than ten times that attained during the main solar-proton event. Axford and Reid (1962) reported riometer observations of this burst of low-energy protons and had previously observed a similar event on February 10, 1958 (Reid and Axford 1962). Other events of this kind have been reported by Charakhchyan, Tulinov, and Charakhchyan (1961).

After a full rotation of the Sun, when the plage region responsible for the flare of September 28 was again close to central meridian, there was another burst of low-energy

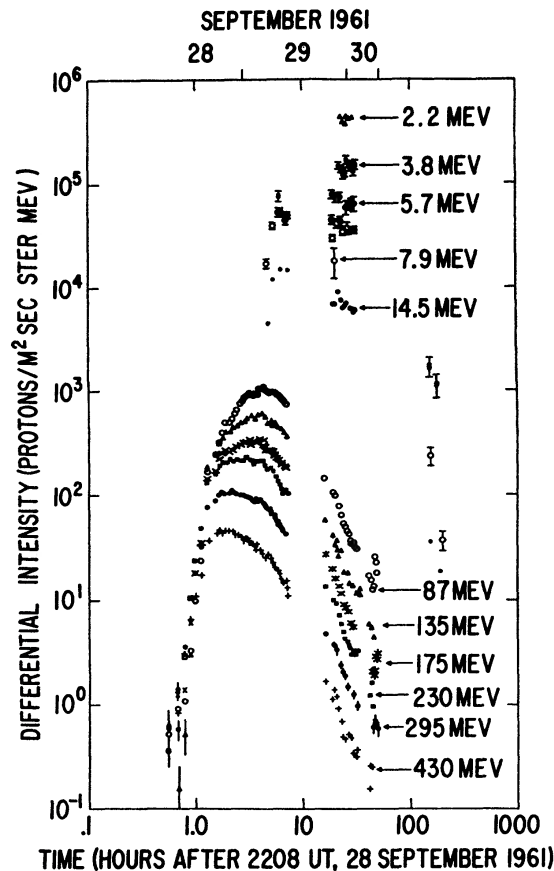


FIG. 3.—The event of September 28, 1961. The differential intensities of solar protons are plotted against time after the X-ray burst at the Sun. The data are interrupted when the satellite passed through the magnetosphere and when the delayed increase occurred on September 30, 1961.

protons. This time the increase was much smaller. Figure 5, which is a plot on a further-compressed linear time scale of the intensity of protons of energy above 3 MeV, shows the full sequence of events. This recurrent event was associated with a recurrent geomagnetic storm and a recurrent Forbush decrease. We have put forward this event and a similar one following the November 10, 1961, flare as new evidence for the existence of long-lived solar streams (Bryant *et al.* 1963).

a) Velocity Dependence

The energy dependence of the rate of rise of intensity suggests that the propagation of the particles is a velocity-dependent process. A striking linear dependence on velocity is revealed by the following analysis.

We assumed that all particles were accelerated at the same time or, more strictly, that they were all accelerated within a time interval short compared with the interval between acceleration and observation. We may then determine the distance a particle has traveled between acceleration and observation by taking the product of particle velocity and time from the beginning of the event. The time used here for the beginning of the event is 2208 U.T., the time of the X-ray burst at the Sun. We then convert the intensity versus time profile to an intensity versus distance profile. The intensity versus

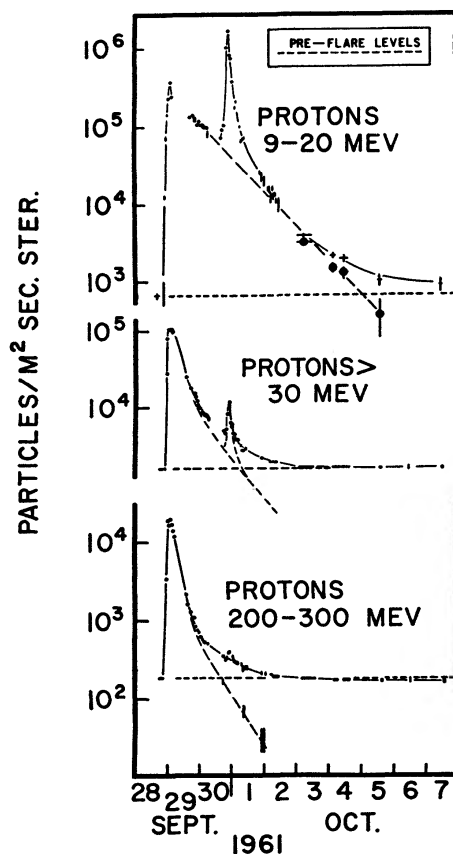


FIG. 4.—The secondary event of September 30, 1961. Representative proton intensities between September 28, and October 7 show this delayed-intensity increase of predominantly lower-energy protons. The energy spectra of these particles are relatively constant with time, unlike those of the velocity-ordered primary solar-proton event, and their arrival times are essentially constant with energy. The event occurs when the enhanced solar plasma, omitted by the flare on September 28, reached the Earth.

distance profile is effectively a distribution in distance traveled. This distribution is a property of the medium through which the particles have traveled. Figure 6 shows the result of this treatment in which the distance traveled is measured in astronomical units. In constructing this figure the intensities of each component have been scaled to give the best fit to a common curve. The physical meaning of this normalization will be examined further below.

We note from Figure 6 that all components lie very closely on a common curve, apart from small-scale deviations to be discussed later as a separate topic. The fact that we have essentially a common curve shows that particles of all energies have traveled a given path length with equal probability; this is true for all path lengths to the extent that the various components of Figure 6 do lie on a common curve. We note that the distance

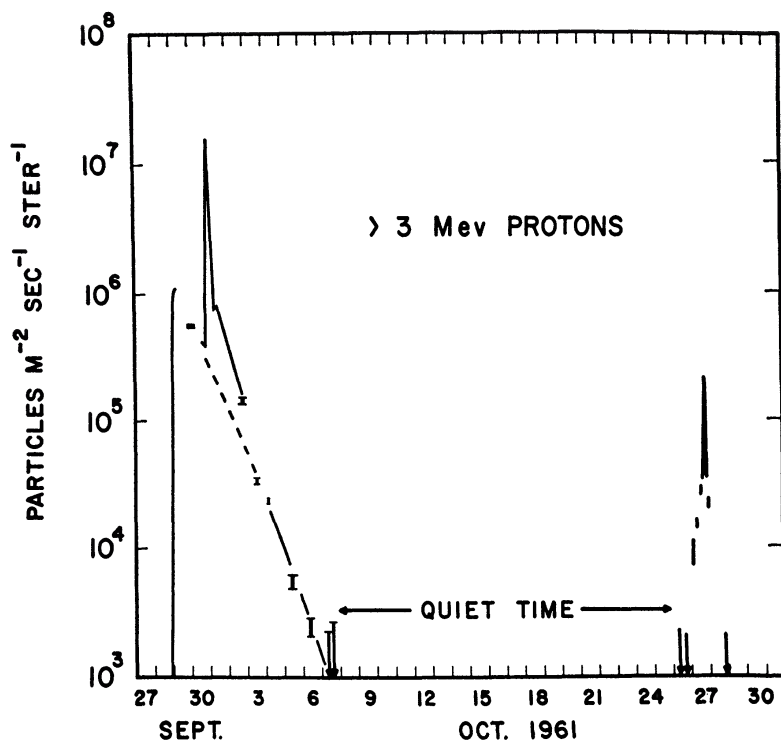


FIG. 5.—The recurrent event of October 27, 1961. The intensity of protons of energy above 3 MeV between September 28 and October 28, 1961, is plotted, showing the primary event, the 2-day delayed increase superposed on the primary intensity decay and the recurrent event on October 27 following a completely event-free intervening period. This recurrent event is the result of the arrival at the Earth of a long-lived stream of plasma originating at the region of the parent flare of the September 28 event.

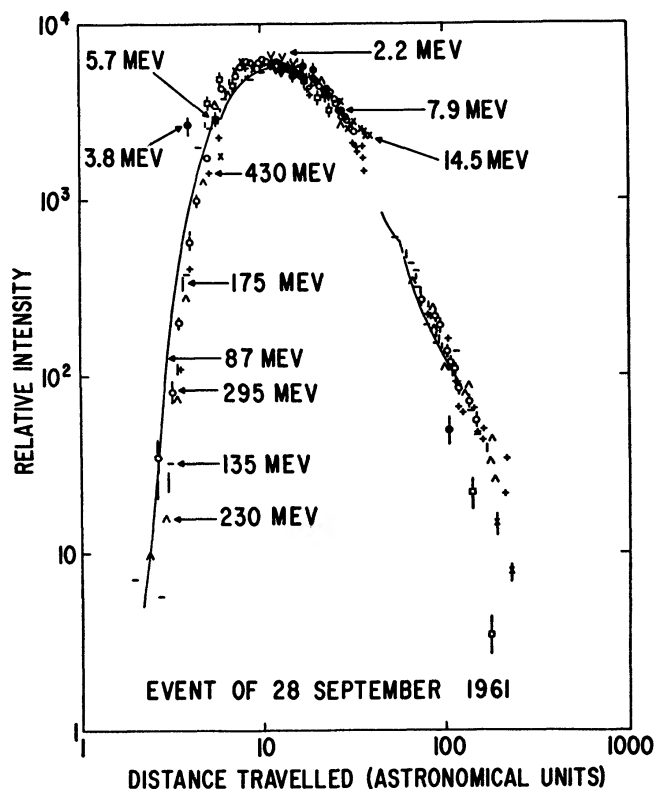


FIG. 6.—The event of September 28, 1961, in which the intensity versus time plots of Figure 3 are converted to relative intensity versus distance plots. The distance traveled for each energy component is the product of the corresponding particle velocity and time from the flare. The intensities are scaled to give the best fit to a common propagation-curve; this fit occurs over a dynamic range in energy of a few hundred and a velocity range of 14, and over a time duration of several days.

traveled by most particles is many astronomical units, which indicates that propagation involved an important degree of scattering. Further, the degree of scattering is not a function of energy over the observed range. This suggests that the mode of propagation is a diffusion-like process and that energy-dependent processes, such as drift across magnetic field lines, play a minor role. In fact, it has been shown that the equation for simple diffusion describes the propagation-curve of this particular event through its maximum (Bryant *et al.* 1962). It fails to do so, though, during both the early anisotropic phase and the later stages where boundary conditions are important.

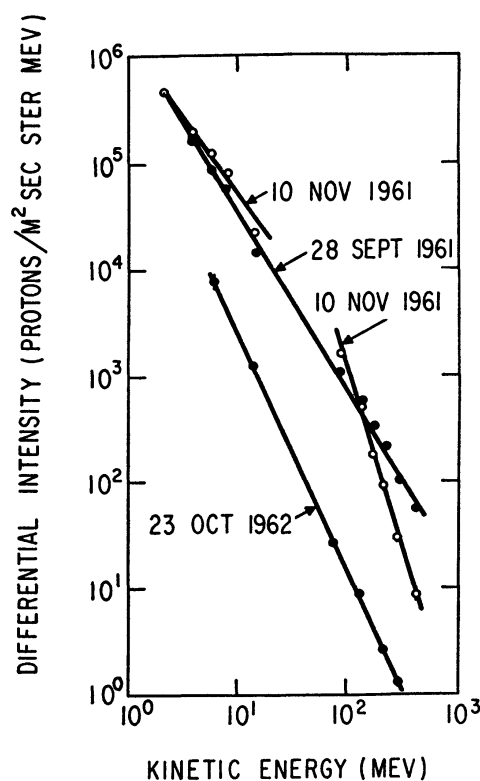


FIG. 7.—The source spectra of three solar-proton events. The scale is arbitrarily chosen to show the maximum intensities reached at the Earth. For each event which conforms to a velocity-dependent behavior, such as that of September 28, 1961, or that of October 23, 1962, we believe the spectrum shown to be proportional to the unique differential-energy spectrum of the protons at the time of their escape from the Sun; in each event the scaling factor depends in an unknown way on the geometry of propagation.

b) Source Spectrum

We now discuss the physical meaning of the scaling factors used to construct Figure 6. Let us consider the relative intensity of any two components of the event. We have recorded the intensities not as a function of time but as a function of distance traveled, and found that the relative intensity is essentially constant over a range from 2 to more than 100 astronomical units. There is nothing to suggest that an extrapolation back to zero distance is invalid. The relative intensity of two components at zero distance is, by definition, a measure of the shape of the source spectrum.

The scaling factors used to produce Figure 6 provide these relative intensities, and Figure 7 shows the source spectrum obtained directly from them. The source spectra of two other events analyzed in a similar way are also shown. The ordinate of Figure 7 is arbitrarily chosen to show the maximum intensity reached at the Earth. The spectra shown are proportional to the spectra of protons produced at the Sun and retain, there-

fore, the same spectral form, but the constant of proportionality which depends on the geometry of propagation is unknown. The spectrum for the event of September 28, 1961, is well represented by a power law in kinetic energy with a slope of about -1.7 .

We note that, apart from small-scale fluctuations, this event is completely described by two graphs: the source spectrum (Fig. 7) and the path-length distribution (Fig. 6).

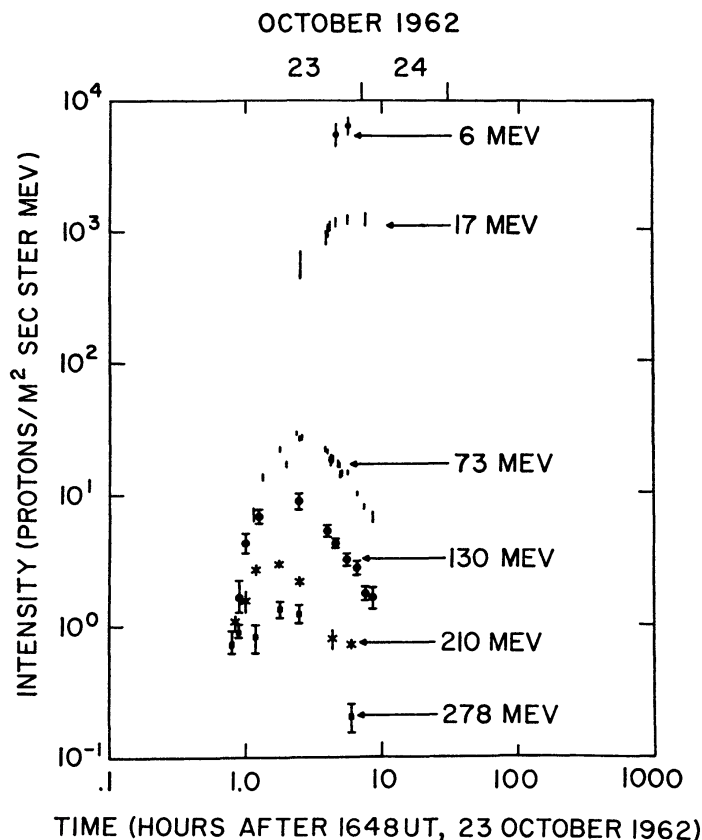


FIG. 8.—The event of October 23, 1962. The differential intensities of solar protons during this event are plotted against time after the onset at the Sun of Type IV radiation. The behavior of this event is qualitatively similar to that of the early portion of the September 28, 1961, event. Due to the relatively low intensity of the event, the differential intensities of protons of energy above 300 MeV could not be measured; the protons of energy below 5 MeV did not arrive until after the satellite entered the magnetosphere.

V. EVENT OF OCTOBER 23, 1962

The event of October 23, 1962, is probably the lowest-intensity primary solar-proton event studied to date. It was initiated by a class 2 flare occurring 70° west of central meridian. Some details of the flare and associated phenomena are listed in Table 3. The event was also observed by the cosmic-ray equipment on Mariner II (H. Anderson and V. Neher, J. Van Allen, private communication).

Figure 8 shows the intensity versus time profiles of various components of the event. We see that again the higher-energy components reach a maximum earlier than the lower-energy components. The intensity versus distance profiles, obtained in the same way as those for the event of September 28, 1961, are shown in Figure 9. We find a good fit to a common curve, so again the fact that higher-energy particles arrive earlier is explained quantitatively as a dispersion effect. The source spectrum obtained from

the relative normalization used to construct Figure 9 is shown in Figure 7. We note that again it is well represented by a power law in kinetic energy. The slope of the spectrum in this case is about -2.3 .

VI. EVENT OF NOVEMBER 10, 1961

The solar proton event of November 10, 1961, was one of two events observed by Explorer XII resulting from flares on the west limb of the Sun (Table 3). A long-lived solar stream emanating from the flare region produced a recurrent event 21 days later on December 1 (Bryant *et al.* 1963).

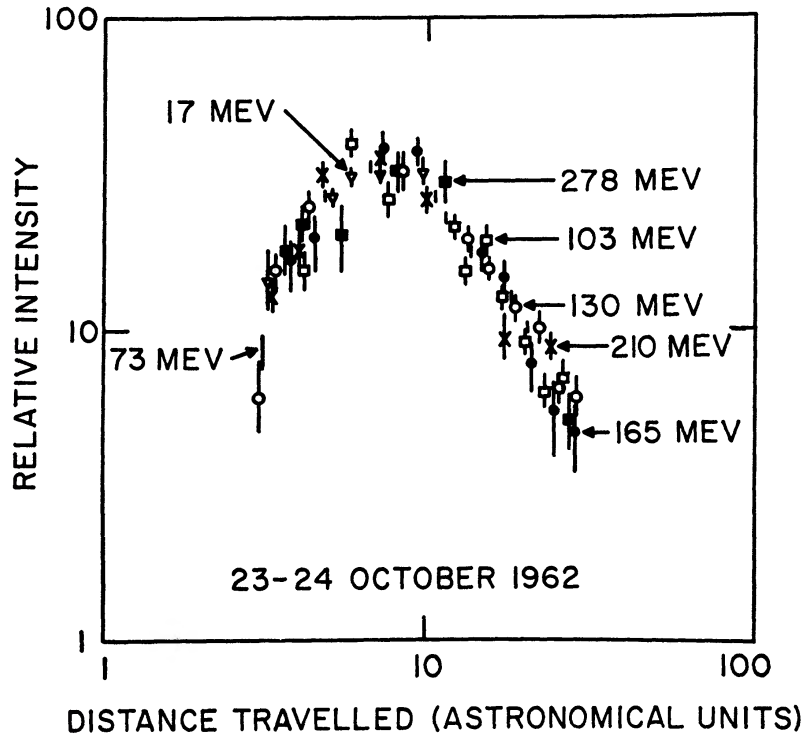


FIG. 9.—The event of October 23, 1962. The intensity versus time plots of Fig. 8 are converted to a relative intensity versus distance plots and scaled to give the best fit to a common propagation-curve.

Intensity versus time profiles for this event are shown in Figure 10. A feature of these curves is a sudden drop in intensity at 1.3 hours (1546 U.T.). It occurs in all components that show a measurable intensity at this time. A second drop occurs at 3 hours (1730 U.T.). As we shall mention again in Section VII, these fluctuations are very likely unusually large cases of a feature common to all four primary events discussed here, namely, a periodic intensity fluctuation with a period of about 1 hour. However, since these particular changes are so unusually large and sharp, they may be due to some other cause. The flare producing this event was accompanied by unusual loop activity, so it may not be by chance that the solar-proton intensity exhibits unusual behavior. We are unable to link any specific happening at the Sun with the changes taking place near the Earth, but we are able to deduce when it should occur. Figure 11 shows the integral intensities above 60 MeV and above 200 MeV plotted in a linear scale to show how drastically the behavior changed. The data are consistent with the breakdown having occurred simultaneously at all energies, but the time resolution of the measurements would permit a 15-min dispersion and so is consistent with the dispersion to be expected from the veloci-

ty difference acting over a distance of 1 a.u. The breakdown occurs in the 87-MeV component somewhere between 1546 and 1556 hours. Since 87-MeV particles take 20 min to travel 1 a.u., the first ones to bring information of a change would have left the Sun between 1526 and 1536 if they traveled in a straight line, but (more likely) between 1521 and 1531 if they traveled along a curved path defined by the interplanetary magnetic field. Optical or radio information would reach the Earth 8 min later, somewhere between 1529 and 1539. Although the flare showed great activity (see Table 3 for comments), we have found no evidence for any drastic change of conditions in this period.

a) Velocity Dependence and Source Spectra

This complicated event defies description in terms of velocity dependence alone. As will be shown below, there are occasions on which a velocity dependence is revealed. Figure 12, *a* and *b*, shows intensity versus distance profiles for the higher and lower energies taken separately. The higher-energy components are velocity-dependent before

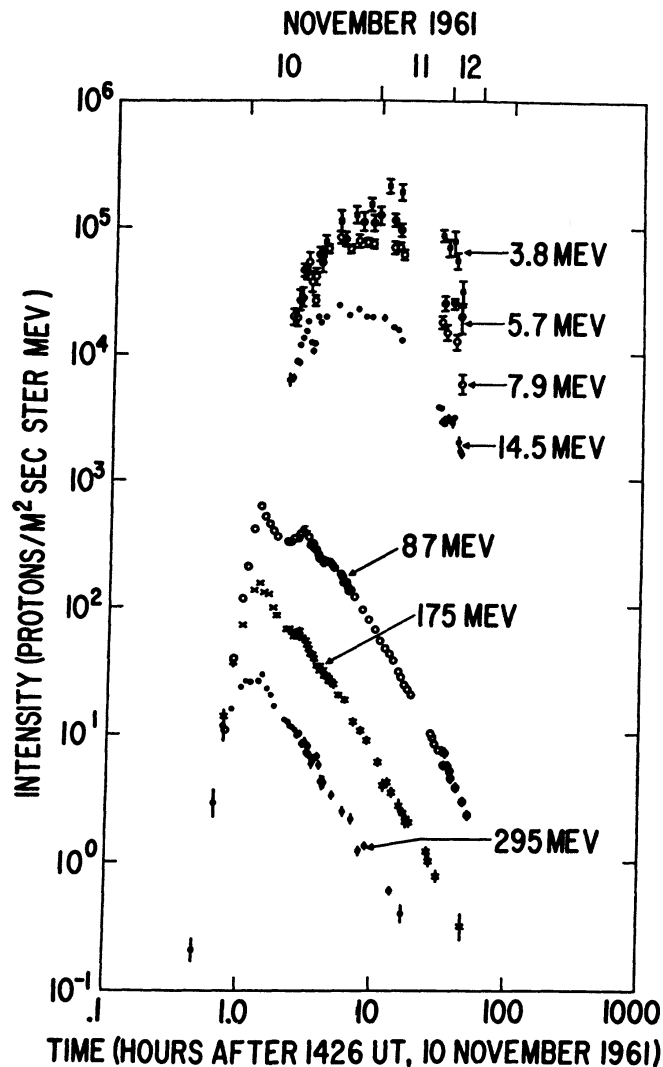


FIG. 10.—The event of November 10, 1961. The differential intensities of solar protons during this event are plotted against time after the flare. There is a sudden drop in the intensities of the higher-energy protons at 1.3 hr; it occurs before the arrival of most of the lower-energy protons.

the sudden drop in intensity at 1.3 hours, and the lower-energy components are velocity-dependent throughout the event. The fact that the lower-energy components do not show a measurable intensity until after the breakdown of velocity dependence at higher energy introduces a further uncertainty in interpretation.

Two source spectra are shown for this event in Figure 7, one for the higher energies and one for the lower energies. Since the intensity versus distance profiles are different, the relative normalization of the two sections of the spectrum is not meaningful. The normalization for each section of the spectrum is arbitrarily chosen to be the maximum intensity reached at the Earth.

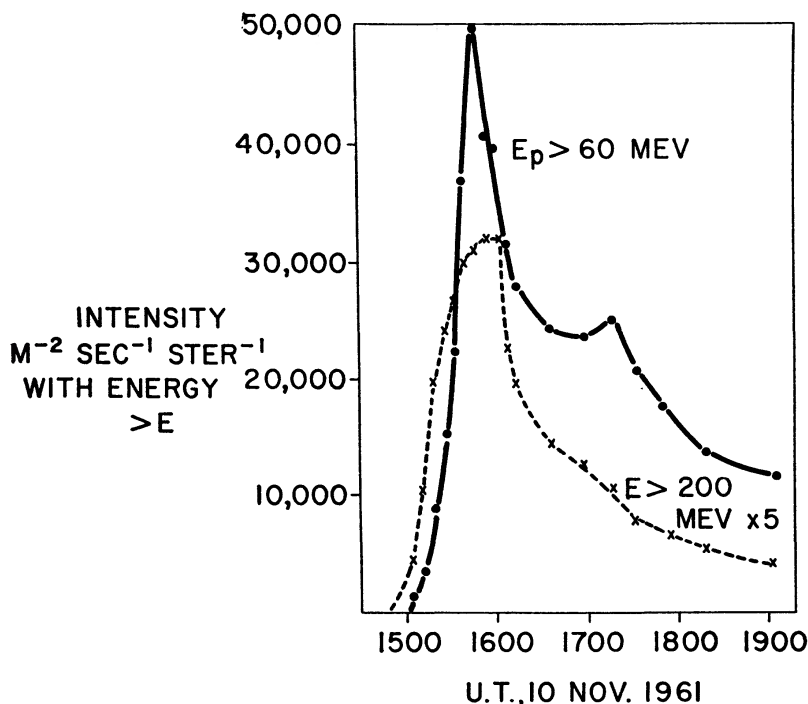


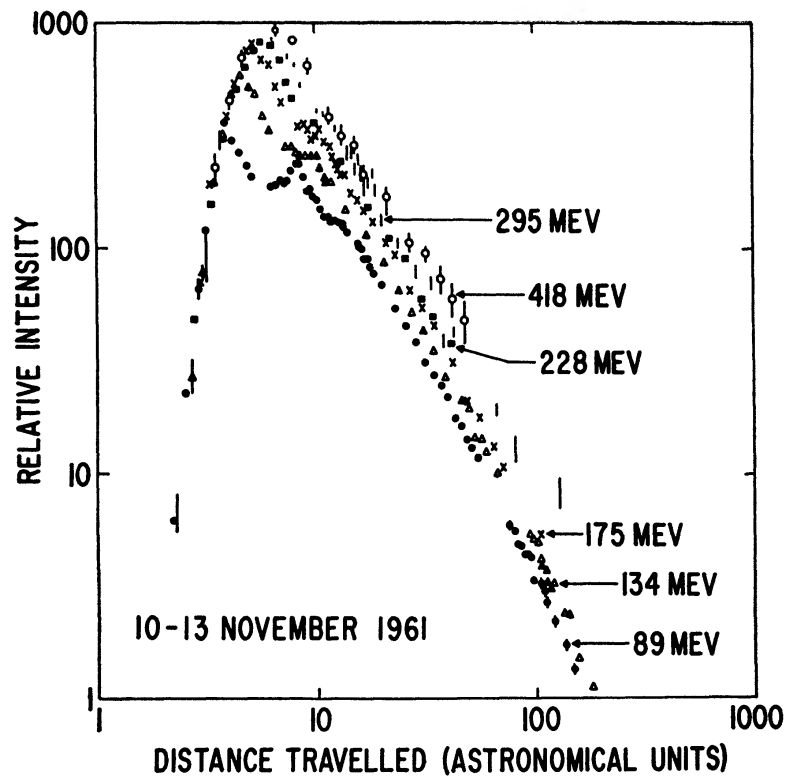
FIG. 11.—The event of November 10, 1961. The integral intensities of protons above 60 MeV and above 200 MeV are plotted during the first few hours of the November 10, 1961, event.

b) Time Dependence

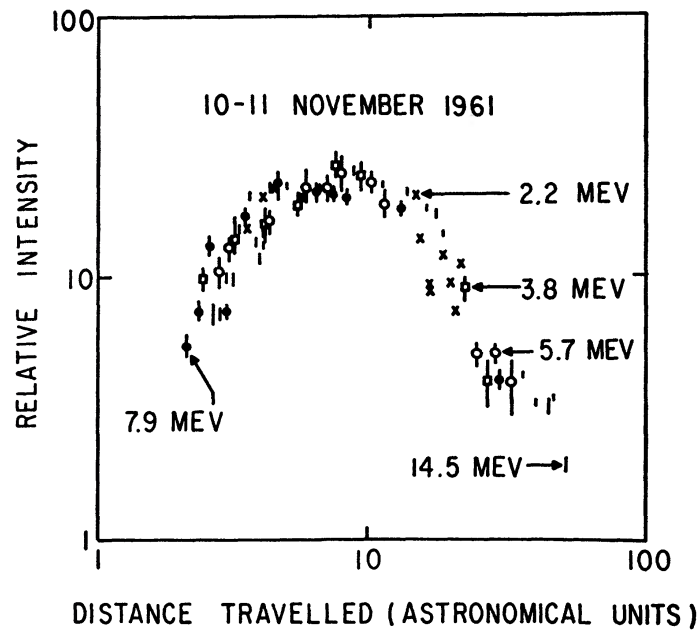
Although this event shows a velocity dependence that holds very well at certain times, it cannot be completely described by a single source spectrum and single propagation-curve. There are two sudden changes in intensity that occur over a wide energy range with no dispersion. They almost certainly result from sudden changes in the propagation medium which probably take place near the Earth but, from the above discussion, which may also take place at the Sun. Other effects of this kind are described in the next section and discussed more fully in Section VIII.

VII. EVENT OF SEPTEMBER 10, 1961

The event of September 10, 1961, was initiated by a flare on the west limb of the Sun. The intensity versus time profiles of Figure 13 show that the event was dominated by intensity changes occurring simultaneously at all energies. Only gross features, such as the fact that the lower-energy components reach maximum intensity later than the higher-energy components, can be attributed to dispersion. There is no systematic change of behavior with energy and consequently no simple velocity dependence. A linear plot of three sample components (Fig. 14) typifies the irregular behavior of the



a



b

FIG. 12, *a* and *b*.—The event of November 10, 1961. The intensity versus time plots of Fig. 10 are converted to relative intensity versus distance plots. Two groups are separately scaled to give the best fit to a common high-energy curve before the 1.3-hr peak, and to a common low-energy curve after it. A unique high-energy propagation-curve does not exist throughout the event but appears to be approached asymptotically with increasing energy. A common low-energy curve is apparent, but it may relate more directly to a local modulation than to interplanetary propagation.

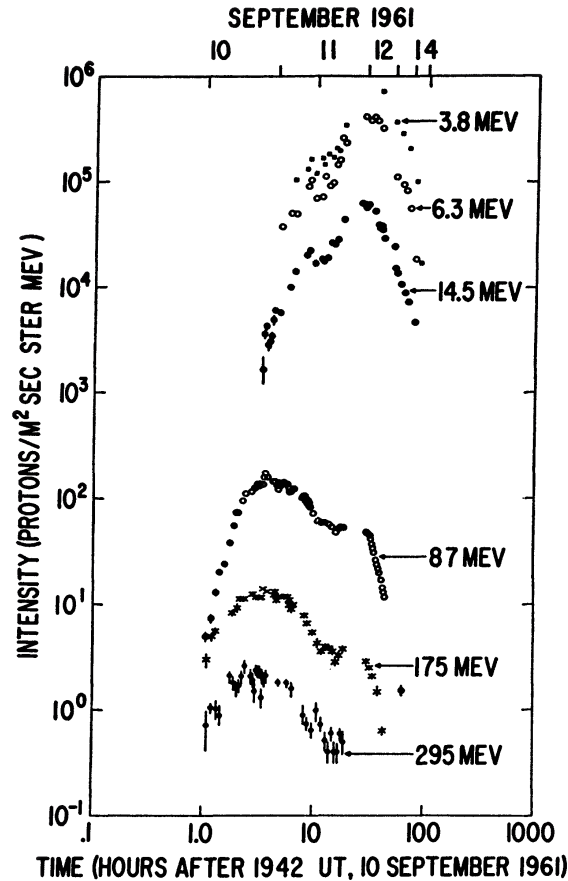


FIG. 13.—The event of September 10, 1961. The differential intensities of solar protons during this event are plotted against time after the flare. There is only a qualitative velocity ordering for the first 10 hours; during this time the higher-energy protons tend to increase in intensity before the low-energy protons do. Later in this event the intensities of protons of all energies increase together at the time of a cosmic-ray decrease and geomagnetic fluctuations associated with the arrival of enhanced solar plasma.

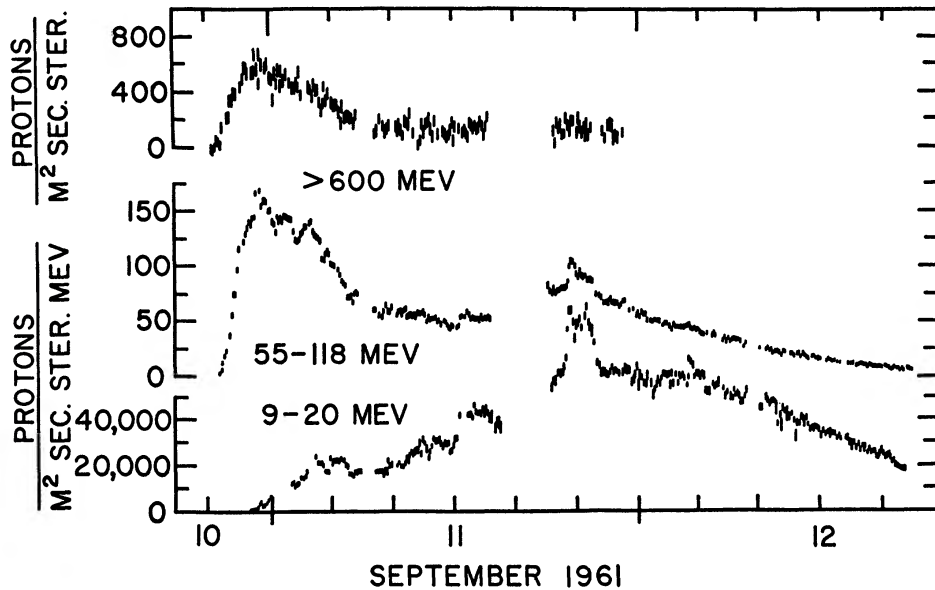


FIG. 14.—The event of September 10, 1961. The intensities of relativistic protons and of two lower-energy groups indicate the complicated structure of this event.

event. High intensities are simultaneously reached by the lower-energy components when a small sea-level cosmic-ray decrease occurs about 1 day after the flare following geomagnetic activity at 1106 U.T. on September 11. This increase is like the delayed arrival of low-energy particles seen about 48 hours after the September 28, 1961, event, but in this case there is a much slower onset perhaps having to do with the west-limb location of the flare.

Fluctuations

Superimposed on the large-scale features of the intensity versus time profiles is a series of fluctuations. These fluctuations are nearly periodic, with the same frequency and phase at all energies. Figure 15, which shows the integral intensity versus time profiles on a linear scale for the 5.7-MeV and the 30-MeV components of this event, illustrates these fluctuations more clearly, the lower fre-

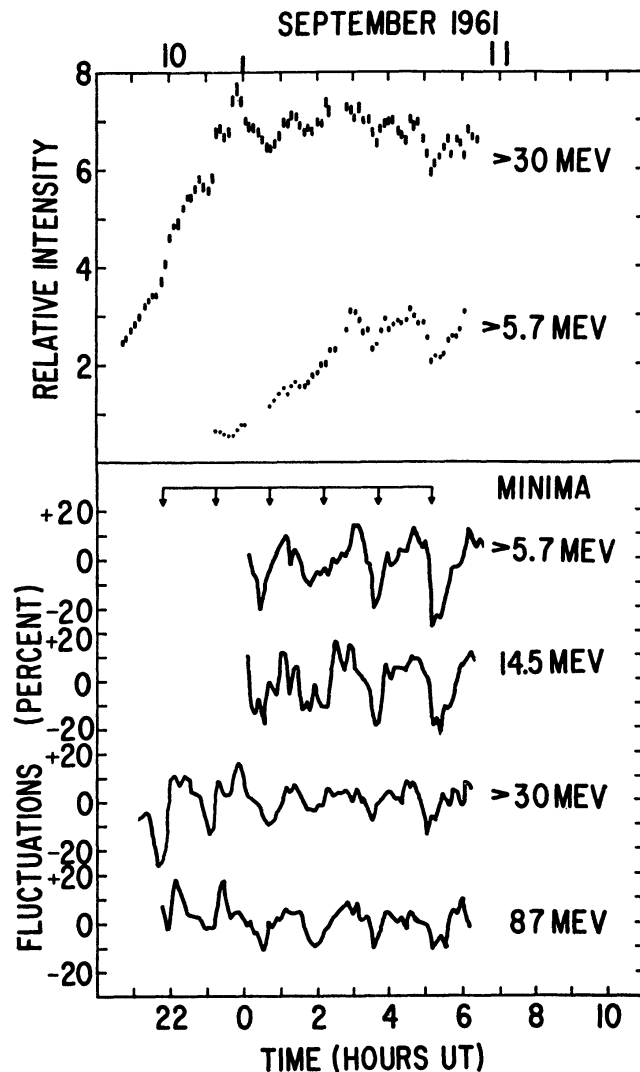


FIG. 15.—The event of September 10, 1961. Several components of the event are plotted to illustrate the intensity fluctuations. In the bottom half of the figure the lower frequencies have been numerically filtered out to display the fluctuations more clearly. The modulation appears to have a period and a phase independent of energy.

quencies have been removed by subtracting the running mean of one period length. The result for several energy components is shown in the lower half of the figure. Fluctuations of this kind occur to some extent in all events: Figure 16 shows the fluctuation of the 87-MeV component for all events. We note that the sudden drops in intensity near the beginning of the November 10, 1961, event have the same frequency and phase as the other fluctuations, and this suggests that they may not be isolated happenings caused directly by activity at the Sun but the first two members of a series of fluctuations. The amplitude of the fluctuations depends little on energy in any of the events. Table 4 summarizes the periods and amplitudes of the fluctuations.

VIII. DISCUSSION

The following general statements can be made summarizing the results presented above.

1. Solar-proton events observed in the 2–600-MeV energy region fall into at least

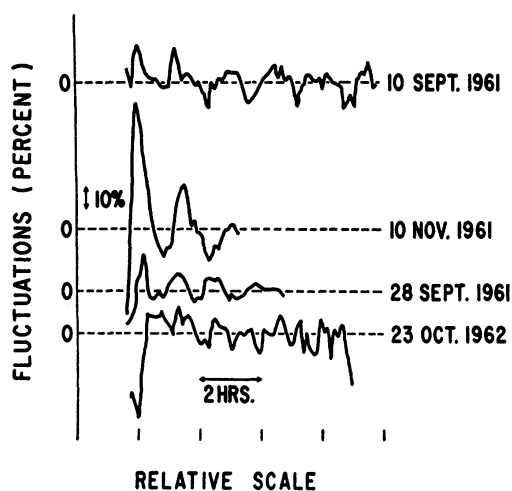


FIG. 16.—Intensity fluctuations during four solar-proton events. An arbitrarily chosen component, centered on 87 MeV, illustrates the fact that the frequency of the fluctuations varies from 1.0 to 1.5 hr with the event.

TABLE 4
SOLAR-PROTON EVENT CHARACTERISTICS

EVENT	SEPT 10, 1961	SEPT. 28, 1961	Nov. 10, 1961		OCT 23, 1962
			Low Energy	High Energy	
Energy range of velocity dependence (MeV)	None detected	1.4–500	1.4–22	55–500	4–330
Exponent of source spectrum	.	–1.7	–1.5	–3.5	–2.3
Scale of source spectrum at maximum intensity ($\text{cm}^2 \text{ster sec MeV}^{-1}$)	.	1.6×10^6	1.4×10^6	7×10^9	4×10^6
Most probable distance (a.u.)	.	12	8	9	8
M.F.P. (a.u.) from diffusion theory	.	0.04	0.06	0.055	0.06
Fluctuation period (hours)	1.4	1.3	None detected	1.5	1.0

three categories: (i) primary events have maximum intensity soon after the parent flares; (ii) secondary events occur with the arrival of the solar plasma about 2 days later; (iii) recurrent events occur when the plage region of the parent flare passes near central meridian.

2. The intensity versus time profiles often show a linear velocity dependence. In two of the events under discussion (September 28, 1961, and October 23, 1962) this velocity dependence lasts throughout the events. Exceptions occur in the event of November 10, 1961, which shows some early departure from this behavior and in the event of September 10, 1961, which shows no quantitative agreement with velocity dependence.

If we convert those intensity versus time profiles which show a quantitative, linear velocity dependence to intensity versus distance profiles, we are led directly to the following conclusions: (i) properties of the propagation medium and properties of the source can be studied separately and, in particular, the shape of the energy spectrum at the source can be obtained; (ii) propagation involves an important degree of scattering (since the most likely distance traveled is about 10 a.u.); (iii) the degree of scattering is independent of particle rigidity in the region below 1.5 BeV (since all the propagation-curves are the same).

3. All events show a series of periodic intensity fluctuations with a period of from 1. to 1.5 hours. These occur without dispersion.

a) Velocity Dependence

The analysis described in Section IV, showing the velocity dependence of these events, has constituted a necessary but insufficient test. For example, we might have found an even closer fit had we compensated the intensity versus time profiles by velocity raised to the power n , where n is close to but not equal to 1. We now show that the best value of n is indeed 1. To find the best value of n , the various intensity versus time profiles were shifted horizontally and vertically to give the best fit to a chosen reference curve. No account was taken of particle velocity at this stage. The factors by which the curves were horizontally shifted were then plotted against particle velocity. The result is shown in Figure 17, *a*, in which, for comparison, lines of slope unity have been drawn through the points. The normalizations are arbitrary and depend on the curves chosen for reference. We find that the slopes of all lines are close to unity, the mean value being 1.0 ± 0.1 . The energy intervals over which this test could be performed are implied by the figure and are indicated in Table 4. The various parts of Figure 17, *a*, have been superimposed in Figure 17, *b*, where, as in 17, *a*, a line of slope unity has been drawn through the points for comparison. (The energy range studied here does not extend sufficiently far into the relativistic region to permit a test of rigidity dependence as opposed to simple velocity dependence.)

Further evidence of velocity-dependent propagation in solar-proton events was provided by a comparison of alpha-particle and proton intensities during the events of November 12, 1960, and November 15, 1960, by Biswas, Fichtel, and Guss (1962) and Biswas, Fichtel, Guss, and Waddington (1963). Several rockets carrying nuclear emulsions were fired into these events, and the relative intensity of alpha-particles and protons having the same velocity was found to be the same at certain times even though the energy spectra of protons and alpha-particles were changing with time.

b) Source Spectrum

We note from Figure 7 that a given source spectrum is well represented by a power law in kinetic energy, although the event of November 10, 1961, is an exception in that two power-law spectra are required. The September 28, 1961, spectrum is remarkable in that it fits a power law over a dynamic range of nearly three decades in energy. The fact that there is no deviation from this smooth, simple spectral representation, even at the

low-energy portion of this source spectrum, prompts us to put forward the argument, based purely on aesthetic grounds, that the amount of matter traversed by the solar protons after acceleration was less than the range of 1 MeV proton, that is, about 1 mg cm^{-2} . If we consider a beam of particles penetrating an absorber, we find the emerging spectrum very much depleted in particles with energies near that required to just penetrate the absorber. There is consequently a rapid change of slope at low energies. It seems unlikely, therefore, that an excess production of lower-energy protons would occur in such a manner as to exactly compensate their absorption in an amount of material greater than their range resulting in so simple a form of source spectrum.

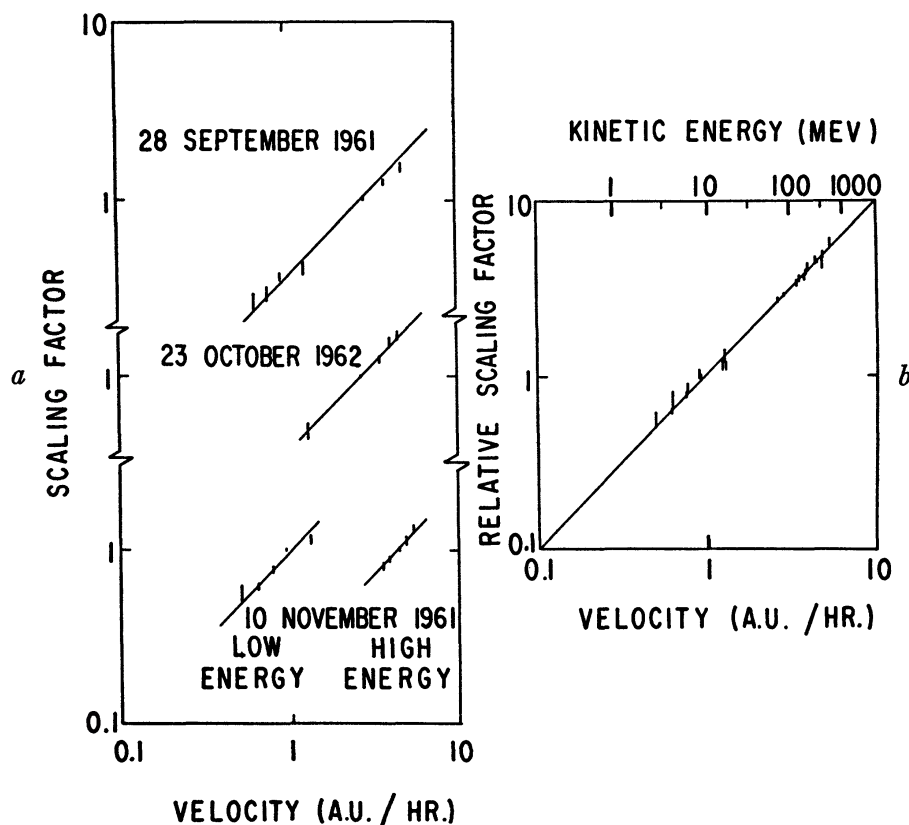


FIG. 17, *a, b*.—Tests of velocity dependence: the scaling factors by which the differential intensity versus time plots of each event were shifted horizontally to give the optimum fit to a common curve. This effort determines the nature of the dependency on velocity; comparison lines of slope 1 are used to indicate the closeness of fit to a linear velocity dependence.

We can draw no conclusions here about the solar-proton acceleration process from the shape of the source spectra since there probably are a number of processes that would produce the observed spectra. Table 4 gives the slopes of the spectra observed in the events under discussion.

c) Propagation Medium

For the purpose of this discussion we define the propagation medium to be the medium through which solar protons travel after acceleration and escape from the acceleration mechanism. Let us now consider where the scattering takes place.

Meyer, Parker, and Simpson (1956) suggested that during the February 23, 1956, event scattering took place in interplanetary space beyond the Earth's orbit. Parker (1963) has discussed a mechanism of simple diffusion throughout interplanetary space;

E. Roelof (private communication) has found that scattering by magnetic fields in interplanetary space that are irregular in space and/or time would produce a degree of scattering that is a function of particle rigidity. McCracken (1962) introduced the idea of small-angle scattering caused by irregularities in an otherwise quasi-radial interplanetary field to account for the onset of isotropy in several solar proton events. Anderson, Arnoldy, Hoffman, Peterson, and Winckler (1959) and Gold (1962) have suggested that the processes of scattering and drift in the strong magnetic fields near the Sun must play an important part in solar-proton propagation. Bryant *et al.* (1962) and Hoffman and

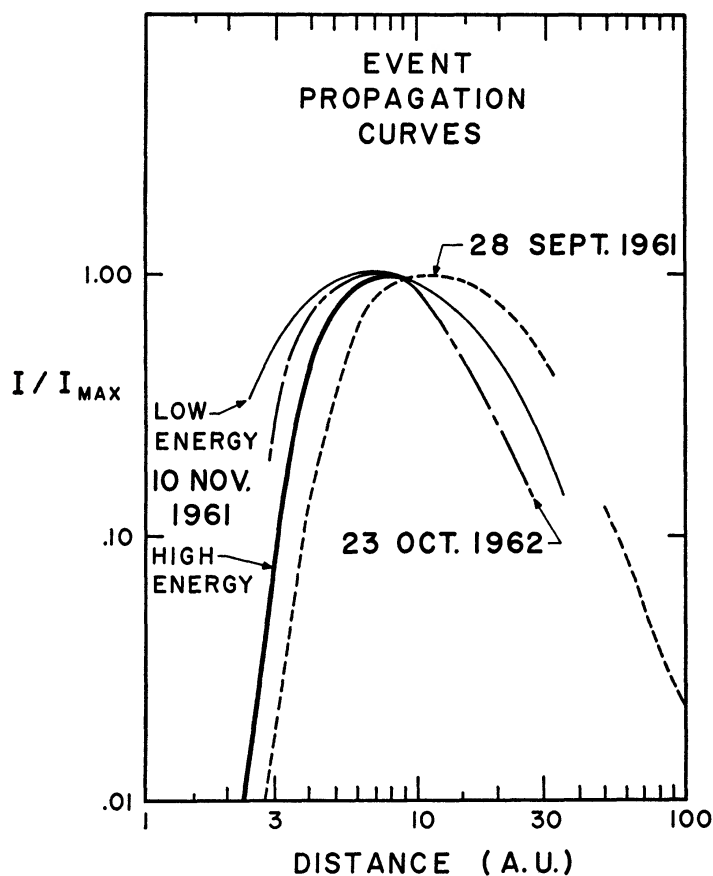


FIG 18 —The propagation-curves of the three velocity-dependent events. These curves show these distributions in the distance traveled by solar protons in reaching the Earth from the Sun.

Winckler (1963) found that the intensity versus time profiles of several solar-proton events are well represented by those to be expected from a process of simple diffusion in interplanetary space.

The propagation-curves of the three velocity-dependent events are compared in Figure 18. Apart from that of the low-energy component of November 10, 1961, the curves are geometrically similar to a remarkable degree. It is meaningful, therefore, to associate with each of the curves a parameter describing the rate of propagation of the event. A convenient parameter, though somewhat poorly defined, is the most probable distance traveled—that is, the distance traveled by the particles arriving at maximum intensity. These distances are listed in Table 4. (We notice that the ordering of the propagation geometry in the three events correlates either with the phase of the solar cycle or with the displacement in longitude of the flare from about 70° west, the origin of the Earth-

intercepting garden-hose line. For example, the slowest event is that from a flare at 29° east; it is also the first in time. No significance is claimed for either correlation on the basis of such a small number of events.)

We have mentioned that the intensity-curves which fit a common propagation-curve in a given event also fit the equation for simple diffusion. The resulting effective mean free paths and other parameters are listed in Table 4. In spite of this fit, it is difficult to see how solar protons could undergo a process of simple diffusion in interplanetary space, especially since the garden-hose magnetic field has been observed to play an important part in guiding solar protons away from the Sun. Another difficulty is that the observed velocity independence of the scattering implies that the scattering takes place at discrete scattering centers, rather than as a continuous process, as would otherwise seem more reasonable. The finding that the degree of scattering is independent of rigidity, combined with Roelof's result for continuous scattering in irregular magnetic fields, rules out such a mechanism at least for the events under discussion.

In order to reconcile a diffusive propagation with the previously observed guiding by the garden-hose interplanetary field, we consider a model in which scattering occurs near the Sun and the particles escape to the Earth after diffusing from the flare to the foot of a line of force providing direct access to the Earth (Gold 1959). We meet at once with two difficulties. First, particle drift produced by gradients and curvatures in any general field near the Sun would lead to a rigidity-dependent propagation. Second, there must be a certain amount of scattering in interplanetary space to account for the onset of isotropy (McCracken 1962). Since any pitch-angle scattering would in general be accompanied by a change of guiding center, there would be some motion across the lines of force. The question then arises of the relative importance of motion along the lines of force and motion across them. We have then reached a process of anisotropic diffusion in interplanetary space instead of one of simple isotropic diffusion. Anisotropic diffusion conceivably could account for the observations, but there is no present theoretical treatment against which to test the data.

d) Stability of the Propagation Medium

One important consequence of a velocity-dependent propagation is that low-energy protons travel through the propagation medium later than the high-energy protons and yet suffer the same degree of scattering. The average properties of the propagation medium can, therefore, remain constant for at least 2 days. It is important to remember, though, that changes must have been occurring in the magnetic-field structure during the period of propagation. During the event of September 28, 1961, for example, there was an enhanced solar plasma moving out from the Sun. Where the solar protons are isotropic in interplanetary space, even gross changes in magnetic-field structure can produce only small effects if they take place many mean free paths from the point of observation. Only changes in magnetic-field structure occurring near the satellite could strongly influence the measured intensity. We suggest that the character of the September 10, 1961, event was largely determined by such effects, dominating the intensity versus time character more than the dispersion that otherwise should have been present. One can only speculate at this stage on the details of the mechanism producing time-dependent effects.

e) Local Disturbances of the Propagation Medium

As was mentioned above, the periodic intensity fluctuations are almost certainly a result of magnetic-field structure in the region of interplanetary space near the Earth. The fluctuations could result from, for example, adjacent regions of strong field and weak field constituting a trapping region or "magnetic bottle." Such regions would exclude some incident particles, thereby lowering the particle density in the region of the weaker field. Such regions might eventually become filled as a result of scattering from magnetic

irregularities, and, in fact, the magnitude of the fluctuation does decrease with time. This mechanism does not account for the regularity of the fluctuation unless there is postulated a characteristic wave motion of interplanetary plasma. The wave motion may not be a property of all interplanetary plasma but may be confined to the region near or immediately within the quasi-stationary bow wave postulated by Axford (1963) and others. They pointed out that interaction between the solar wind and the magnetosphere should create a bow wave standing several Earth radii from the magnetosphere on the sunlit side of the Earth; this phenomenon was recently observed with a plasma detector (Bridge, Egidi, Lazarus, Lyon, and Jacobson 1964) and a magnetometer (Ness, Scarce, and Seek 1964) on Explorer XVIII. All solar-proton measurements reported here were made outside the magnetosphere but behind this bow wave. It is possible that the modulation of solar-proton intensity was confined to this region alone, but the fact that the dimensions of this region are comparable to or smaller than the radii of curvature of protons of the energies studied leads one to suspect that the modulation was due to regular structure in the solar wind.

Fluctuations with a period of approximately 1 hour were noted in the Explorer X magnetic field and plasma data (Heppner, Ness, Scarce, and Skillman 1963; Bonetti, Bridge, Lazarus, Rossi, and Scherb 1963) where they were interpreted as a result of the passage of the space probe in and out of the pulsating boundary of the magnetosphere. Mathews, Tambyahpillai, and Webber (1961) noted fluctuations with a period of 1.25 hours in neutron monitor records of the event of November 12, 1960. They suggested that these fluctuations were a direct result of pulsating decreases in the horizontal component of the Earth's field measured at the equator. Winckler, Bhavsar, and Peterson (1960) also observed similar fluctuations in balloon measurements of solar-proton intensity. All of these forms of fluctuation may have been due to the same cause, namely, a regular structure inherent either in the interplanetary plasma density or in its geomagnetic interaction in the region between the bow wave and the magnetosphere.

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