THE DEGREE OF ANISOTROPY OF COSMIC RAY ELECTRONS OF SOLAR ORIGIN*

F. R. ALLUM and R. A. R. PALMEIRA
The University of Texas at Dallas, Dallas, Texas
U. R. RAO
Physical Research Laboratory, Ahmedabad, India
and
K. G. McCRACKEN, J. R. HARRIES and I. PALMER
University of Adelaide, Adelaide, Australia

(Received 20 October, 1970)

Abstract. Data obtained by the Explorer 34 satellite regarding the degree of anisotropy of $\gtrsim 70$ keV electrons of solar origin are reported. It is shown that the anisotropies are initially field aligned, and that they decay to $\lesssim 10\%$ in a time of the order of 1 hr. The decays of the concurrent ionic and electronic anisotropies for one well observed event are in good agreement with the diffusive propagation model of Fisk and Axford. The data suggest parallel diffusion coefficients for both ions and electrons that are rigidity independent. From considerations of a long lived electron event, it is shown that the electronic fluxes exhibit 'equilibrium' anositropies at late times. These are interpreted as indicating that convective removal at the solar wind velocity is the dominant mechanism whereby solar cosmic ray electrons ($\simeq 70$ keV) leave the solar system. They also indicate that there is a positive density gradient at late times in a solar electron event. The data suggest that this was established prior to the establishment of a similar gradient for the cosmic ray ions.

1. Introduction

With the introduction of suitable instrumentation in 1963 it became apparent that the electron populations accelerated in solar flares (e.g. Kundu, 1965) could be sampled directly near Earth (Van Allen and Krimigis, 1965; Anderson and Lin, 1966; Cline and McDonald, 1968). By 1967, the detection sensitivity for electrons >40 keV had been improved to the point that the probability of detecting the electron population from a flare became comparable to that of detecting the >1 MeV ionic population (e.g., Lin, 1970a). Since the velocity of 40 keV electrons is $\simeq 0.5\ c$, they propagate rapidly to Earth, arriving $\sim$10–30 min after the observation of the flash phase of the parent flare. Hence, the probability of a spurious correlation with the wrong flare is greatly reduced below that pertaining for the ionic component. That is, on the criteria of sensitivity, and uniqueness, the electron flare event is a more useful indicator of the acceleration of suprathermal particles in a solar flare than is the ionic event.

* This research was supported by the National Aeronautics and Space Administration under contracts NASr-198 and NAS5-9075. The research in India was supported by funds from the Department of Atomic Energy, Government of India and funds from the grant NAS-1492 from the National Academy of Sciences, U.S.A. Support in data analysis was also provided by Air Force Cambridge Research Laboratories, and by the Australian Research Grants Committee.

Solar Physics **17** (1971) 241–268. *All Rights Reserved*

The solar electron event is influenced by features of the interplanetary magnetic field that are of little consequence to the ionic component detected by contemporary instrumentation (i.e. $E > 1$ MeV/nucleon). Thus the scale size of the interplanetary irregularities of majoı importance to the scattering of the electrons ($\simeq 40$ keV) is $\lesssim 0(10^{-2})$ times the scale size of importance for ions of energy >1 MeV/nucleon. Stated in another way, it would be necessary to study 0.01 MeV protons to explore the portion of the interplanetary magnetic field power spectrum that influences 40 keV electrons. Since the velocity of such ions is approximately that of the solar wind itself, their time variation would be completely dominated by convective effects and consequently unsuitable for studies of propagation effects. By way of contrast, convective effects are of minor importance for ~ 40 keV electrons, the near-Earth behaviour being dominated by propagation effects.

In previous papers we have studied the degree of anisotropy of the ionic component of the solar cosmic radiation for 1 MeV $< E \lesssim 90$ MeV (McCracken *et al.*, 1967; McCracken *et al.*, 1968; Rao *et al.*, 1971). In this paper, we report the results of a study of eighteen solar electron events that were observed by instrumentation on Explorer 34 during the period May 1961–March 1968.

2. The Instrument

Our cosmic ray instrument on Explorer 34 has been briefly described by Rao *et al.* (1969), and in considerable detail by Bartley *et al.* (1971). Very briefly, electrons of energy >70 keV are detected by a thin window proportional counter of area 3.1 cm^2, filled with xenon and methane at 1 atmospheric pressure, while low energy protons are measured using a totally depleted silicon solid state detector. A slat type aluminum collimator mounted on the proportional counter serves to define the geometrical response of the counter to 5° full width half maximum in ecliptic azimuth for X-rays, protons up to a maximum energy of 10 MeV, and for electrons up to a maximum energy of 500 keV. The response in ecliptic latitude extends to 60° from the ecliptic plane. The proportional counter itself has an energy resolution of 30% full width half maximum for 5.9 keV X-radiation from a Fe^{55} radioactive source. Table I

TABLE I

Energy characteristics of the Explorer 34 anisotropy detector

Detector	Particles	Energy range	Spectral data
Solid state	Protons	0.7–55 MeV	Differential, 6 channels
Proportional counter	Protons Electrons X-rays	$>$ 2 MeV $>$ 70 keV 2–12 keV	Integral Integral Differential, 2 channels

summarizes the energy response characteristics of various elements of the detector for different types of particles and radiation.

The pulses from the various detectors are accumulated into one of eight binary counters, depending upon the direction of viewing of the detector at the time. In this manner, the counting rates corresponding to eight different directions in space are obtained as the spacecraft spins about its axis, which is normal to the ecliptic. Figure 1

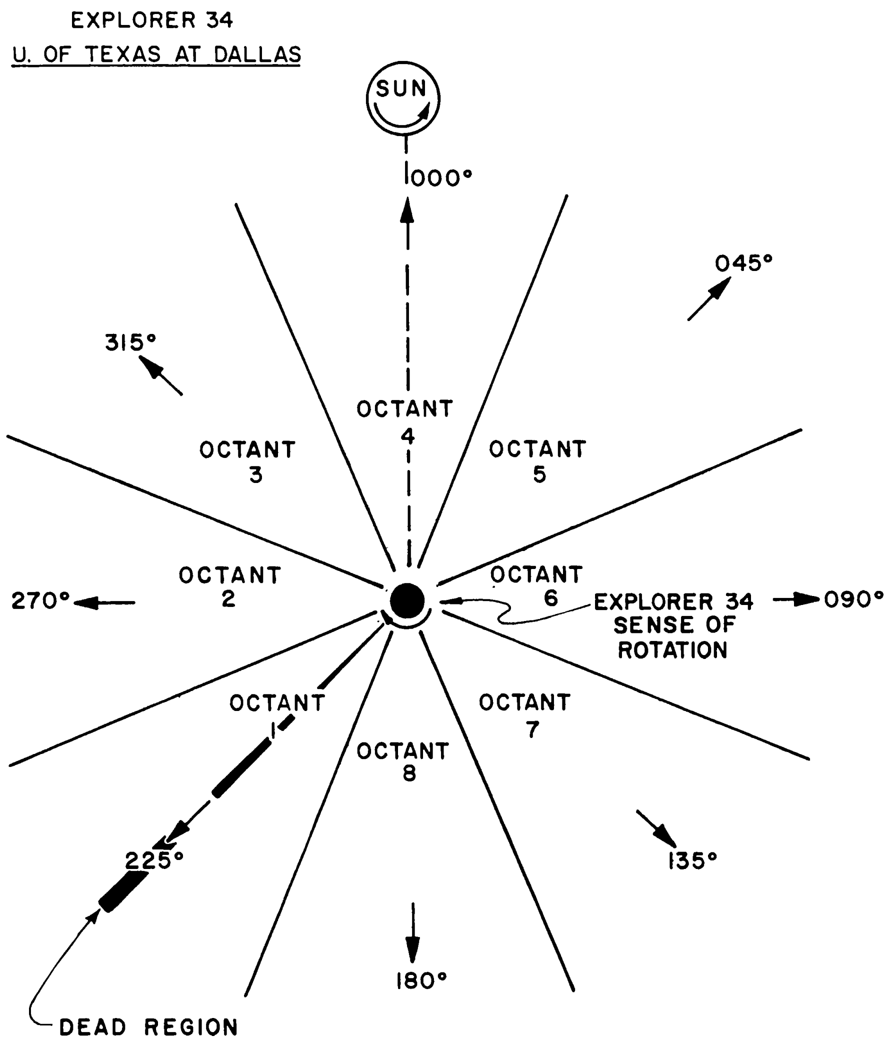

Fig. 1. The mean directions of viewing of the eight octants relative to the spacecraft-Sun line. These mean directions lie in the ecliptic plane.

defines the relationship between these directions, and the spacecraft-Sun line. All eight mean directions lie in the plane of the ecliptic.

The eight directional accumulators are time shared between the proportional counter, the solid state detector, and the other portions of our instrument. All the electron data of interest herein are accumulated over intervals of 9.28 sec, during, which time data are obtained from all eight directions. After 81.92 sec have elapsed, another such measurement is made. That is, the data constitute essentially instantaneous 'snapshots' of the electron anisotropy, repeated every 81.92 sec.

3. The Identification of Electron Events

The proportional counter responds to electrons, solar X-rays and also high energy protons. The response to a solar X-ray event, however, is highly anisotropic, the only octant exhibiting a significant response being that centered on the Sun (octant 4). Consequently, the proportional counter data from octant 4 are not used in the study of solar electrons. The data from the remaining seven octants are essentially free from

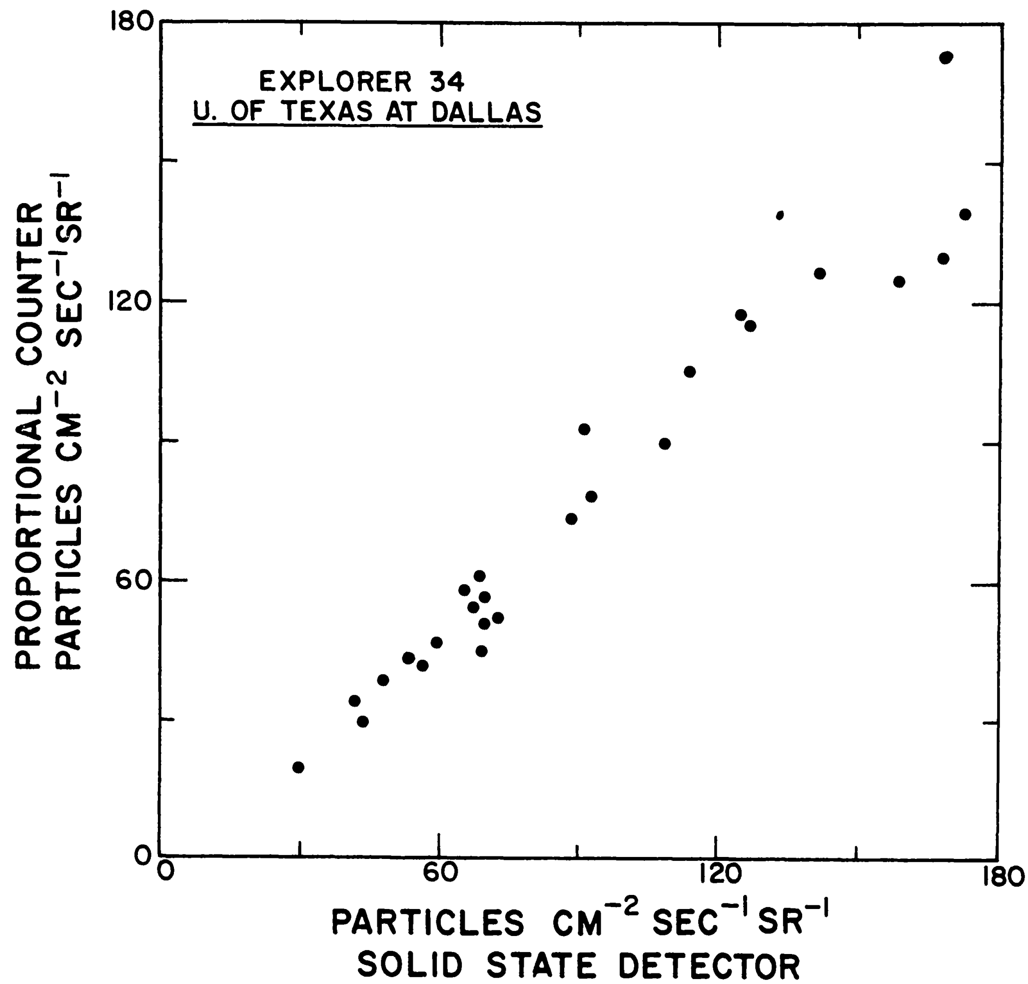

Fig. 2. Illustrating the agreement of the flux measurements made by the solid state detector and proportional counter for 'pure' proton events of 1967, August 10 and September 19. Lin (1970a) has reported an electron event of maximum flux, 150 particles (> 40 keV) cm^{-2} sec^{-1} ster^{-1}, on September 18, commencing around 0500 UT. At that time, the proportional counter response on Explorer 34 was contaminated by the presence of trapped electrons. The data used for the September event in the above analysis were obtained some 42 hr later. Allowing for the normal decay process and for our higher threshold energy for electrons, the response of the proportional counter at this later time (> 2300 UT, September 19) would be due entirely to protons.

any X-ray contamination, and correspond to the sum of the responses to the cosmic ray electrons and ions.

As summarized by Table I, the proportional counter is sensitive to protons of energy >2 MeV, while the solid state detector responds to protons with energies $0.7 < E < 55$ MeV, and is essentially insensitive to electrons. The similarity of the proton response characteristics of the two detectors therefore suggests that the solid state data should permit removal of the protonic response from the proportional counter data.

The validity of the above premise is demonstrated by Figure 2, in which the particle flux as derived from the proportional counter is plotted against that derived from the solid state detector, for two flare events 1967, August 10 and 1967, September 19 for which no electron component was evident at Explorer 34. The correlation coefficient between these data is 0.95, indicating the validity of a correction for protons based upon the data from the solid state detector which has the form

$$F_e = F_p - kF_{ss} \tag{1}$$

where F_p and F_{ss} are the particulate fluxes observed by the proportional counter and

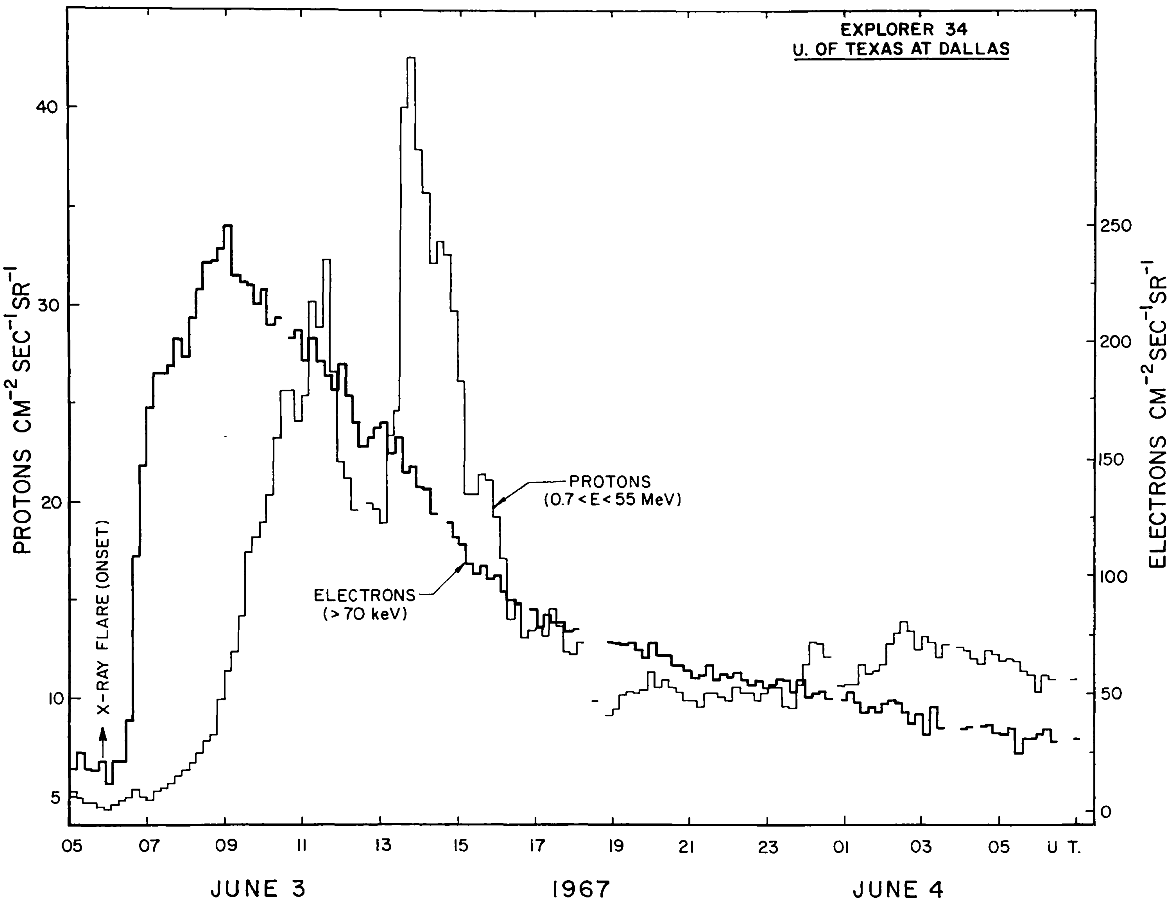

Fig. 3a. Illustrating the difference in time profile, and difference in particulate flux, for the proton (0.7–55 MeV) and electron (> 70 keV) fluxes on 1967, June 3. The 11 min average fluxes are plotted; for protons, the average is over all 8 octants; for electrons, octant 4 is omitted from the average. The electron data are expressed as deviations from the pre-event level.

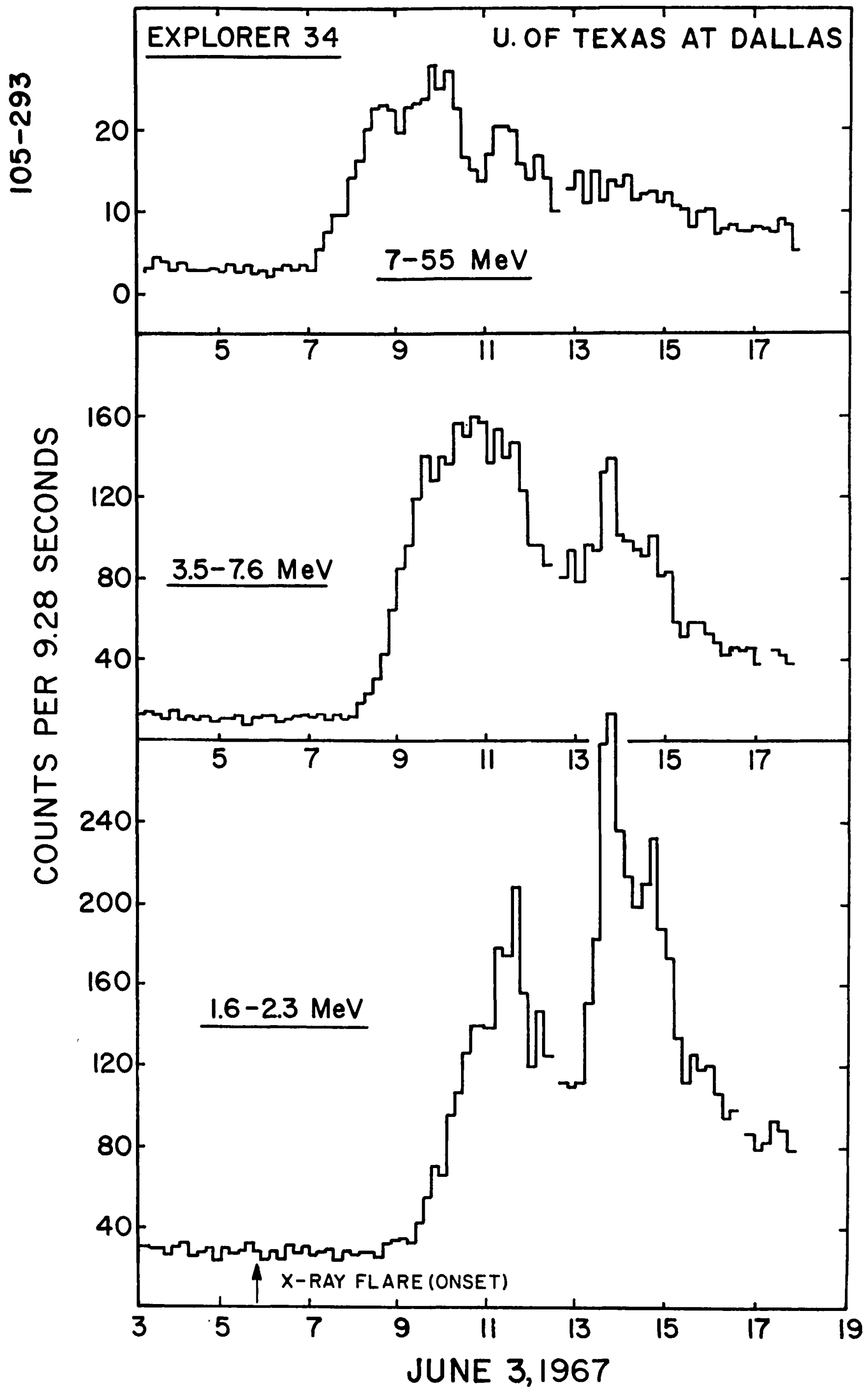

Fig. 3b. Illustrating the differences of onset time, and of time profile, for the proton fluxes in the energy range 1.6–55 MeV.

solid state detectors, respectively, k is the regression coefficient derived from Figure 2, ($k=0.94$) and F_e is the estimated electron flux.

Figures 3a and 3b display the proportional counter, and solid state detector data for a flare event which occurred on June 3, 1967. It will be noted that there is a marked time dispersion in the onset of the proportional counter event (0634 UT), and those recorded by the various energy levels of the solid state detector (0710–0920 UT). The several species of solid state detector data are consistent with the hypothesis of protons leaving the Sun at ~0610 UT, and suffering dispersion over the 1.3 AU Sun-Earth path length on account of their different velocities. This interpretation therefore indicates that the proportional counter response starting at 0634 UT is primarily due to solar electrons. A further indication that the proportional counter response starting at 0634 UT is primarily due to electrons is to be found in the fact that the absolute particulate counting rates for the proportional counter are a factor of $\simeq 8$ times that of the $0.7 < E < 55$ MeV proton rate recorded by the solid state detector.

In view of the high correlation evident in Figure 2, we estimate that the errors incurred in the correction given in Equation 1 for the protonic contribution to the proportional counter data are $\simeq 10\%$ of the absolute protonic flux. Since the absolute magnitude of the electronic flux is frequently $\simeq 10$ times the protonic flux, this implies $\simeq 1\%$ residual contamination of the electron data. This is of no consequence in the studies that follow.

4. The Anisotropy Measurements

To establish an in-flight verification of the accuracy of the electron anisotropy measurements, we have compared the anisotropy vectors calculated from the pro-

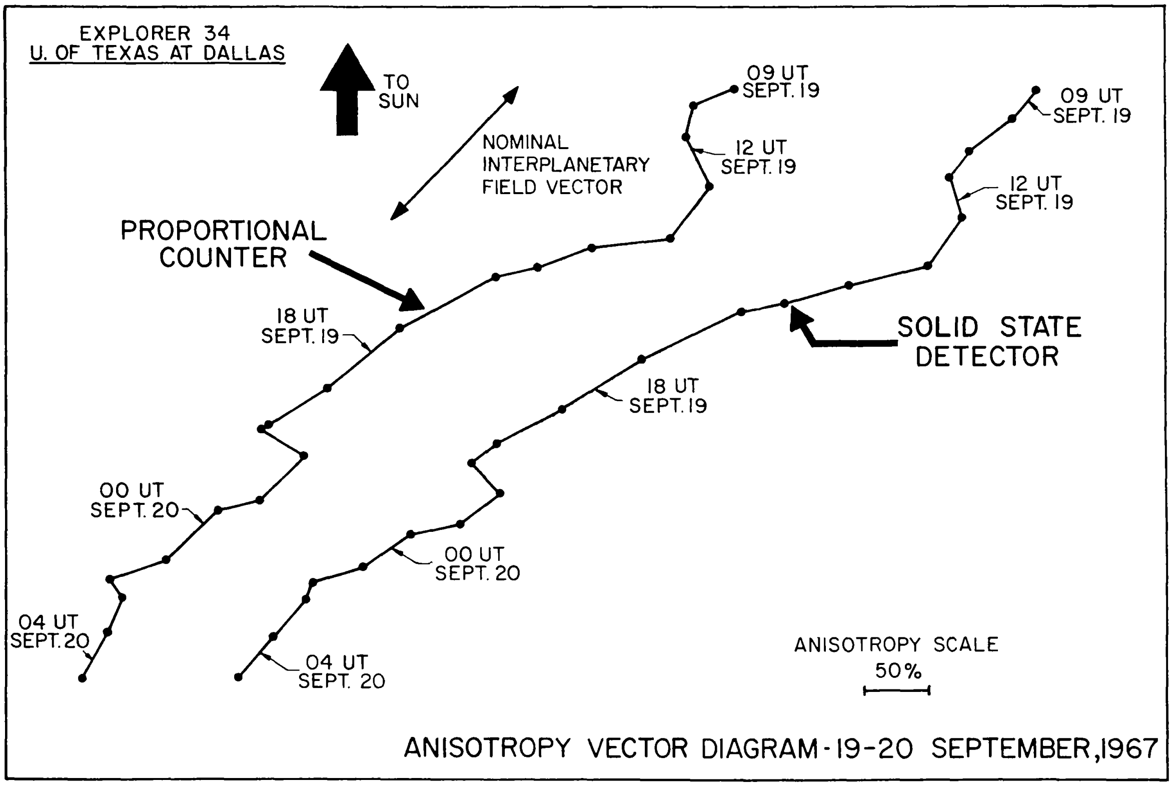

Fig. 4. The anisotropy vector diagram for the 'pure' proton event of 1967, September 19. This diagram is constructed by vector addition of individual anisotropy vectors computed on an hourly basis from both the solid state detector and the proportional counter data. This diagram shows the excellent agreement in the calculated anisotropies between the two independent detection systems when both are responding to the same species of particle influx.

portional counter with those derived from the solid state detector during solar flare effects which were seen in the ionic component, alone (i.e. no electrons). Figure 4 presents such a comparison for the event of 1967, September 18–20. It is evident from the figure that the anisotropy measurements made by the two detectors show a good hour to hour agreement both in amplitude and direction. The correlation coefficients between the amplitude and direction of maximum of the anisotropies of the two species of data are found to be 0.9 and 0.8 respectively.

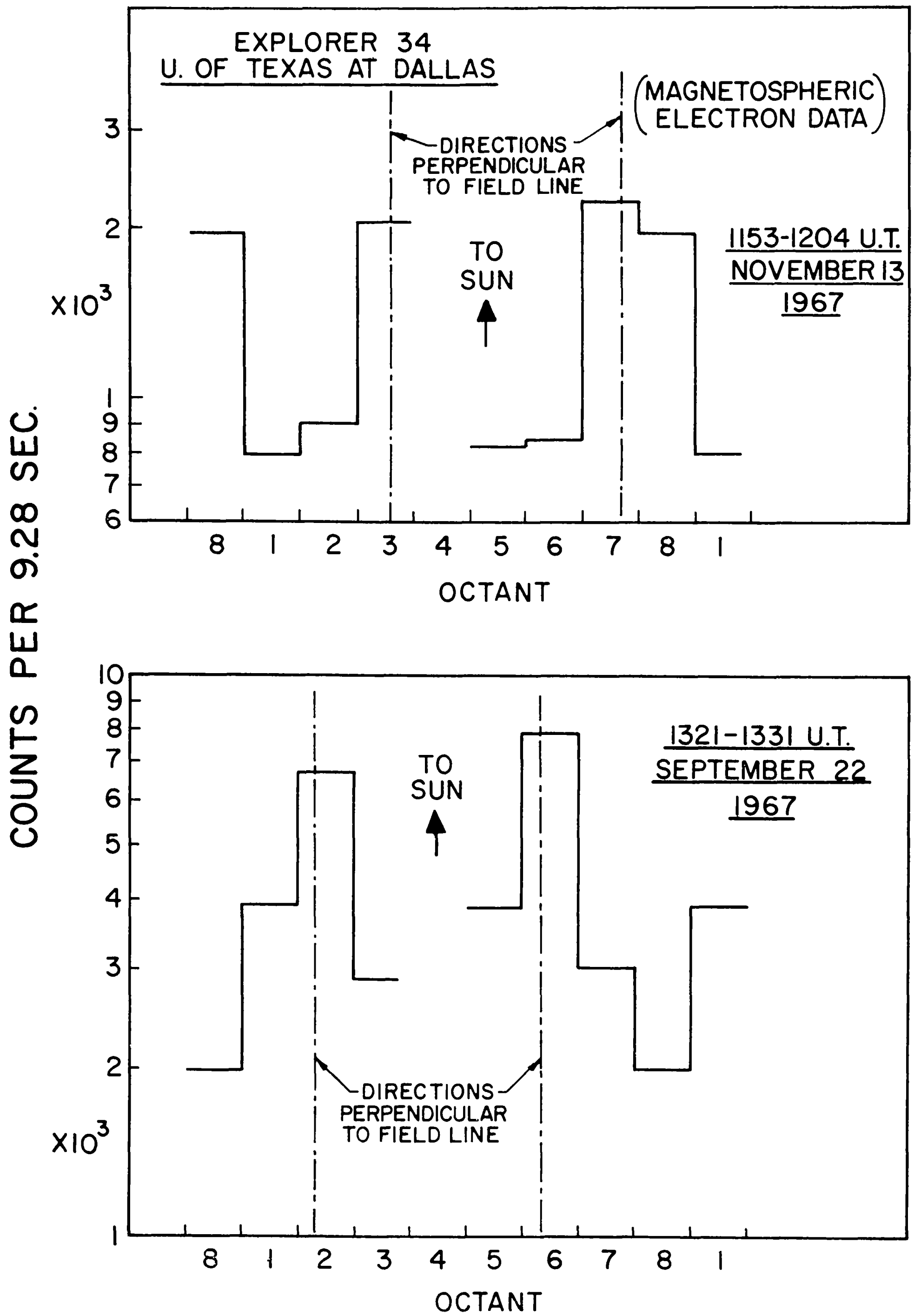

Fig. 5. The response of the electron anisotropy detector to the anisotropic electron fluxes in the magnetosphere. The normal to the magnetic field in the plane of the ecliptic is indicated.

A strong bidirectional anisotropy was observed by the solid state detector during the period 1121–1350 UT on September 20, 1967. The average amplitude and phase of the second harmonic of 28% incident from 40° E of the spacecraft-Sun line in the solid state detector data are in good agreement with the 20% amplitude and 50° E phase of the second harmonic observed by the proportional counter for the same period.

A further verification of the correct operation of the proportional counter has been made by examining its ability to detect a strong bidirectional anisotropy of quasi-trapped electrons within the magnetosphere when the detector is at a suitable orientation relative to the magnetic vector. Between 1321–1332 UT on September 22, 1967, and 1153–1204 UT on November 13, 1967, the direction of the magnetic field as observed by the magnetometer on the same satellite was within 10° of the plane of ecliptic. A trapped electron population in this field should therefore show a strong bidirectional anisotropy in the proportional counter data with the maximum fluxes incident from the directions perpendicular to the field line. Figure 5 presents pertinent proportional counter data for the two periods, and it is clear that both sets of data show strong bidirectional anisotropies, in reasonable agreement with the observed direction of the geomagnetic field vector. On both the above occasions the satellite was on the Sunward side at a radial distance of 63000 km and 53700 km respectively, thereby ensuring that the proportional counter is responding essentially to a pure electron flux.

A portion of the observing time of the proportional counter was devoted to measuring the azimuth of the detector axis for selected counter pulses, with an angular accuracy of 1°. When these data are averaged over $\simeq 6$ months, the X-ray source Sco X-1 is clearly resolved. The position and observed FWHM of the Sco X-1 response is further evidence of the valid operation of the anisotropy measurements based on the proportional counter data for the whole period of data considered herein (see Figure 4 in Bartley *et al.*, 1971, and Harries, 1969).

5. The Statistics of Occurrence of Electron Events

During the period 25 May, 1967–March, 1968, our experiment on Explorer 34 observed 18 solar electron events (see Table II) as compared to more than 40 solar proton events (see Rao *et al.*, 1971). The relative infrequency of electron events in our data is attributable to (a) the high threshold energy (70 keV) and (b) the high background counting rate, and consequent high threshold of our detector; namely 10 particles/(cm^2 sec ster) as compared to the threshold of 0.2 particles/(cm^2 sec ster) for the solid state detector.

Table II summarizes the data relevant to the solar electron events observed by our instrument, while Figure 6 presents the frequency of electron events and the peak electron flux as a function of the position of the parent flare on the solar disc. The figure shows that there is a strong tendency to observe solar electrons when the parent flare is on the Western portion of the solar disc, the maximum occurrence corre-

TABLE II

Summarizing the characteristics of the electron events observed by the Explorer 34 electron anisotropy detector. The intensity rise times quoted are (1) initial onset to 60% of maximum intensity, (2) from 10% to 90% maximum intensity. The decay time is the period from maximum, to one third maximum intensity. The anisotropies quoted are (a) during the rise time and (b) at the time of maximum electron flux.

Date	Onset time			Flux $(cm^2 \text{ sec ster})^{-1}$		Optical flare				Rise time		Decay	Anisotropy	
	Electrons	Protons	X-ray	Electron	Proton	Time	Imp.	Region	Coord.	60%	10–90%	time ⅓ of max.	Onset	Max.
1967														
June 03	0634	0712	0548	210	30	Not identified				26 m	88 m	12.5 hr	40%	7%
June 06	~0610	~0627		>400[a]	160	Not identified								
June 12	Long lived		Event	≈155	11.3									
July 05	0810	0850	0740	48	4	Not identified				19 m	26 m	4.0 hr		
July 30	0522	0710	0510	90	3	0508	1B	8905	N24, W26	7 m	8 m	1.6 hr	85%	
Aug. 02	1743		1726	90		1726	1N	8905	N26, W76	4 m	7 m	0.17 hr		
Aug. 03	0937	1620	0922	125	25	0918	1N	8905	N26, W82	29 m	32 m	2.1 hr	17%	12%
Oct. 30	0017	0300	2342	100	28	2347	1B	9034	N10, W90	28 m	110 m	16.0 hr	60%	26%
Nov. 02	~1000	~1040	0853	210	108	0855	1B	9047	S18, W02	150 m	240 m	19.0 hr		
Nov. 04	1213	1325	1151	105	7	1152	1B	9047	S18, W33	11 m	27 m	2.5 hr	30%	12%
Nov. 07	0226		0156	12	1.4	0157	−N	9047	S15, W51					
Nov. 10	Long lived		Event	≈230	≈120									
Dec. 03	~0910	0940	0853	[a]	250	Not identified								
Dec. 16	0448	0520	0247	[a]	232	Not identified								
1968														
Jan. 11	~2000	0110	1658	75	20	1659	1B	9145	S25, W39					
Feb. 01	1820		1758	40	2.2	1759	−B	9184	N09, W34					
Feb. 08	1410	1450		140	25					< 22 m	?	2.7 hr		5%
Feb. 17	0310	0520	0251	190	30	0251	1B	9204	N17, W47	21 m	33 m	~ 4.7 hr		6%

[a] Proportional counter response contaminated by presence of high energy protons (> 35 MeV).
[b] Proportional counter response contaminated by magnetospheric electrons.

sponding to about 45°W longitude relative to the spacecraft-Sun line. The distribution is similar to that reported by Lin (1970a), and agrees with the distribution of parent flares that give rise to ionic cosmic ray increases (see review, McCracken and Rao, 1970).

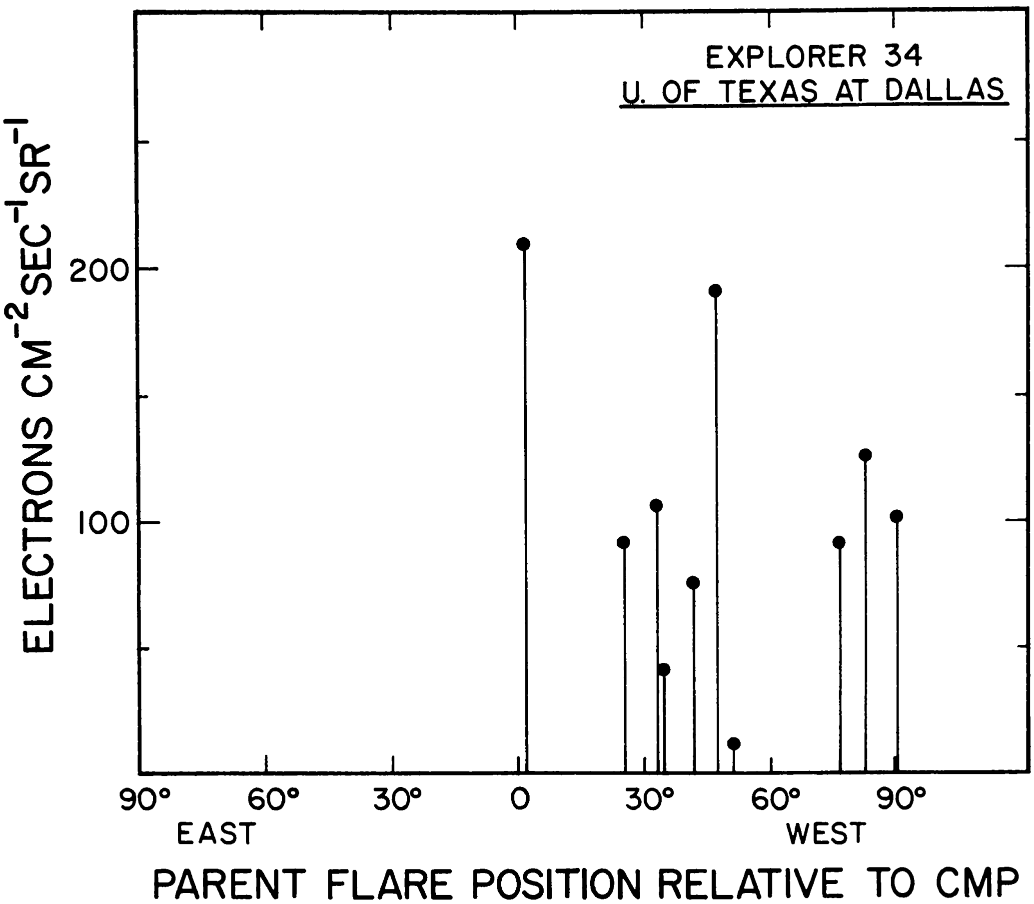

Fig. 6. Demonstrating that the probability of observing an electron flare effect is greatest when the parent flare is on the Western portion of the solar disc. Only events that are unambiguously identified with solar flares (see Table II) are plotted herein.

Figures 3, 8 and 10 display the temporal dependence of the electron and proton fluxes for three events that are representative of the totality of our data. Data pertaining to the parent flares, the onset and rise time of the cosmic ray events, and the degree of anisotropy are listed in Table II. As noted previously, electron events exhibit simple time profiles, rapid onsets, and rapid increases to maximum intensity; while the proton events exhibit complex temporal variations at energies $\simeq 1$ MeV and frequently exhibit dispersion in onset time consistent with particle release near the Sun at about the time of the maximum of the soft X-ray burst (as provided by octant 4 of our proportional counter data). These characteristics are all well known from previous work (e.g., as reviewed by McCracken and Rao, 1970).

6. The Degree of Anisotropy of the Electron Fluxes

To provide a quantitative measurement of the anisotropy phase and amplitude, a sinusoid has been fitted to each set of directional data points. As noted earlier, octant 4 is omitted from this calculation. Anisotropy phases and amplitudes were also calculated in this manner for earlier spacecraft data (McCracken *et al.*, 1967).

To display the temporal evolution of the electron anisotropy, and to display the consistency of the individual measurements, the anisotropy amplitudes and phases are used to construct anisotropy vector diagrams (e.g. McCracken and Ness, 1966; McCracken *et al.*, 1967; Rao *et al.*, 1967). The anisotropy vector diagrams corresponding to the events in Figures 3, 8 and 10 are given in Figures 7, 9 and 11 respectively. It is clear that the phase of the anisotropy varies with time in a manner which

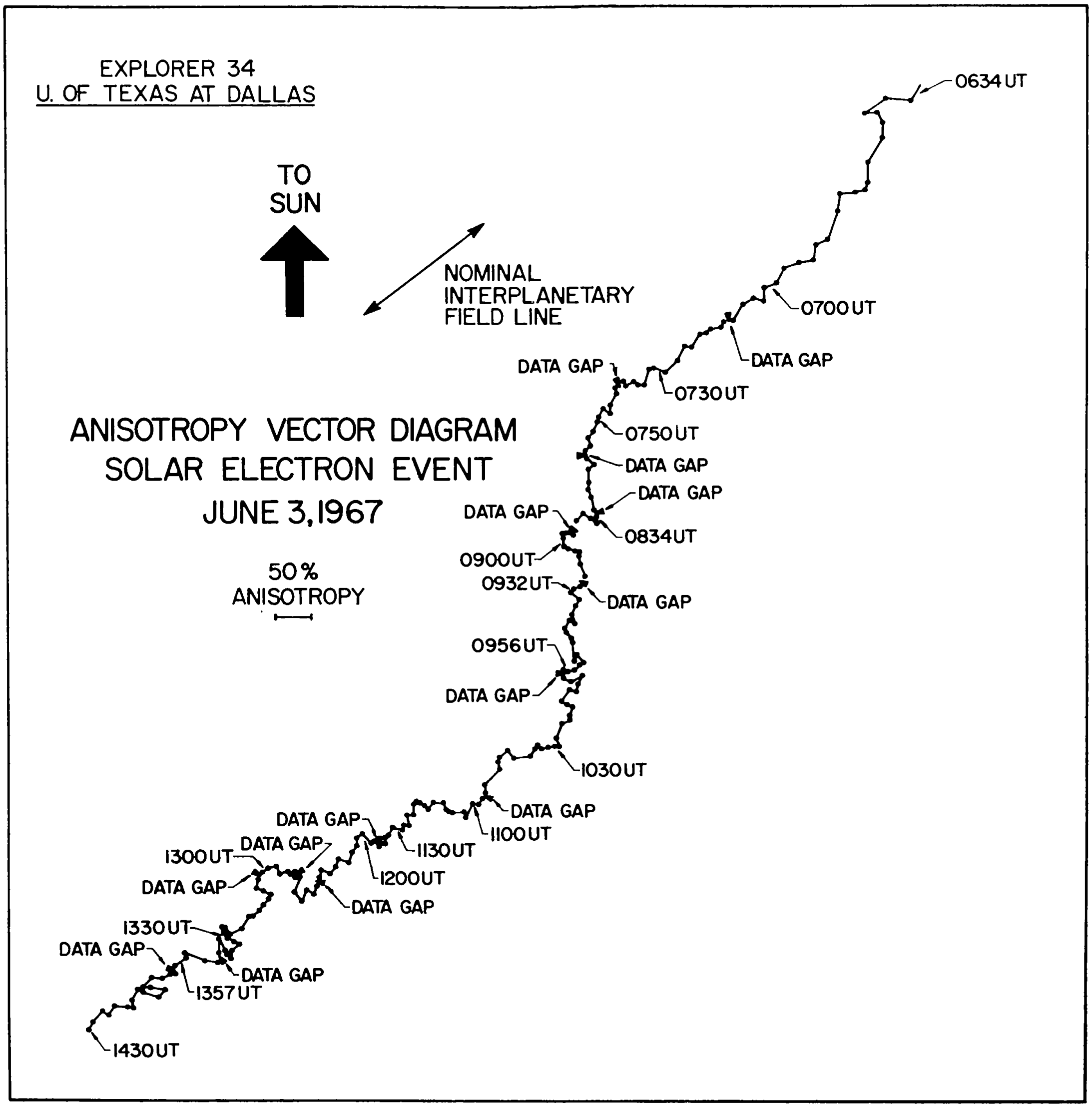

Fig. 7. The anisotropy vector diagram for the electron event of 1967, June 3. This diagram is constructed by vector addition of individual anisotropy vectors computed for each consecutive 9.28 sec sample of data.

is qualitatively similar to that noted for the ionic component. Thus the phase remains essentially constant for periods of hours, or more, and then suffers abrupt changes to a new, quasi-permanent value. In Figure 12 the phase of the electron anisotropy is plotted against the concurrent phase of the ionic anisotropy, and close correlation is evident. The correlation coefficient corresponding to these data is 0.9; with a mean regression coefficient of ≈1.0. Since the anisotropy of the ionic radiation is aligned with the interplanetary magnetic field at early times (McCracken *et al.*, 1968), this implies that the electron anisotropies are field aligned at early times.

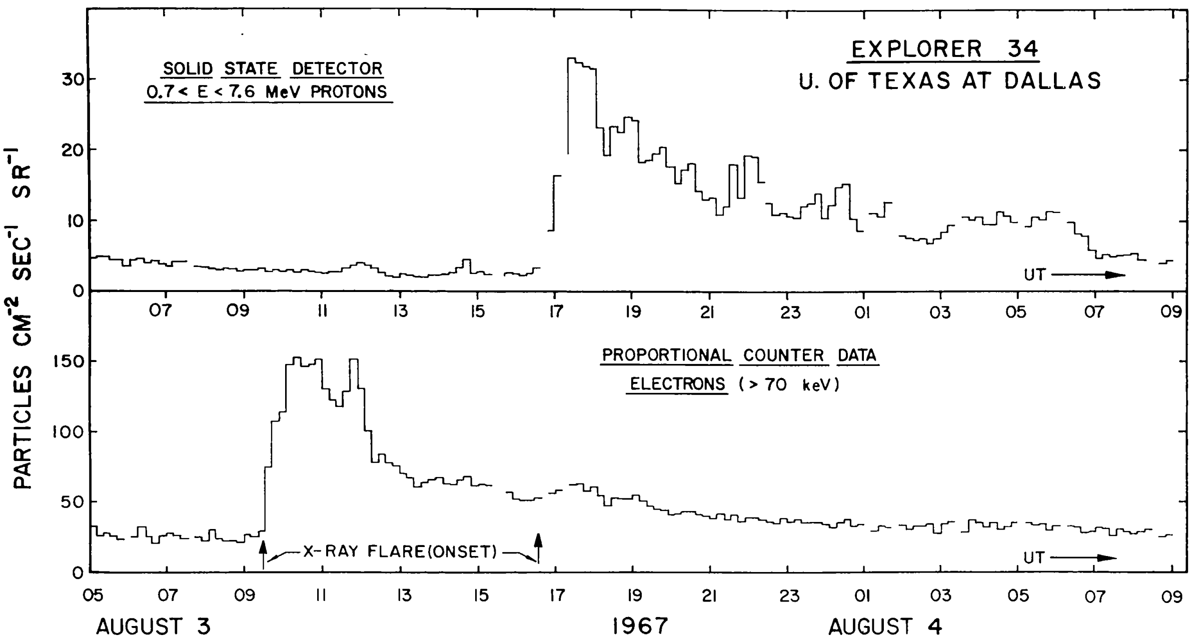

Fig. 8. The temporal dependence of both the electron and proton fluxes during the flare effects of 1967, August 3.

This is constructed in Figure 12 where the phase of the electron anisotropy has also been plotted against the direction of the interplanetary magnetic field measured by the same spacecraft for the 1967, October 30 and 1967, November 4, electron events (we are grateful to Dr. D. Fairfield for supplying these magnetic data). It is clear from both regression relationships in Figure 12 that the electron anisotropy is field aligned at early times. The fact that the phase varies abruptly as demonstrated in Figures 7, 9 and 11 indicates that the electron fluxes stream in the filamentary magnetic field in the same manner as does the ionic cosmic radiation (Bartley *et al.*, 1966).

We have reported previously (Rao *et al.*, 1969) the relative absence of an anisotropy in the electron fluxes in the 1967, August 3 flare event, and Van Allen has foreshadowed a paper reaching similar conclusions (Van Allen and Ness, 1969). Tables II and Figures 7, 9 and 11 provide further information in this regard. Thus it is clear from Figures 7, 9 and 11 that the amplitude of the electron anisotropy is small (≃10 to 20%) compared to the large anisotropies (≃50 to 100%) commonly noted

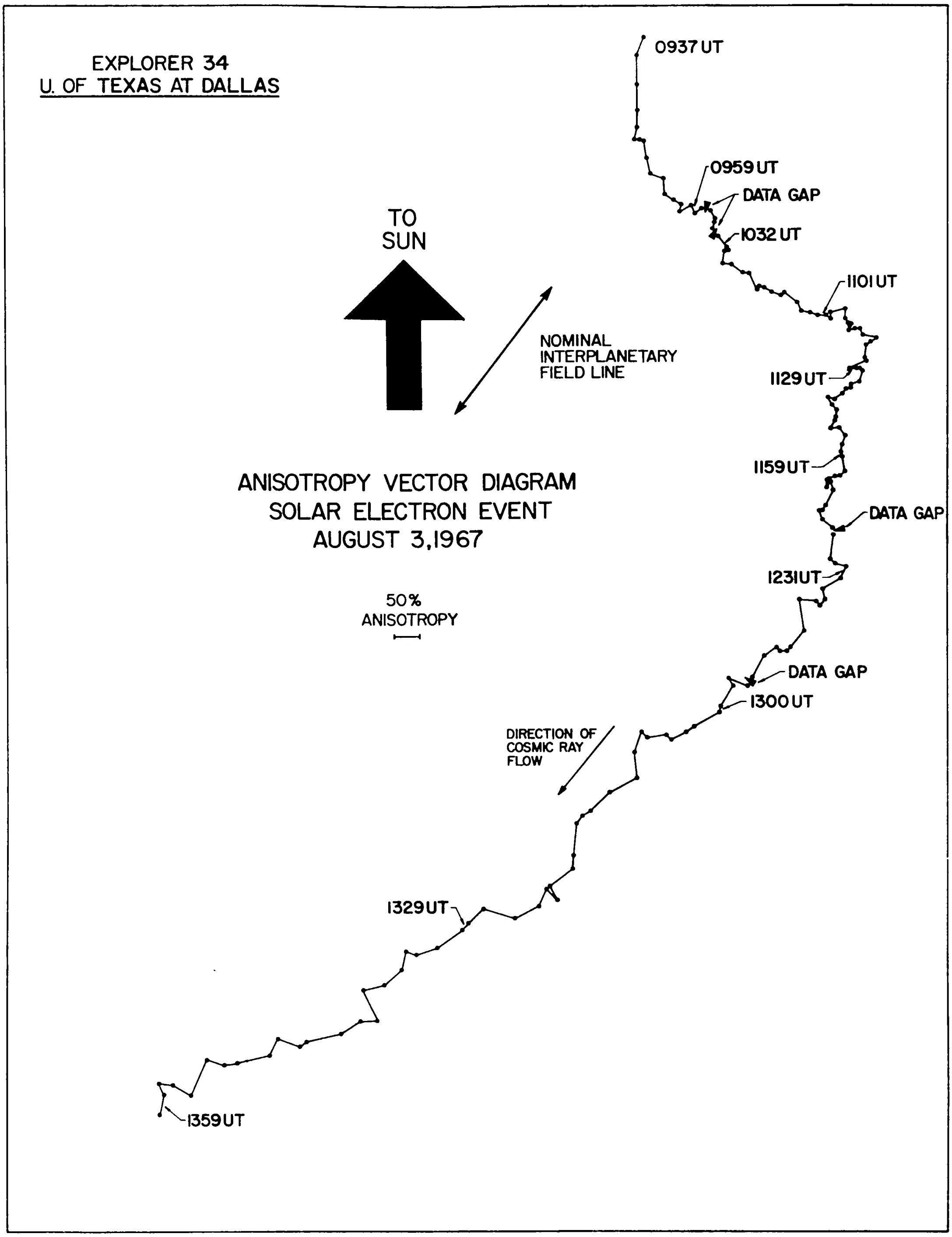

Fig. 9. The anisotropy vector diagram for the electron event of 1967, August 3. Further details are identical to those noted for Figure 7. At 2345 UT on August 3, the observed anisotropy is less than 10%.

in the 0(1–10 MeV) ionic radiation of solar origin for 0(10 h) after the onset of a flare effect.

The anisotropy amplitudes for both the electron and proton (7–55 MeV) radiation from the 1967, June 3 flare effect are plotted versus time in Figure 13. It will be noted that while the electron anisotropy was initially $\gtrsim 30\%$, it decreased very rapidly to a value of $\lesssim 10\%$. By way of contrast, the ionic anisotropy remained $\gtrsim 30\%$ for many hours. A close inspection of our data from all 16 electron events, as summarized in Table II, indicates that the data in Figure 13 are quite typical, in that the initial anisotropies of the electron fluxes are considerable (30 to 60%), but that they decay to $\simeq 10\%$ within an hour or two. The only minor exception to this rule is the event of 1967, October 30 (Figures 10 and 11), for which the anisotropy remained $\gtrsim 30\%$ for 3 h after the start of the electron increase. We note that this was a relatively long lived electron event.

Fisk and Axford (1969) have considered the time dependence of the anisotropy of solar cosmic rays using a model that assumes guiding center motion, plus simple pitch

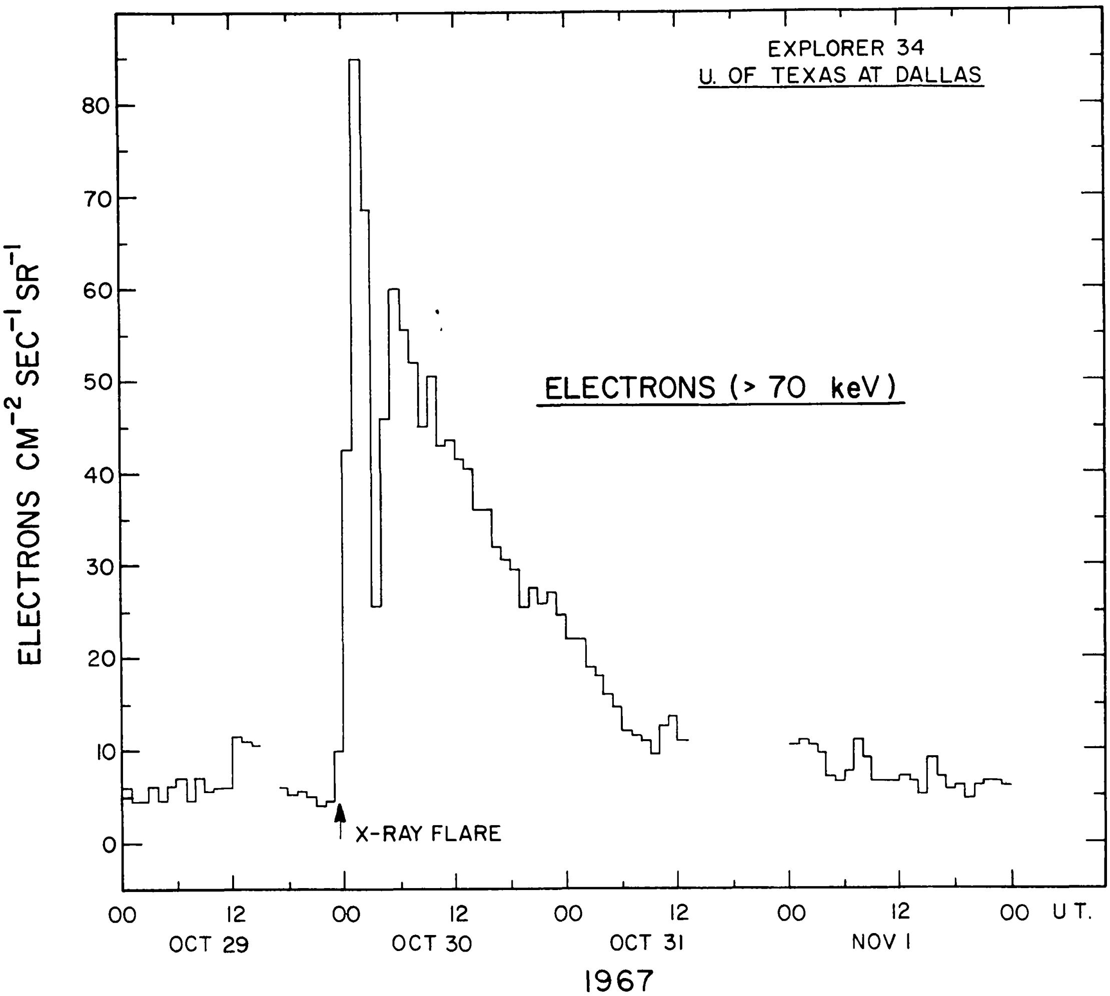

Fig. 10a.

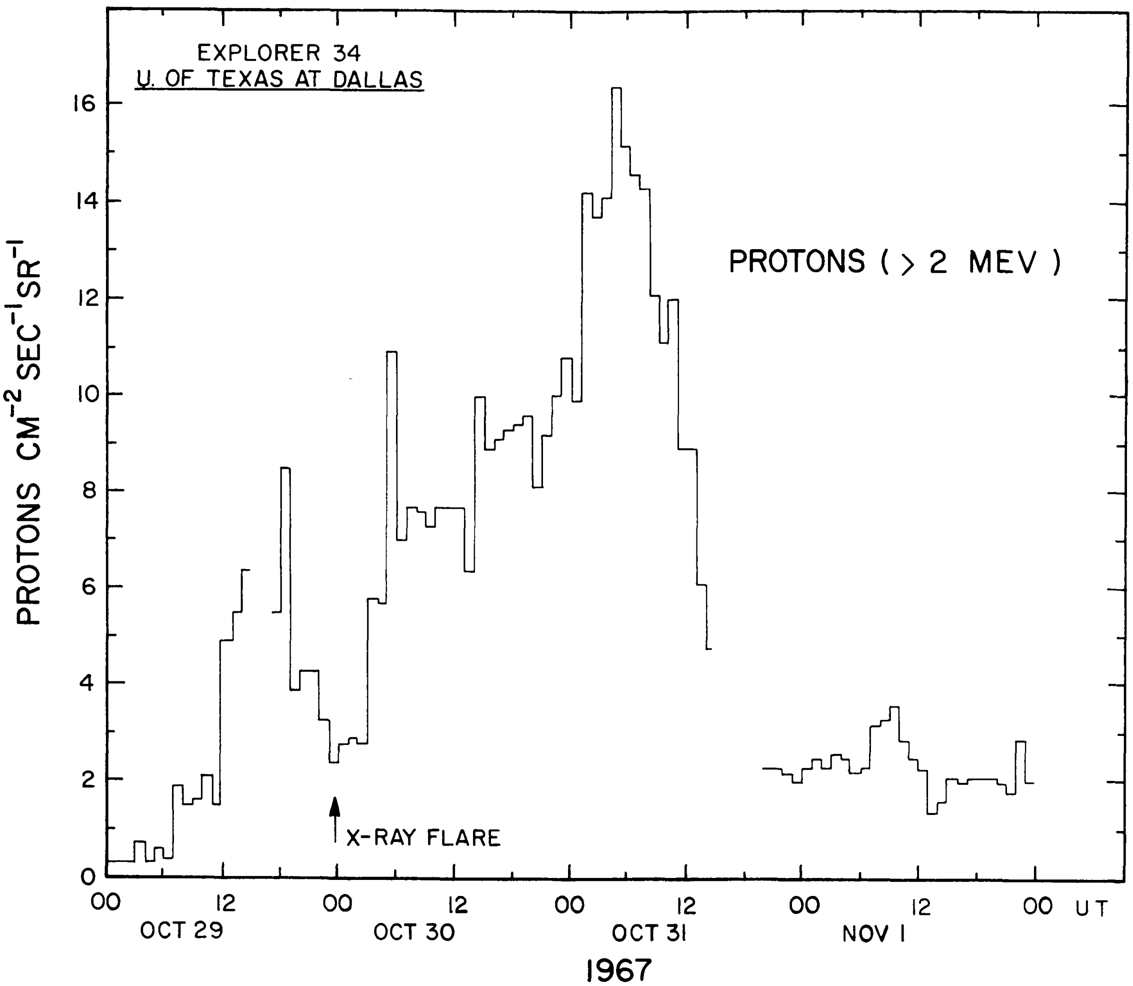

Fig. 10b.

Fig. 10. The temporal dependence of both the electron (a) and proton (b) fluxes during the flare effects of 1967, October 30.

angle scattering. For a pitch angle distribution that is only allowed to be bi-directional: i.e. $\theta = 0$, or π only, and on the assumption that both pitch angles are equally probable following a collision with a magnetic irregularity, they predict that the anisotropy will be given by

$$\delta = \frac{r}{2vt}$$

where r is the source to observer distance (along the field line), v is the particle velocity and t is the time after the particles are released into the solar system. That is, the functional dependence upon time is determined solely by the product vt, and consequently the anisotropy of 70 keV electrons ($E_{av} \approx 105$ keV, $\beta \simeq 0.56$) should decay much more rapidly than that of the protons detected by our detector ($\beta \simeq 0.03$ to 0.08).

The Fisk and Axford anisotropy prediction is plotted in Figure 13. It is clear that the amplitude of the anisotropy of both the electrons, and the protons, decreases with time in a manner that agrees closely with the theoretical prediction. In particular, we note that the agreement pertains, despite the 0(10) difference in particle velocity, and despite the 0(300) difference in particle rigidity and gyroradius.

The latter feature is of particular significance. It demonstrates that the effectiveness of the scattering process, insofar as the destruction of an anisotropy is concerned, does not depend upon particle rigidity. Stated alternatively, the degradation of a given pitch

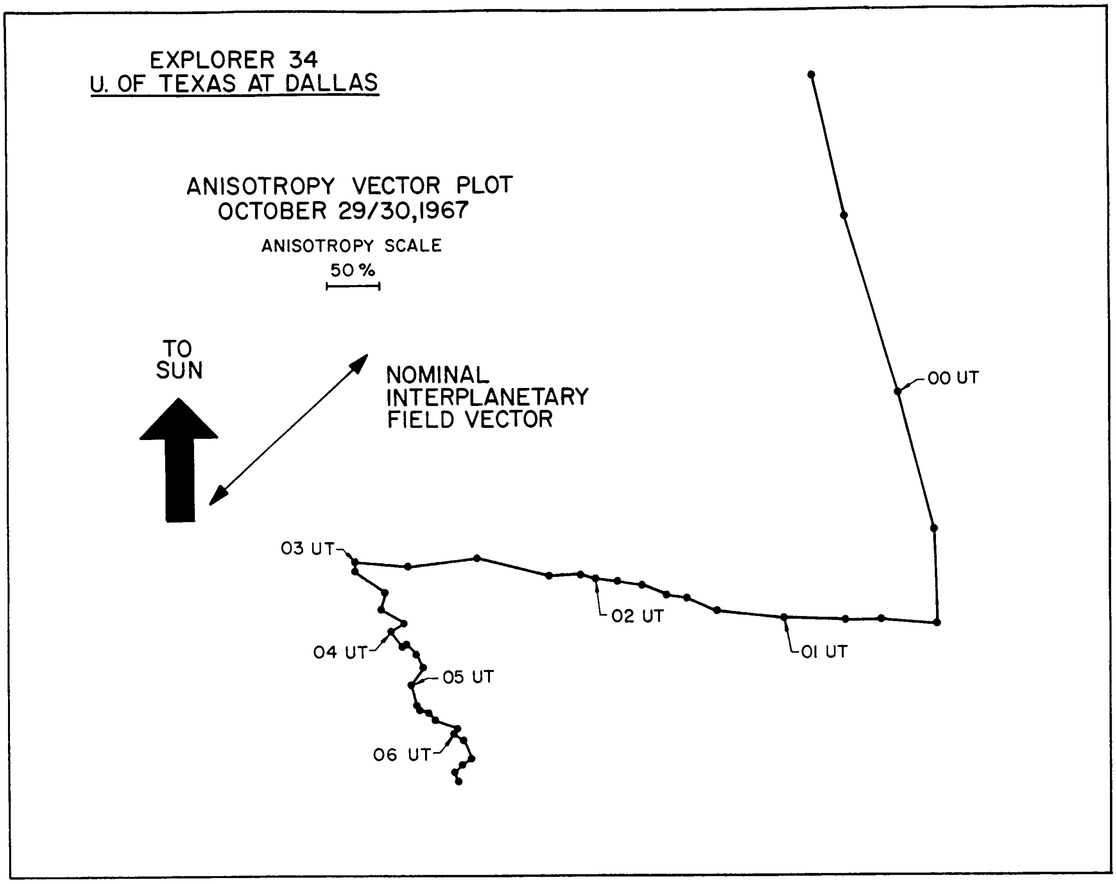

Fig. 11. The anisotropy vector diagram for the electron event of 1967, October 30. The vectors in this case are computed for 11 min average data. The data from the proportional counter during the period covered by the first four anisotropy vectors are contaminated by a penetrating X-ray flux. The onset of the solar electron flux occurs during the time interval covered by the fourth anisotropy vector. Beyond this point, the anisotropy data are clearly not contaminated by a solar X-ray flux.

angle distribution depends only upon the total distance traveled by the particle in question, i.e., upon vt. It depends neither upon the degree of complexity of the orbit, nor upon the dimensions of the tube of force circumscribed by the gyrating particle. In terms of a diffusion model, this implies a parallel diffusion coefficient, $k_{\|}$, that is independent of rigidity, that is, $k_{\|} \sim \beta R^0$.

Similar conclusions have been reached previously from comparisons of the time profiles of cosmic ray increases observed at different particle rigidities (Bryant *et al.*, 1965; Lin, 1970a). We note here, however, that while the event of 1967, June 3 implies

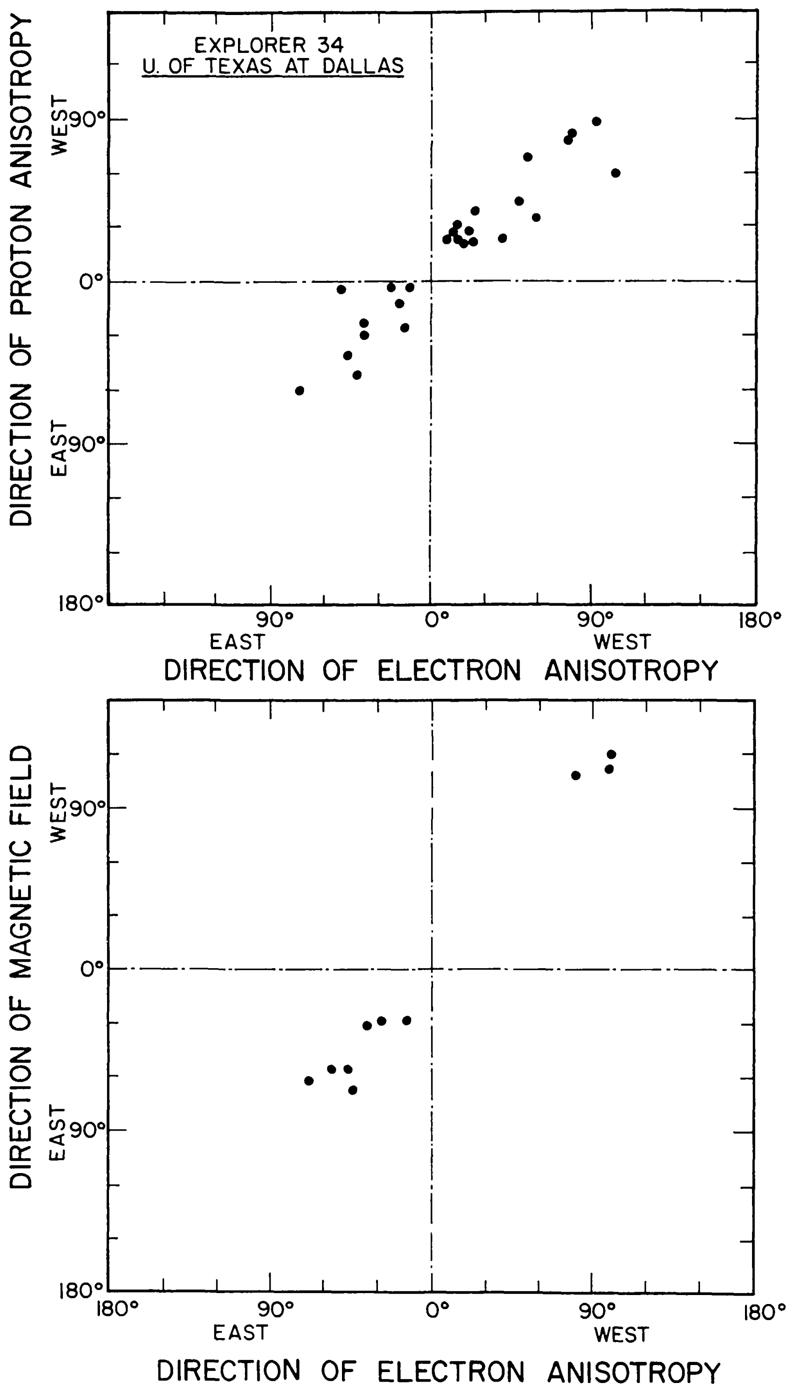

Fig. 12. Illustrating the regression relationships between the direction of the electron anisotropy, the direction of the ionic anisotropy, and the direction of the interplanetary magnetic field. Eleven minute averages are plotted.

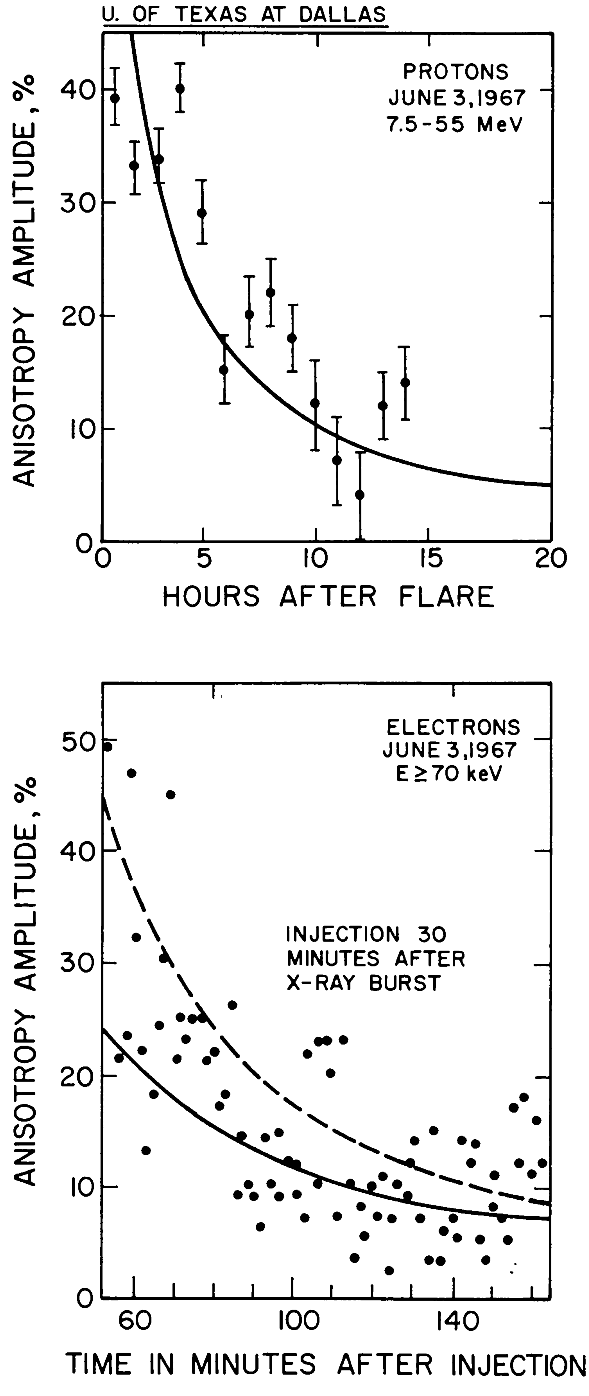

Fig. 13. Illustrating the manner in which the anisotropy of cosmic ray electrons andi ons decreases with the passage of time. The theoretical variation predicted by Fisk and Axford (1969) is shown, where the distance from the injection point is taken as 1.3 AU. The solid lines in both diagrams are based on injection at the time of the X-ray maximum: the dotted line assumes electron injection 30 min later.

scattering that is dependent upon (vt) alone, this is not true for the time profile of the electron and proton events. That is, the time profiles are not identical when plotted against (vt).

The implication of Figure 13 that $k_{\parallel} = \text{const} \times \beta R^0$ leads to conclusions such as have been reached from study of the time profiles observed for different particle rigidities; that is, either (a) the magnetic power spectrum varies as f^{-2} for $2.7 \times 10^{-4} < f < 0.5$ Hz, (Nathan and Van Allen, 1968) or (b) the scattering process for electrons $\simeq 70$ keV and protons of $E \simeq 10$ MeV are such that the mean free path approximates the correlation length L of the interplanetary magnetic field, and hence $k_{\parallel} = \frac{1}{3} c\beta L$ (Jokippi, 1968).

The ephemeral anisotropy evident in our data is in direct disagreement with the observations of Anderson and Lin (1966) and Lin (1968). Using the Moon as an 'occulting disc', they interpret the decrease in electron flux when the Moon intercepts the magnetic field line through the spacecraft as the flux from the occulted direction. Thus, at 2345 UT on August 3, 1967 (see Figure 8), Lin (1968) observed an order of magnitude decrease in electron flux when the interplanetary magnetic vector through the Explorer 35 spacecraft intercepted the Moon. This was then interpreted as a 10 to 1 electron flux anisotropy, at a time many hours after our instrument had observed the anisotropy attain a value $< 10\%$. This is clearly a major disagreement between the two series of measurements.

We suggest that the argument that Van Allen and Ness (1969) have used to explain lunar shadows in the geomagnetic tail, and which Anderson and Lin (1969) themselves have used in a different context, can equally well explain these electron occultations, even if the electron flux is *completely* isotropic. Thus the small $k_{\perp}$ for electrons means that there is little transverse diffusion, and hence the cavity between the Moon, and the magnetosphere, as defined by the interplanetary magnetic field lines that intercept both objects, will be inaccessible to solar electrons. The cavity will therefore be rapidly 'drained' of electrons ($\tau = 0$ (5 sec)), and hence a deep 'electron shadow' produced, even through the electron flux be isotropic. Thus we propose that the technique employed by Lin can lead to erroneous conclusions, and that this was certainly the case for the 1967, August 3 event as noted above.

Recently, Lin (1970b) has suggested that the tendency towards isotropy noted for the 1967, August 3 event (Rao *et al.*, 1969) was due to an anisotropic electron flux being scattered and rendered isotropic by hydromagnetic waves proceeding upstream from the magnetopause (Fairfield, 1969). That is, he proposed that these waves constitute a local diffusion region on the Sunward side of the Earth that will render a strongly anisotropic electron flux, isotropic at Earth. Such a model would require that the electron flux would be isotropic at all times greater than 0 $(L/\beta c)$, where L is the thickness of the region traversed by the shock waves. For $\beta = 0.5$, realistic values of $L/\beta c \simeq 4$ sec. Contrarywise, substantial anisotropies are observed to persist for periods 0 (10^2) to 0 (10^3) greater than this in all the electron events we have observed. Lin's proposition would therefore require that the diffusing region would be largely absent at the beginning of a flare effect, and become stronger thereafter. We do not see any physical reason why the shock wave phenomena should respond in this manner to the arrival of the electron pulse from the Sun.

We therefore conclude that the electron flux in interplanetary space behaves as shown in Figure 13, that is, exhibiting strong anisotropies at early time, but rapidly decaying to $\lesssim 10\%$ within 0 (1 hr). The agreement with a special case of diffusion theory suggests that no other explanations of this behaviour need be sought.

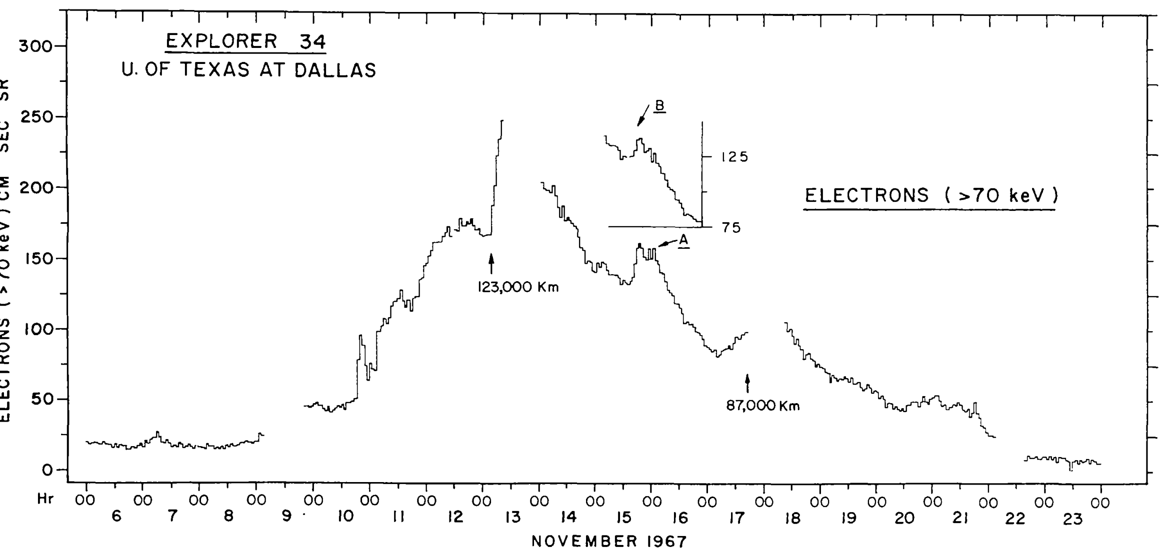

Fig. 14. The temporal dependence of the electron flux during the period 1967, November 12–19. The only periods for which the correction for proton flux is significant is the labeled 'A'. The insert shows the time profile for this period after correction for the proton flux.

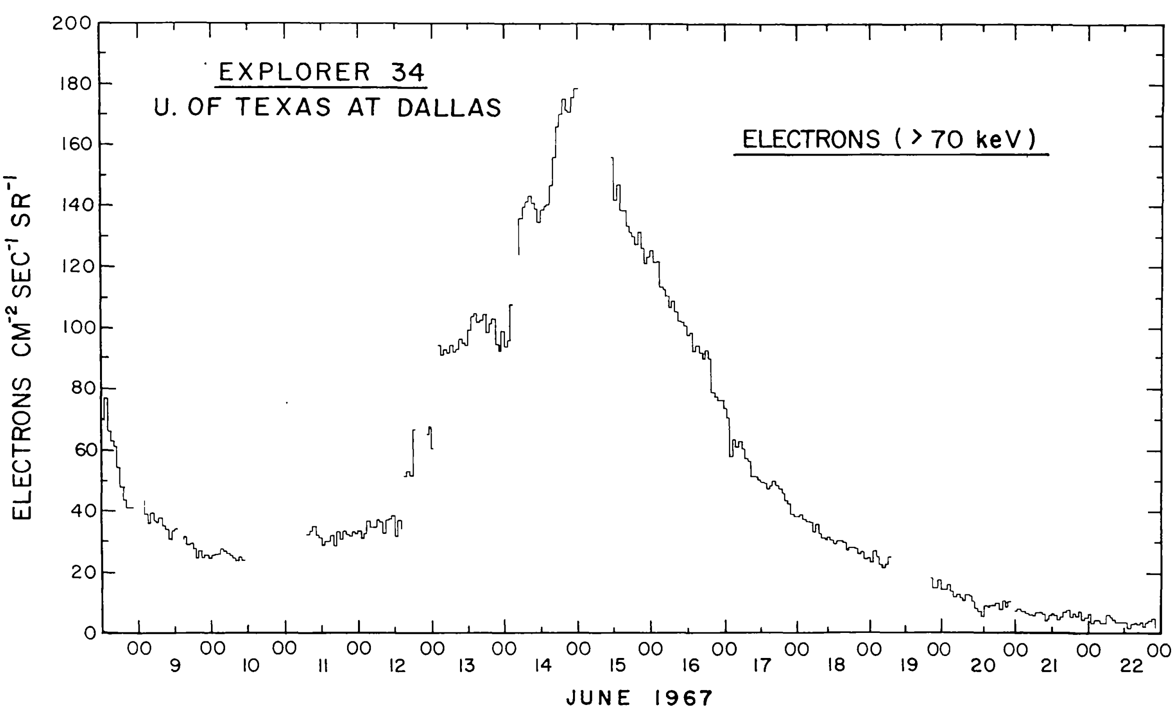

Fig. 15. The temporal dependence of the electron flux during the long lived electron event of 1967, June 12–19.

7. Long Lived Electron Events

Figures 14 and 15 present data obtained during two long-lived electron enhancements. Anderson (1969) and Fan *et al.* (1968) have previously reported other examples of such long phenomena in both the electron and ionic radiation. The complexity, longevity and association with very active centers of solar activity indicate that these events are probably the result of successive injections of electrons (and likewise ions) by a number of unrelated flares in the active center.

The vector addition diagram for the ionic anisotropy is presented in Figure 16, and will be noted that the anisotropy is alternatively from the Sun, and from a direction to the East of the Sun. Identifying the former as the 'convective' anisotropy due to convection of the ions by the solar wind (Parker, 1965; McCracken *et al.*, 1968; Gleeson and Axford, 1968; Forman, 1970), we have selected these periods of time for analysis of the concurrent electron anisotropy. The periods so selected are listed in

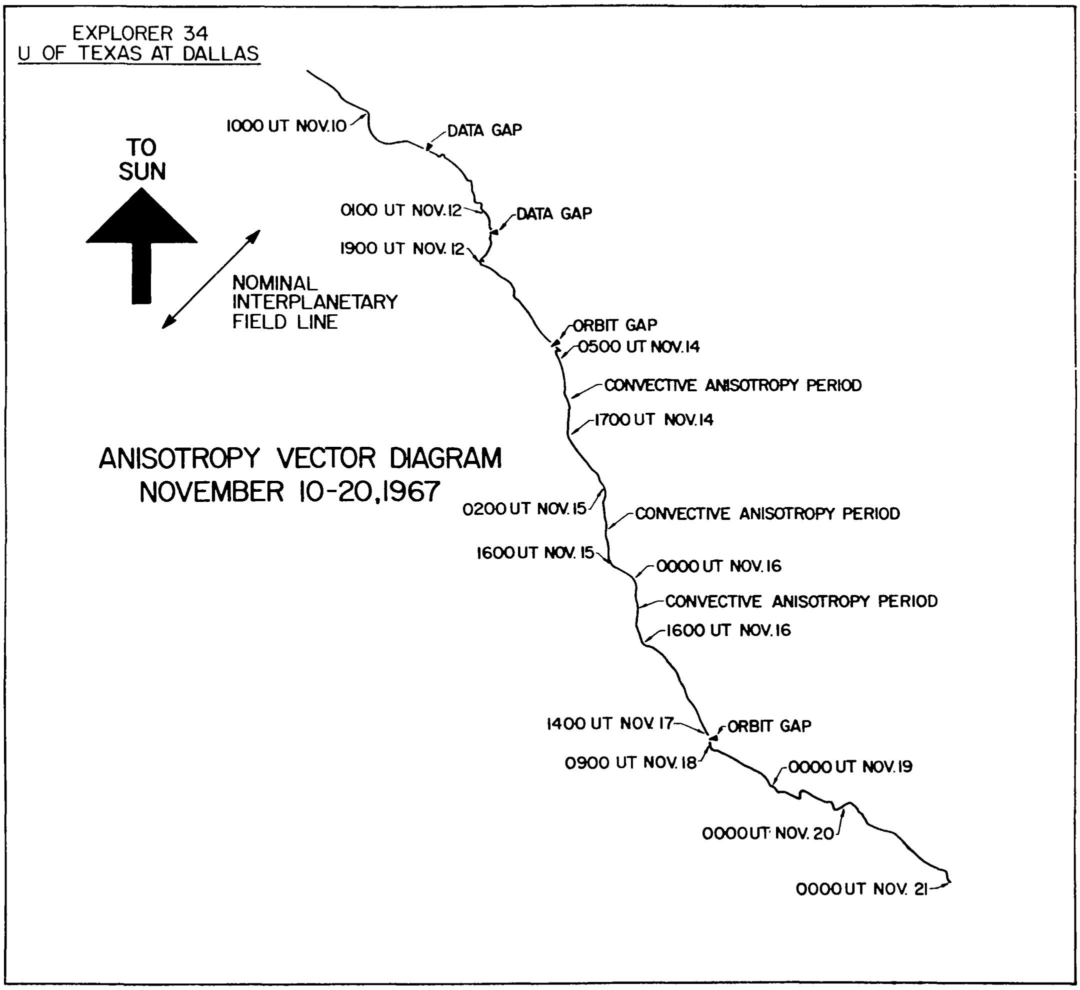

Fig. 16. The vector addition diagram for the long lived electron event of 1967, November 12–19. In this case, the individual anisotropy vectors are not shown. The direction of the anisotropy is alternately from the Sun, and from a direction East of the Sun. The time intervals used in the study of the convective anisotropy (see text and Table II) are clearly indicated.

TABLE III

Summarizing the study of the equilibrium anisotropies of the electron and ion fluxes during the long lived event of 1967, November. The data used to study the convective anisotropy were derived from the intervals:

Nov. 12; 0100–1900 UT
Nov. 14; 0500–1700 UT
Nov. 15; 0200–1600 UT
Nov. 16; 0000–1600 UT

The remainder of the data were used to determine the characteristics of the anisotropy from the East. The parameters assumed in the calculation of the theoretical amplitude were V = plasma velocity = 500 km sec^{-1}; electron spectrum $\mathrm{d}j = kE^{-4}\,\mathrm{d}E$; proton spectrum $\mathrm{d}j = kE^{-1}\,\mathrm{d}E$.

	Ions		Electrons	
	Amplitude	Phase	Amplitude	Phase
Convective anisotropy	9.8 ± .1%	5° E ± 2°	2.6 ± .1%	24° E ± 4°
Convective anisotropy, theoretical	9.0%	0°	2.9%	0°
Anisotropy from east	11.2 ± .1%	40° E ± 2°	3.3 ± .1%	41° E ± 4°

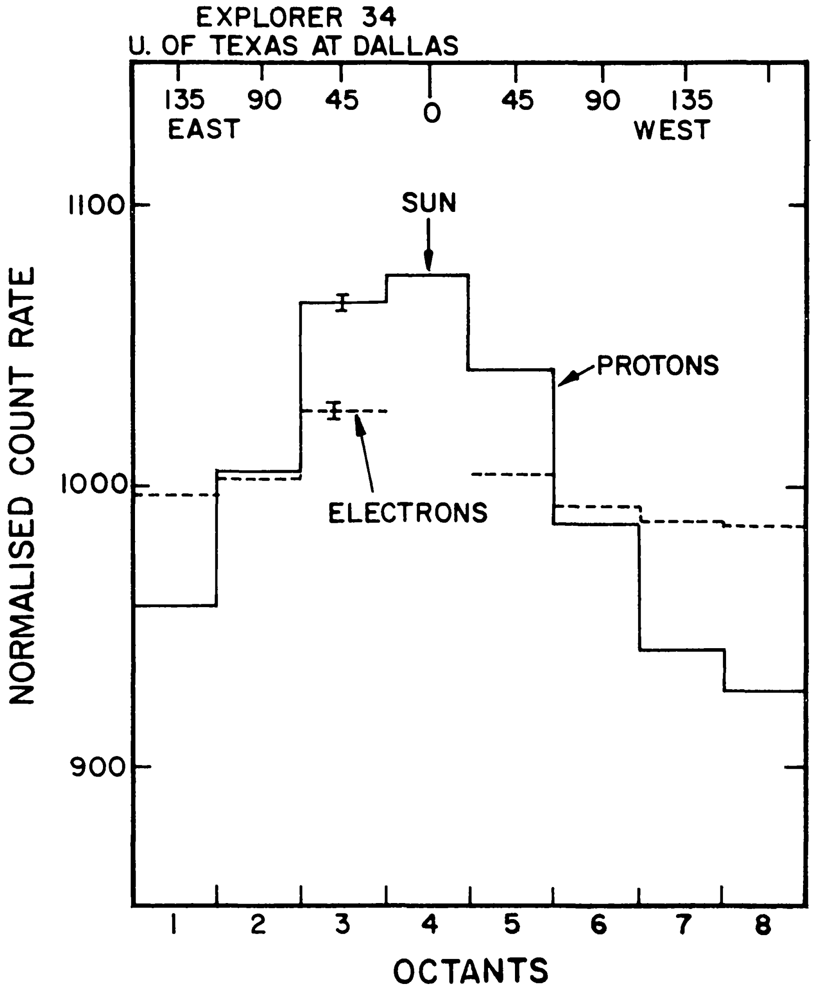

Fig. 17. The counting rate versus azimuth for the 'convective' phases indicated in Figure 16, and Table III. Allowing for geometrical effects, the true proton anisotropy is 1.27 times the observed anisotropy.

Table III. The anisotropy data summed over these periods are displayed in Figure 17. The amplitudes and phases of the anisotropies derived from these data are listed in Table III, along with similar data pertaining to the remainder of the data (i.e. when the anisotropy was from the East).

It is clear from Figure 17, and Table III, that the electron flux was anisotropic throughout the period of interest. It will be noted that the electron anisotropy was not directly from the Sun during the period that the ionic radiation was exhibiting the convective anisotropy, but that of the two classes of data considered, the electron anisotropy phase was closer to 0° during the period in which the ionic anisotropy was convective (i.e., 0°), than during the non-convective period. When the ionic anisotropy was from the Eastern quadrant, we note excellent agreement between the directions of the ionic and electron anisotropy. We interpret these data as evidence that the electronic cosmic radiation exhibits equilibrium (convective) anisotropies similar to those seen in the ionic component. The deviation in phase from 0° (to 24° E) in the 'convective anisotropy' class will be discussed later.

The anisotropy seen by an observer who is moving with a velocity V relative to an isotropic particle flux is (Gleeson and Axford, 1968; Forman, 1970)

$$\delta = (2 + \alpha\gamma)\, V/v$$

where the particle spectrum is given by $\mathrm{d}j \sim E^{-\gamma}\,\mathrm{d}E$; $\alpha = (2m_0c^2 + T)/(m_0c^2 + T)$; and where v is the particle velocity. During the period 1967, November 10–13, the solar wind velocity observed by the Pioneer 7 spacecraft, situated 38° to the East of Earth (*Solar Geophysical Data*, ESSA) fell in the range 405–630 km sec^{-1}. Taking $V = 500$ km sec^{-1} as a representative value; assuming an electron spectrum $\mathrm{d}j \sim \sim E^{-\gamma_e}\,\mathrm{d}E$, where $\gamma_e = 4$ (as suggested by Van Allen, 1970; Lin, 1970a); and approximating a $\mathrm{d}j \sim E^{-1}\,\mathrm{d}E$ spectrum to the proton data displayed in Figure 18 yield the theoretical values of the convective anisotropies listed in Table III. Bearing in mind the inaccuracies inherent in some of the above assumptions, we consider the agreement to be excellent. The discrepancy in the case of the electron anisotropy amplitude could be explained in terms of $\gamma_e = 3.5$, a value that is still consistent with the results of Van Allen and Lin as cited above.

The anisotropic flow of cosmic rays from the Eastern quadrant for $\gtrsim 8$ days is the most striking feature of Figure 16. As noted above, and as is also evident from Figure 19, this feature applies to both the electron and the ionic populations. More recently, copious evidence has been obtained that this is an inevitable feature of solar cosmic ray fluxes some 3 to 4 days after their injection into the solar system by a solar flare (McCracken *et al.*, 1971). There is strong evidence that the observation of an anisotropy from the East indicates that convective removal of the cosmic rays by the solar wind has established a positive gradient in the solar cosmic ray density.

In terms of the above considerations, we can therefore make the following statements about the electron populations during 12–20 November, 1967.

(a) Since an 'equilibrium' anisotropy was seen in the electron flux, the electron population must have been convected out of the solar system at the plasma velocity.

We therefore infer that the decay of an electron event must be predominantly through convective removal, and not through diffusion (Forman, 1970). That is, $v_p U_e \gg\gg k_{\|,e} \nabla U_e$, where v_p is the plasma velocity, $k_{\|,e}$ is the parallel diffusion coefficient for electrons, and U_e is the cosmic ray electron density. This is of major significance in the determination of the decay characteristics of an electron flux enhancement.

(b) Since the equilibrium anisotropy assumed a direction from the East, the density

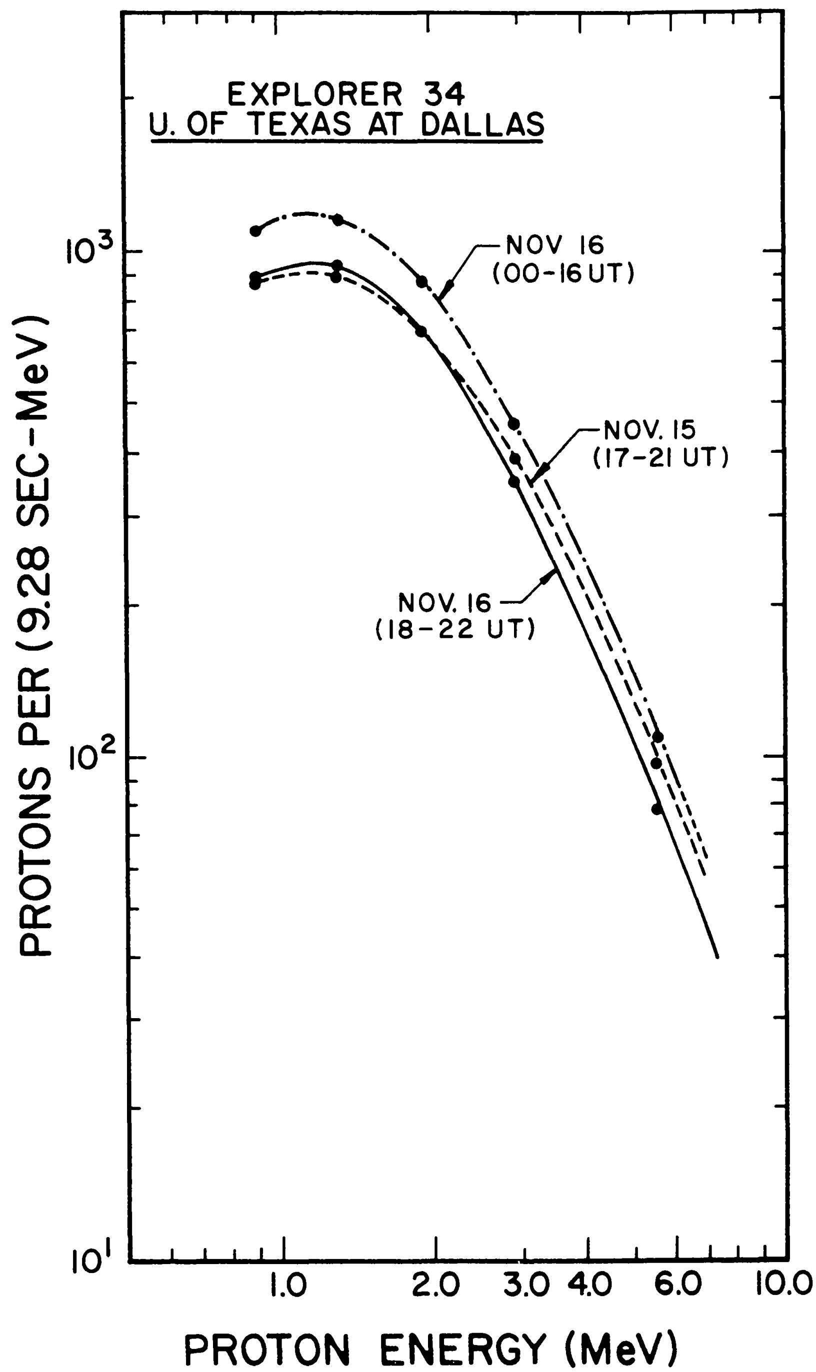

Fig. 18. The proton spectra corresponding to the period 0–16 UT, 1967, November 16, which exhibits the 'convective' anisotropy, and two adjacent periods for which the anisotropy is from the East of the spacecraft-Sun line.

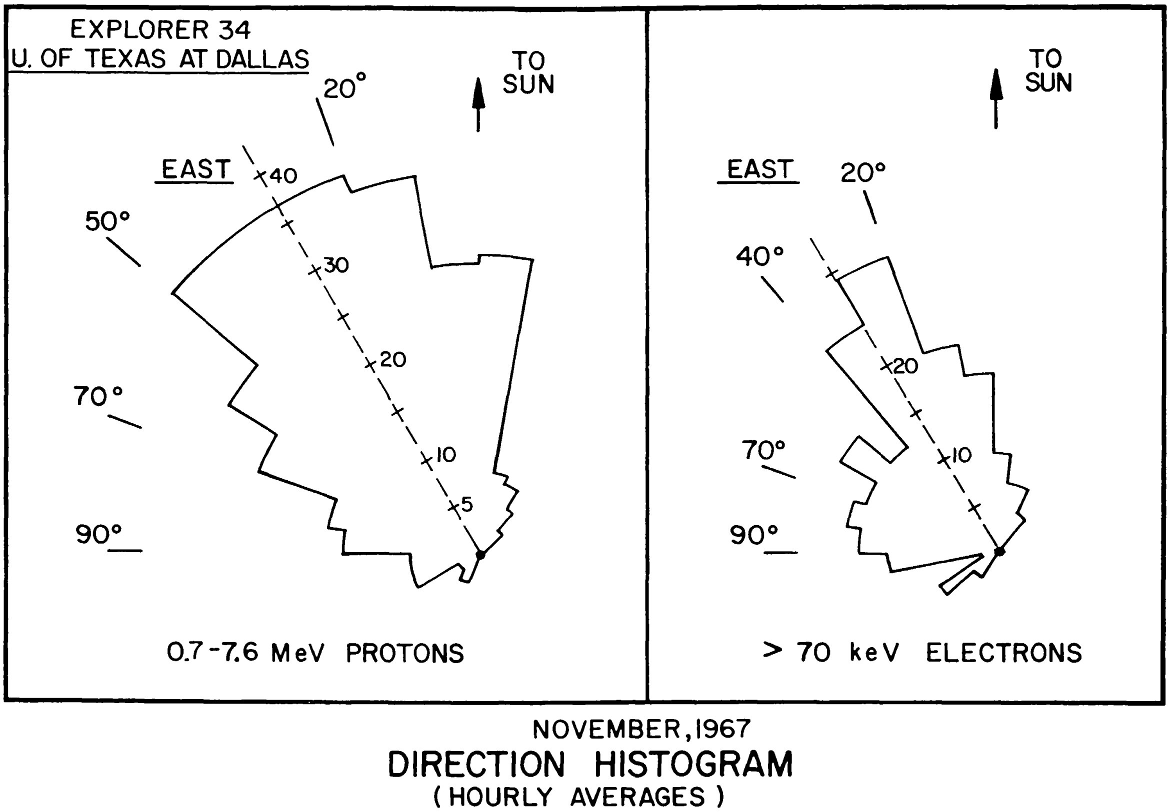

Fig. 19. The frequency of occurrence histograms for the electron and ionic anisotropy phases for the period 1967, November 12–20.

gradient of electrons must have been positive, resulting in a diffusive cosmic ray current towards the Sun along the interplanetary magnetic field lines. That is, at late times in the life of an electron population, the electron density near the orbit of Earth increases with increasing distance from the Sun.

(c) Since the electron equilibrium anisotropy attained Easterly directions while the ionic anisotropy was still directed from the Sun, we infer that a positive gradient in electron density developed prior to the development of a similar gradient in ionic density.

8. Conclusions

On the basis of the evidence presented above we advance the following statements regarding the life history, and properties of solar flare electrons.

(1) The probability of observing electrons released by a solar flare is a strong function of the solar longitude of the parent flare. Electrons from any given flare are preferentially routed to a restricted range of solar longitudes. We conclude that the propagation process is most efficient when the parent flare is about 45° W relative to the point of observation. This evidence is in accord with the idea of electrons propagating along the Archimedes spiral interplanetary magnetic field.

(2) The onset of the enhancement of electrons of energy $\gtrsim 70$ keV takes place

about 20 min earlier than the onset of protons of energy 1 MeV. The time dispersion is consistent with their velocity of travel along the field lines.

(3) The rise times of solar electron events are fast compared to those of proton events. The electron events are impulsive and last for much shorter time ($\lesssim 1$ day) than the solar proton events.

(4) The rise and decay of electron events are relatively smooth functions of time. The proton events ($E \simeq 1$ MeV), on the other hand frequently exhibit major short term fluctuations.

(5) The solar electrons (circa 70 keV) exhibit anisotropies of lesser magnitude than do the low energy protons ($\simeq$1–10 MeV) of solar origin. Even when large electron anisotropies are seen at the onset of a prompt electron event, the electrons relax toward isotropy within 1–2 hr of the onset. The anisotropy of the electron flux is field aligned at early times in the life of an electron population.

(6) The decay of the electron anisotropy is in good accord with the diffusive theory as enunciated by Fisk and Axford (1969). This suggests that the electron anisotropies ($\beta \approx 0.58$) will behave in a quantitatively similar manner to relativistic ions (e.g., as seen by neutron monitors, $\beta \simeq 0.8$). This prediction is in accord with experience.

(7) There appears to be no need to postulate that the anisotropies observed on Explorer 34 have been seriously affected by scattering in shock waves due to the presence of the geomagnetosphere.

(8) Long lived increases of electrons are observed that are not separable into events due to individual flares. At late times these electron fluxes exhibit equilibrium anisotropies, whose properties are in good accord with theory.

(9) The equilibrium anisotropies indicate that the electron populations leave the solar system through convection alone. They do not escape through diffusion. Diffusion is of primary importance, however, at late times in that, it opposes the convective removal of the electrons at the solar wind velocity. As a result, the electron anisotropy is from the East at late times.

(10) At late times near the orbit of the Earth the electron density increases with increasing distance from the Sun.

Acknowledgements

This research was supported by the National Aeronautics and Space Administration under contracts NASr-198 and NAS5-9075. The research in India was supported by funds from The Department of Atomic Energy, Government of India and funds from the grant NAS-1492 from the National Academy of Sciences, U.S.A. Support in data analysis was also provided by Air Force Cambridge Research Laboratories under contract AF19-(628)-5039, and by the Australian Research Grants Committee. We also gratefully acknowledge assistance provided by Dr. D. E. Hagge and Miss A. E. Dillinger of the Manned Spacecraft Center Houston, Texas. One of us (J. R. H.) acknowledges a post graduate studentship provided by the Commonwealth Scientific and Industrial Research Organisation of Australia.

The assistance of L.N.D., Inc. in the provision of a suitable electron detector is gratefully acknowledged. The assistance of W. C. Bartley, Jr., J. M. Younse, and D. Stang was indispensible throughout the construction phase of our detector. W. R. Chronister, and J. Hall were responsible for writing the computer program, while R. Hayes, J. Jaschob, K. Hapeman and L. Summers provided indispensable assistance in the data analysis.

References

Anderson, K. A.: 1969, *Solar Phys.* **6**, 111.
Anderson, K. A. and Lin, R. P.: 1966, *Phys. Rev. Letters* **16**, 1121.
Anderson, K. A. and Lin, R. P.: 1969, *J. Geophys. Res.* **74**, 3953.
Bartley, W. C., Bukata, R. P., McCracken, K. G., and Rao, U. R.: 1966, *J. Geophys. Res.* **71**, 3297.
Bartley, W. C., McCracken, K. G., Rao, U. R., Harries, J. R., Palmeira, R. A. R., and Allum, F. R.: 1971, this issue, p. 218.
Bryant, D. A., Cline, T. L., Desai, U. D., and McDonald, F. B.: 1965, *Astrophys. J.* **141**, 478.
Cline, T. L. and McDonald, F. B.: 1968, *Solar Phys.* **5**, 507.
Fairfield, D. H.: 1969, *J. Geophys. Res.* **74**, 3451.
Fan, C. Y., Pick, M., Pyle, R., Simpson, J. A., and Smith, D. R.: 1968, *J. Geophys. Res.* **73**, 1555.
Fisk, L. A. and Axford, W. I.: 1969, *Solar Phys.* **7**, 486.
Forman, M. A.: 1970, *J. Geophys. Res.* **75**, 3147.
Gleeson, L. J. and Axford, W. I.: 1968, *Astrophys. Space Sci.* **2**, 431.
Harries, J. R.: 1969, Ph.D Thesis, Physics Department, University of Adelaide, Adelaide, Australia.
Jokipii, J. R.: 1968, *J. Geophys. Res.* **73**, 6864.
Kundu, M. R.: 1965, *Solar Radio Astronomy*, Interscience, New York.
Lin, R. P.: 1968, *J. Geophys. Res.* **73**, 3066.
Lin, R. P.: 1970a, *Solar Phys.* **12**, 266.
Lin, R. P.: 1970b, *J. Geophys. Res.* **75**, 2583.
Lin, R. P. and Anderson, K. A.: 1967, *Solar Phys.* **1**, 446.
McCracken, K. G. and Ness, N. F.: 1966, *J. Geophys. Res.* **71**, 3315.
McCracken, K. G. and Rao, U. R.: 1970, *Space Sci. Rev.* **11**, 155.
McCracken, K. G., Rao, U. R., and Bukata, R. P.: 1967, *J. Geophys. Res.* **72**, 4293.
McCracken, K. G., Rao, U. R., and Ness, N. F.: 1968, *J. Geophys. Res.* **73**, 4159.
McCracken, K. A., Rao, U. R., Bukata, R. P., and Keath, E. P.: 1971 (in preparation).
Nathan, K. V. S. K. and Van Allen, J. A.: 1968, *J. Geophys. Res.* **73**, 163.
Parker, E. N.: 1965, *Planetary Space Sci.* **13**, 9.
Rao, U. R., McCracken, K. G., and Bukata, R. P.: 1967, *J. Geophys. Res.* **72**, 4325.
Rao, U. R., Allum, F. R., Bartley, W. C., Palmeira, R. A. R., Harries, J. R., and McCracken, K. G.: 1969, *in Solar Flares and Space Research*, North Holland, Amsterdam, p. 267
Rao, U. R., McCracken, K. G., Allum, F. R., Palmeira, R. A. R., Bartley, W. C., and Palmer, I. D.: 1971 (in preparation).
Van Allen, J. A.: 1970, *J. Geophys. Res.* **75**, 29.
Van Allen, J. A. and Krimigis, S. M.: 1965, *J. Geophys. Res.* **70**, 5737.
Van Allen, J. A. and Ness, N. F.: 1969, *J. Geophys. Res.* **74**, 71.