[20]Because of cylindrical symmetry about the beam axis, the physically relevant variable is $\varphi_{c.m.}-\varphi_\gamma$.

[21]A. Donnachie and P. J. O'Donnell, Nucl. Phys. 53, 128 (1964).

[22]P. F. M. Koehler, K. W. Rothe, and E. H. Thorndike, Bull. Am. Phys. Soc. 11, 303 (1966).

[23]Recent measurements at 158 MeV (W. J. Shlaer, private communication) show that the anisotropy in $\varphi_{c.m.}-\varphi_\gamma$ persists down to that energy. The required corrections to the results of Ref. 15 of 20% to 100% have been made in the comparison of cross sections at 204 and 158 MeV.

OBSERVATIONS ON THE PROPAGATION OF SOLAR-FLARE ELECTRONS IN INTERPLANETARY SPACE*

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Recently, Van Allen and Krimigis[1] measured fluxes of electrons with energies of 40 to 150 keV in interplanetary space following solar chromospheric flares. The flux-versus-time profile of these events strongly suggests that the electrons had undergone propagation by diffusion in some spatial region. These authors assume that the diffusion took place in interplanetary space and showed that the flux-versus-time behavior could be empirically fitted to a simple, isotropic diffusion equation. The purpose of this Letter is to report additional examples of solar-flare electron events and to show that the propagation of electrons in the neighborhood of the earth is highly anisotropic in two respects. The observations were made from the first and third interplanetary monitoring platform satellites during 1964, 1965, and 1966. The University of California experiment consists of two Geiger-Müller tubes and an ionization chamber. One of the counter tubes is used in conjunction with a high atomic number scattering foil so that its directional response is to electrons only. With this apparatus it is possible to identify and measure fluxes of protons and electrons in pure or mixed beams provided that the counting rates due to the particle fluxes are comparable with or larger than the counter backgrounds. A description of this apparatus has been previously published.[2]

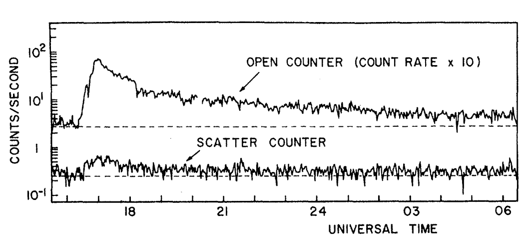

FIG. 1. The solar-flare electron event of 8 October 1965.

We have identified a total of eight solar-flare electron events to date. These include two of the events observed on Mariner IV and already reported by Van Allen and Krimigis.[1] The general features of solar electron fluxes which have propagated to the earth are illustrated here in Figs. 1 and 2. These events are seen to be characterized by a rapid buildup of flux requiring 15 to 30 minutes followed by a slow decay over many hours. This behavior also characterized the events studied by Van Allen and Krimigis. All known solar electron events to date are summarized in Table I. Included there are not only the events by us but the events of Van Allen and Krimigis. Table I also gives information on the associated solar flares obtained from the ESSA-ITSA Bulletin, Pt. B, Solar and Geophysical Data. Inspection of this table leads to the following conclusions:

(1) All but one of the solar electron events are clearly associated with solar flares. The associated flare is often accompanied by radio noise and sometimes by x-ray emission. The appearance of the electrons is delayed from 23 to 55 minutes with respect to the radio burst, or in cases when that has not been reported, with respect to the flare maximum. These time delays are reasonable in view of the fact that the travel time of an unscattered 50-keV electron with small pitch angle from sun to earth along the interplanetary field line is 24 minutes.

(2) The importance of the flares is seen to be small in most cases. Thus 1−, 1, and 1+ flares are able to accelerate and eject large numbers of energetic electrons.

(3) The flares ejecting the electron fluxes occur in several different plage regions. Most

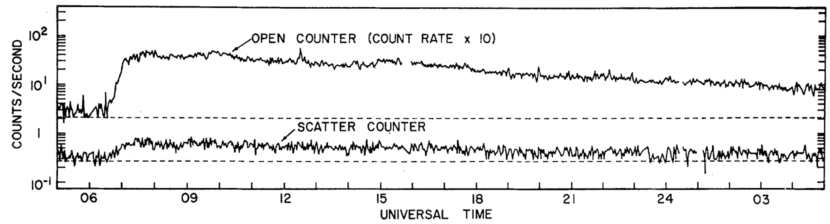

FIG. 2. The solar-flare electron event of 27 December 1965.

of these regions are in the solar northern hemisphere, but one electron event originates in the south. The same plage region does give rise to more than one electron-emitting flare. This occurred in December 1965 when three such flares appeared in a single plage region. The events in mid-January and mid-March 1966 have a different character than the first eight events in the table. The solar flares in this case are near the central meridian or somewhat to the east. These solar electrons are associated with the great radio-noise emission which covered a large fraction of the visible disk. On both these occasions, a series of several solar electron injections were observed. A full discussion of these events will be reserved for a future publication.

A result which shows the control of the interplanetary field over the electron fluxes also follows from the table. The flares occur, with one exception, at westerly solar longitudes ranging from 29 to 84°W. Four of these flares occur within 10° of 60°W. This result is of great interest since many flares of importance 1− and greater accompanied by radio emission and x-ray emission have occurred distributed rather uniformly in longitude over the entire visible solar disk. It must be presumed that many such flares ejected fluxes of electrons of energy >40 keV which were then unable to reach the earth where they would have been detected by our experiment. It is clear that special conditions must be met in order for these electrons to propagate from the sun out to distances the order of 1 A.U. The interpretation given to this result is based on the large-scale structure of the interplanetary field. There are theoretical[3] and observational[4] grounds for believing that this field lies within a few degrees of the ecliptic plane but is curved into the shape of an Archimedean spiral. The angle between the line of force and the sun-earth line a distance r from the sun is given by

$$\psi = \tan^{-1}(r\omega/v),$$

where ω is the angular velocity of the solar rotation and v the speed of the solar wind. The average velocity for the solar wind during the time of the measurements being discussed here is 350 km/sec (sun-earth travel of 4.5 days). The angle ψ is then about 50°. In 4.5 days the sun has rotated 58°. The arrival of electrons at the earth only from flares near 60°W solar longitude can now be understood if the particles travel along the interplanetary field lines.

From this conclusion the following picture can be formed of the region in interplanetary space occupied by the electrons ejected from small solar flares: It is bounded by a curved conical surface with half-opening angle of 15° to 20°. The axis of the cone is a line curved in the same manner as an interplanetary field line.

We also find that within this cone of propagation a greater flux of electrons comes from the direction of the sun than from the antisolar direction even late in these solar electron events. This result follows from analysis of the counting rates of the two Geiger-Müller tubes which point in different directions. One detector has a full opening angle of 60° and points at a direction 64° off the spin axis of the satellite. This counter has a directional response to electrons of energy >45 keV but no directional response to protons due to the scatter geometry arrangement. A second Geiger tube with full opening angle of 45° detects electrons at >40 keV and protons at >550 keV. For the 27 December 1966 solar-electron event, the counter in scatter geometry measured about 50% more flux than the open detector. Since the counter in scatter geometry has a higher electron-energy threshold, this observed difference in flux cannot be accounted for by the energy spectrum. The presence of protons with energy below 25 MeV which could enter the open counter directed along the spin axis would reduce the measured value of the anisotropy of the electrons. Therefore, the degree of anisotropy we obtain is a lower limit. The true electron anisotropy may

Table I. The solar electron events known to have occurred up to early 1966.

Date	Electron arrival time	Peak flux > 40 keV $(cm^2 sr\ sec)^{-1}$	Importance of associated flare	Flare begins	Flare maximum	Flare ends	Flare location	McMath plage region	2800-Mc/sec radio emission	Electron delay time minutes
16 March 1964[a]	1640 UT	150	1	*E*1555	1608	1656	N05 W75	7182	Peak at 1610 UT (intense)	38
25 May 1965[b]	2312[c]	80	1	2240	2245	2251	N19 W69	7809	2242.8 (moderate)	33
5 June 1965[b]	1908[c]	180	1^-	1807	1813	1834	S12 W50	7842	1810-1822 (intense)	39
13 June 1965[b]	0258	10	No flare reported before 0255 No flare patrol 0130-0135						No reports to date	
8 October 1965	1628	230	1^-	1603	1607	1612	N21 W84	8005	Peak at 1605.3	31
25 December 1965	0647	250	1^-	0620	0623	0632	N09 W29	8105	No reports to date	32
29 December 1965	1245 ± 20	25	1^+	1125	1200	1235	N10 W60	8105	No reports to date	30
30 December 1965	0106	300	1^-	Before 0029	0035	0123	N09 W68	8105	No reports to date	44
17 January to 28 January 1966	After 0630 UT 17 January	1000	Many flares 16-22 January. Great radio-noise emission during this time.				Near central meridian	8130 8207	Major radio events on 16 and 18 January	...
19 March to 25 March 1966	After 0100 UT 19 March	3000 (0300 UT on 24 March)	Many flares 18-25 March. Much radio-noise emission during this time.				Around central meridian		Many radio events	...

[a]Solar protons also present in this event.
[b]Events originally reported by Van Allen and Krimigis, Ref. 1. 5 June 1965 event also reported by Arnoldy et al., Trans. Am. Geophys. Union 47, 154 (1966).
[c]Arrival at Mariner IV (1.5 A.U.).

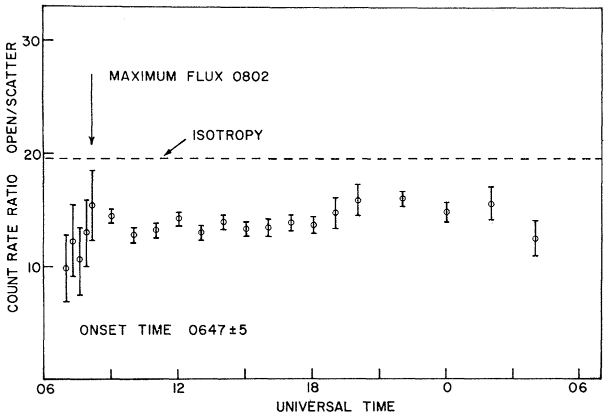

FIG. 3. The anisotropy of solar electrons of 27 December 1965. The value of about 20 on the vertical axis corresponds to isotropy. More electron flux came from directions toward the sun than from directions away from the sun throughout this event.

be larger than 50%. The ratio of the solar particle fluxes detected by the two counters during the 27 December event is shown in Fig. 3. The cosmic-ray background in the two counters has been subtracted before taking the ratios. From Fig. 3 it is seen that the anisotropy is largest at the first arrival of the solar electrons, then decreases as the flux builds up. Following the peak flux the anisotropy maintains a constant value for about 12 hours.

The 8 October and 30 December events also show large initial anisotropy during the flux-buildup phase followed by smaller anisotropy which persists for many hours. In these two cases the count-rate ratios for the first hour are 11 and 7, respectively, while the ratios for the rest of both events is about 18. We emphasize that these large departures from the ratio characterizing isotropic fluxes cannot be accounted for by proton contamination, different energy thresholds, or errors in determining geometric factors. We next relate the direction of the counters with respect to the interplanetary magnetic field on the grounds that those localized spatial anisotropies must be closely correlated with the field direction because of the low magnetic rigidity of these electrons. Taking the magnetic field to lie in the ecliptic plane with a spiral angle of 50°, the axis of the open counter makes an angle of 133° with the field line where 0° is parallel to the field line and pointed inward in the solar system. The counter in scatter geometry which sees the larger flux averaged over many spin periods makes an angle with respect to the interplanetary field line which varies from 69° to 197°. From this it is evident that the flux of electrons moving away from the sun is larger than the flux directed back toward the sun. It is clear from the persistent anisotropy of the solar electrons late in the events that attempts to treat the diffusion as isotropic are not adequate. We also find that the isotropic diffusion theory does not fit our observations particularly at times greater than 4 to 6 hours after the onset of the event. Nonetheless, the electrons appear to have diffused in some spatial region. Since interplanetary space is not likely to be this region judging from the large, observed anisotropies, we suggest that the electron diffusion has taken place in the solar atmosphere, the electrons escape the sun on interplanetary field lines where they are scattered very little, thus accounting for the large anisotropies. This hypothesis is supported by the fact that the solar radio-noise emission is observed to occur from large regions high in the solar atmosphere. We suggest that this electron population is the source of those electrons observed in interplanetary space for several days following solar flares.

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[1]J. A. Van Allen and S. M. Krimigis, J. Geophys. Res. 70, 5737-5751 (1965).

[2]K. A. Anderson, H. K. Harris, and R. J. Paoli, J. Geophys. Res. 70, 1039-1050 (1965).

[3]E. N. Parker, Interplanetary Dynamical Processes (Interscience Publishers, Inc., New York, 1963).

[4]N. F. Ness and J. M. Wilcox, Science 148, 1592 (1965).