X-611-68-154
PREPRINT

RELATIVISTIC ELECTRONS FROM SOLAR FLARES

T. L. CLINE
F. B. McDONALD

MAY 1968

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-611-68-154
PREPRINT

RELATIVISTIC ELECTRONS FROM SOLAR FLARES

T. L. Cline and F. B. McDonald

May 1968

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

RELATIVISTIC ELECTRONS FROM SOLAR FLARES

T. L. Cline and F. B. McDonald
NASA-Goddard Space Flight Center, Greenbelt, Maryland

Abstract

Observations of interplanetary relativistic electrons from several solar flare events monitored through 1964 to mid-1967 are presented. These are the first direct spectral measurements and time histories, made outside the magnetosphere, of solar-flare electrons having relativistic velocities. The 3- to 12-MeV electrons detected have kinetic energies about two orders of magnitude higher than those solar electrons previously studied in space, and measurements of both the time histories and energy spectra for a number of events in the present solar cycle were carried out. These measurements of interplanetary electrons are also directly compared with solar x-ray data and with measurements of related interplanetary solar protons.

The time histories of at least four electron events show fits to the typical diffusion picture. A demonstrated similarity between the electron and the medium-energy proton fits for the event of 7 July, in particular, indicates that at these electron energies, but over several orders of magnitude of rigidity, whatever diffusion does take place is very nearly on a velocity, rather than a rigidity or an energy, basis. Diffusion-fit time histories varied as a function of T_o also indicate that the electrons in certain flare events originate at times near the x-ray and microwave burst, establishing their likely identity as the same electrons which cause the impulsive radiations. Also, the energy spectra

and total numbers of the interplanetary electrons, compared with those of the flare-site electrons calculated from x-ray and microwave measurements, indicate that probably a small fraction of flare electrons escape into interplanetary space.

RELATIVISTIC ELECTRONS FROM SOLAR FLARES

1. Introduction

The existence of many features which frequently accompany large solar flares have demonstrated conclusively that electrons are accelerated by the flare process. These features include energetic x-ray emission as well as the spectral distribution and polarization of types II, III, and IV solar radio bursts. In particular, the impulsive microwave burst and the energetic x-ray emission associated with the explosive phase of the flare, as well as the ensuing type IV radio emission, require electrons to be accelerated to relativistic velocities with the subsequent loss of energy by synchrotron radiation and bremsstrahlung near the flare region (see, e.g., Boischot and Denisse, 1957; Wild, 1962, Takakura, 1967). Type II and type III radio emissions are generally interpreted in terms of lower energy electrons. There has also been established a very good correlation between type IV solar radio emission and solar cosmic-ray events. However, for many years the study of particle events in interplanetary space had been restricted to the measurements of solar protons and heavier nuclei. It was thus not known whether the absence of interplanetary solar electrons in such events was due to an intrinsic trapping of such particles in the near solar environment or simply to the lack of appropriate instrumentation, until, after one balloon-level observation by Meyer and Vogt (1962), nonrelativistic solar electrons were finally found in deep space by Van Allen and Krimigis (1965). Their observations and those of Anderson and Lin (1966) showed that intense and prolonged occurrences of low-energy electrons, (all of which were observed with detector thresholds of around 40 KeV) were actually

common features of the interplanetary environment, particularly in times of increased solar activity. While the MeV electron results reported here may relate to these low-energy electron measurements, they also represent a natural link to some of the proton data, since the electrons we observed are entirely in the relativistic domain. Further, the interplanetary electrons of energy in the few MeV region must be directly related to those at the sun responsible for the energetic flare x-ray emission and the microwave radio emissions. Hence, detailed correlations between the low- and high-energy electron results, proton and nuclei data, and x-ray observations should provide new information both about the flare process itself and about interplanetary particle propagation.

2. Measurements

Our observations were made with the first three IMP satellites, (Explorers 18, 21, and 28) and represent nearly continuous coverage during the three and one-half years from November 1963 to May 1967. As shown in Table 1, the first event to definitely contain an intensity of relativistic electrons exceeding our detector threshold occurred on 7 July 1966, although several other solar events were monitored during the proceeding several years including the perhaps equally large x-ray and particle event of 24 March 1966. All 3 satellites had apogees outside the magnetosphere, in particular, the IMP-III apogee was at about 250,000 km, so that long periods of time were spent in interplanetary space, far outside the trapping region in the earth's geomagnetic tail where uninterrupted measurements of solar particles could be made.

Table 1

Relativistic Electrons in Solar Particle Events *

MONITORED PERIOD	EVENT DATE	FLARE TIME MAXIMUM†	FLARE LOCATION	PEAK RADIO EMISSION♦ at 2800 MHz	> 3 MeV ELECTRON MAX. INTENSITY‡
27 Nov. 63 to 8 May 64 (IMP-I)	16 Mar. 64	1558(r)	NO6/W75	3	$\lesssim$ 0.05
2 Oct. 64 to 2 Mar. 65 (IMP-II)	5 Feb. 65	1810(o)	NO8/EO9	43	$\approx$ 0.4
30 May 65 to 11 May 67 (IMP-III)	4 Oct. 65	0940(o)	S20/W30	24	$\lesssim$ 0.1
	24 Mar. 66	0239(x)	N18/W37	400	< 0.1
	7 July 65	0037(x)	N34/W45	2650	3.0
	28 Aug. 66	1527(x)	N23/E04	1000	< 0.25
	2 Sept. 66	0540(o)	N22/W57	2300	Not available
	14 Sept. 66	1025(o)	S20/W90	25	0.4
	28 Jan. 67	—	None known	—	> 1.0
	1 Feb. 67	—	None known	—	3.0
	2 Feb. 67	—	—	—	2.5
	13 Feb. 67	1814(x)	N22/W10	33	< 0.05
	27 Feb. 67	1649(x)	N27/EO1	560	0.6
	11 Mar. 67	—	None known	—	2.5
	1 Apr. 67	—	—	—	> 0.07

* Only the largest solar particle events are listed; others during the monitored periods have upper limits to relativistic electron intensity below cosmic ray background.

† Notation: x=energetic x-ray, r=microwave radio, o=optical times, U.T.

‡ In units of electrons cm^{-2} sec^{-1} $ster^{-1}$ averaged over a band in the sky perpendicular to the spin axis (see text).

♦ In units of 10^{-22} $w\,m^{-2}$ Hz^{-1}.

The detectors used on all 3 satellites were identical, the first of which was the one used to detect 3 to 12 MeV interplanetary electrons in solar quiet times (Cline, Ludwig and McDonald, 1964). It consisted of 3 scintillators in the familiar energy loss, total energy and guard counter arrangement, providing a geometric factor for stopping particles of about 3 cm^2 ster. The information telemetered from the experiment consists of two types: (a) detailed pulse-height information on a single stopping particle, and (b) counting rates from individual scintillator arrangements, including the total intensity of stopping particles. The detailed pulse-height data consist of the rate of energy loss and, simultaneously, the residual energy of the first particle (after the commencement of each sampling time) which satisfies the coincidence requirement and does not activate the guard counter. The telemetry rate is fixed such that even in quiet times, pulse-height information can be sampled for only about 1 of every 12 stopping particles. During the peak of the 7 July 1966 event, 1 out of each several thousand stopping particles was identified. The particle selection is however, completely random, so that a valid sample is obtained. The absolute intensity of a particular particle species is thereby measured as a function of time with a statistical accuracy reflecting its proportion in the totality of particles detected. The stopping particles consist of two major groups: 3- to 12-MeV electrons and 16- to 80-MeV protons. The accuracy for observing solar electrons depends on the relative intensity of these two components as well as their absolute flux values. In all cases when we report no electrons were present for a given event, we clearly mean that their intensity was below our detection limits. For this purpose the electron intensity increase must exceed ≈ 0.2 electrons cm^{-2} sec^{-1} $ster^{-1}$ and the intensity of 3- to 12-MeV electrons must exceed about ≈ 0.1 the intensity of 15- to 80-MeV protons.

On each satellite the detector is mounted with its aperture perpendicular to the spin axis; the data are collected such that a band in the sky of approximately 25 degrees width forming a great circle in the plane of the spin equator is uniformly sampled. The position of the spin axis of IMP-III remained between declination -10. to -15. degrees and right ascension +65. to +70. degrees for the duration of the useful life of the detector.

Figure 1a shows the energy loss vs. energy counting tabulations of one orbit of quiet-time interplanetary data, and 1b, a typical solar proton event. These plots contrast with the electron response exhibited in several periods during the onset of the 7 July 1966 event, shown in Figure 2. In effect these tabulations represent the raw data from the experiment. The pattern in the pulse grid in Figure 2, taken during the event onset, occurs directly where quiet-time electrons are seen, and is accompanied by a relatively smaller number of background counts due to random coincidences, scattered particles, particles produced by nuclear interactions in the detector or other penetrating particles which escape detection by the guard counter. In fact, since the occurrence of these background events was much lower than in the quiet-time cosmic-ray observations, the solar electron beam at that time was more clearly identifiable. Later in the event the proportion of protons in each grid increased, also with an excellent signal to background ratio, such that the identification of the two patterns of these particles with relativistic electrons and with slower protons can be unmistakably established. Because of the fixed sampling rate it is informative to determine the factor indicative of the fraction of particles actually sampled; these factors are listed in the figure captions.

The question of whether the detected electrons in the 7 July event are primary particles from the sun (not secondaries produced in or near the detector by high-energy solar protons) is resolved as follows. Although no measurements separating high-energy or near-relativistic protons were made on the satellite, some such particles must have been produced since the Alert neutron monitor showed a hourly-average counting rate increase of about 2% between 0100 and 0200 U.T., with a decay during the next two hours. The time history of relativistic electrons in this event is shown in Figure 3. These values were derived by using the monitored counting rate of stopping particles to normalize the electron proportions in the energy loss vs. energy grids for the amount of intensity increase, in which the interplanetary electron background has been subtracted. Also shown is the rate of penetrating particles (which represents the integral rate of protons of energy > 16 MeV and of electrons of energy > 3 MeV), and the rate of stopping particles. During the time interval from 0107 to 0213, all the stopping particles were electrons; this fraction decreases gradually as the protons arrive after about 0200, so that the actual electron intensity is a maximum at about 0230; it becomes unmeasurable after 0600 U.T. due to the increase in the number of low energy protons. The facts that the rate of monitored stopping particles as a function of time for the first hour is half the total intensity of penetrating particles, and that the geometric factor for penetrating particles is about twice that for stopping particles, mean that the > 3 MeV electron intensity was at least as large as that of the totality of other particles evident on the satellite, if not completely dominant. Since this slice in the electron spectrum is narrow, 3 to 12 MeV, and since the proportion of such electrons in the quiet-time cosmic radiation is orders of magnitude

smaller, it appears impossible that the electrons detected could have been secondaries produced by a much lower flux of solar protons. We therefore conclude that the presence of relativistic electrons must be a feature of the primary solar flare radiation.

3. The 7 July 1966 Event

The solar flare of 7 July 1966 was not only the first opportunity to detect relativistic flare electrons in space, but was interesting in several other respects. Both the microwave radio emission and the hard (~100 KeV) x-ray emission, which coincided in time profile and peaked in intensity at 0037 U.T. (Cline, Holt, and Hones, 1967), were unusually intense. The Alert neutron monitor showed a very small increase in high-energy particle intensity. Even at proton energies down to a few MeV this appeared to be a modest-sized event; however, it turned out to be the largest particle event between September 1963 and September 1966. The solar longitude of the flare was between 45 and 48 degrees west, near the probable origin of the earth-intercepting field line, and the solar sector timing agreed with the longitude of that one shown by Guss (1964) to be responsible for most of the large particle events of the last decade. The time history of the electrons indicates (in Figure 3) that although the rise and decay times are relatively short, matters of minutes and hours respectively, the onset of the event is actually not a very prompt one. Considering the 48° west location of the flare where Anderson and Lin (1967) found the most prompt low-energy electron events to originate, (and where the direct field-line propagation time for relativistic electrons should only be a little longer than 8.3 minutes), the half-hour delay in onset and the total 2-hour time to

maximum seen here indicates that considerable trapping and diffusion of the particles is taking place. This behavior is similar to that observed for relativistic protons (Bryant, Cline, Desai, and McDonald, 1965) in that for both cases the intensity maxima occur at a time delay equivalent to 12 to 15 A.U. in travel. This appears to confirm the fact that for certain events the containment, or diffusion, of the particles is on a velocity basis, rather than on kinetic or total energy or rigidity. Because of this time delay, we can then conclude that considerable storage of the particles must have taken place near the sun if they were produced at the time of the microwave and x-ray burst. This conclusion is consistent with that reached by Lin, Kahler, and Roelof (1967) in their study using three spacecraft at different locations during the same flare effect, wherein they conclude that the spatial interplanetary intensity geometry reflects a near-solar profile translated towards 1 A.U. along the spiral field lines. Although one cannot make a distinction between the interplanetary diffusion picture and a near-solar diffusion picture on the basis of time histories alone, it is instructive to use the standard diffusion plot. Figure 4 shows that a straight line fit of $\ell n \left[I(T-T_o)^{1.5} \right]$ against $(T-T_o)^{-1}$ does result, and has a slope within 30% of agreement with the former relativistic proton fits. We do not believe this supports a classical interplanetary diffusion but claim rather that the relativistic protons and relativistic electrons appear to travel in a similar manner, wherever the trapping and propagation takes place. This claim is amply supported by a comparison of the relativistic electron and low-energy proton time histories, illustrated in Figure 5. Several proton components of the 7 July event (J. Kinsey, private communication) having kinetic energies through the 16 to 80 MeV region, (having rigidities between

175 and 400 MV and v/c between 0.18 and 0.40), are plotted with the > 3 MeV electrons (R = 3.5 MV and v/c $\geq$ .99). The first shows the intensities in real time; the second, corrected for velocity so as to form distributions in path length. It is readily seen that all four groups closely fit a common curve to within the statistical accuracy at all path lengths. Since the intervals in kinetic energies and in rigidities are each quite large, between one and two decades, and the velocity interval nearly one decade, the velocity compensated fit is an excellent confirmation of the claim, presented above. Thus, this solar-particle time history is a function of velocity alone (which is to say that path-length distributions, and consequently, the mean free paths for propagation, are nearly entirely independent of velocity). The only discrepancy is that the electrons appear to propagate slightly more directly, having distances to maximum and to decay a little ahead of the protons; thus, there may be some second-order correction for rigidity or other parameters.

However, not all events allow for such a straight-forward interpretation; for example, the 14 September 1966 event does not give good agreement. It is probable that both long term ($\approx$ several hour) trapping in the source region and the condition of the interplanetary medium might introduce rigidity-dependent effects. Moreover this velocity ordering eventually breaks down towards the very low-energy region.

The energy spectrum of the onset and of the decay portions of the 7 July electron event are shown in Figure 6. Due to the small number of sampled events, the differential spectrum of each cannot be well established; a combination of the two portions produces a spectrum with a power-law index of about

-3.2, approximately similar to either fit. (As shown in the picture, the onset and decay portions for later events can be slightly different, but in general agree with this shape). The shape of these spectra are only moderately steep, as compared with some low-energy proton events, but the power-law index is consistent with that predicted by Takakura and Kai (1966) for the solar electrons typically responsible for flare x-rays. It is thus entirely possible that these interplanetary electrons are closely related, through a propagation and diffusion process which leaves their spectral character little changed, to those at the site of the flare. We cannot directly calculate the number of electrons released into interplanetary space since too many of the parameters involved related to the interplanetary geometry (such as beam solid angle and extent of diffusion and of channelling) are unknown, but a consistency argument can be established as follows.

Assuming isotropy (since we cannot distinguish whether an anistropy exists at these energies with our data) and using the diffusion fit exhibited in Figure 4, we can use the slope and intercept numberically derived from that fit to calculate N. Since

$$\ell n(I t^{1.5}) = \ell n \frac{N\beta c}{32\pi(\beta c\lambda\pi/3)^{1.5}} - \frac{3R^{2}\cdot}{4\beta c\lambda t}$$

is seen to fit 16.2 - 28. R/ct, N is found to be $5 \times 10^{31\cdot}$ electrons of energy above 3 MeV. Further, assuming a power law in total energy with index $\approx$ -3.2, the total number of electrons above $\approx$ 100 KeV at the sun is found to be $3\times10^{33\cdot}$ in agreement with the lower limit to, but about 2 orders of magnitude below, the best estimate of the value expected for the flare of 7 July 1966, based on

calculations involving the x-ray data (Holt and Cline, 1968). Of course, the possible interplanetary channeling and anisotropy have been neglected, which may each introduce factors as much as or greater than an order of magnitude, but since these may effect the calculation in opposite directions, the result is at least qualitatively meaningful. It is therefore reasonable to relate the observed electrons to those at the flare site, but to conclude that most of the flare electrons do not escape into interplanetary space.

The only previous observation of high-energy solar electrons was that made at balloon altitudes by Meyer and Vogt (1962). Their measurement showed an increase in the 100- to 1000-MeV electron component during a period of time several days after the flares of 18 and 20 July 1961. Their data also differed in that the spectrum was much flatter, having an index of -2. If we relate their result (for which the integral intensity above $\approx$ 100 MeV was $\approx$ 0.03 electrons cm^{-2} sec^{-1} $ster^{-1}$ late in the event) to the 7 July 1966 event (for which the integral intensity above $\approx$ 3 MeV was $\approx$ 3. electrons cm^{-2} sec^{-1} $ster^{-1}$ at event maximum), we find that the relative electron productions for the two flares can be only very roughly compared, due to the great difference in energy and due to the lack of information as to the time history of the 1961 event. Assuming a time dependence like that of the 1966 event, and assuming that the 18 July flare was more likely to be the particle producer, a ratio of $\approx 10^5$ results, perhaps too large for the electrons of the 1961 event to be ascribed to the same process as those of the 7 July 1966 event.

4. The 28 August and 24 March 1966 Events

The 28 August and 24 March 1966 events are two primary solar particle events which provide valid comparisons with the 7 July event. The 28 August flare took place 4 degrees each of central median in the same source region as did the 7 July flare and was followed by a proton event slightly smaller than, but comparable to that of 7 July. It also produced an x-ray burst in the high-energy region having the same spectrum and about half the intensity as that of 7 July (Cline, Holt and Hones, unpublished), both of which indicate that the July and August flares were very similar in their particle-producing aspects. The 28 August flare, on the other hand, showed no indication of interplanetary electron emission similar to the data shown for the July flare in Figure 2; an analysis of the detected particles produced only upper limits to the electron intensity, as indicated in Figure 7, which were more than one decade below the intensities recorded for the 7 July event. Since both the overall particle output and the x-ray intensities of the two flares compared within a factor of 2 to 3, the electron upper limit of the August event is sufficiently low such as to indicate that the relativistic electron propagation properties of these events are significantly different. It should be further noted that Lin and Anderson (1967) find the 7 July event to be simple and prompt, while the 28 August event is complex in its > 40 KeV electron property, correlating with the facts that the 7 July flare was $\approx 45°$ west and the 28 August flare was east of central meridian. It might be concluded from these indications that a trend exists towards correlating relativistic electron propagation towards the earth with the simple events which have an origin near the Archimedes spiral line which connects the sun to the earth. However the data from some other events do not support this

view. For example, the 24 March 1966 event was more intense both in high-energy x-ray production and in medium-energy protons than the other two flares discussed here, and is ascribed to a flare at 37 degrees West of central meridian. Thus, it would seem to be an excellent candidate for observable electron production. Our detector exhibited no relativistic electron response however, and again only an upper limit well below that of the 7 July intensity level can be set. The absence of electrons in this March event, like that in the 28 August event, does at least correlate with the categorizing of both these events by Lin and Anderson (1967) as complex in their low-energy electron production (this flare is one of very few out of several dozen west of central meridian events they examined which is complex). Another anomaly noted in this event was the occurrence of a weak-intensity proton precursor which took place hours before the x-ray burst and high-intensity particle buildup. The description of this event is thus not as simple as that for the 7 July event.

5. The 14 September 1966, 28 January, 27 February and 11 March 1967 Events.

The 14 September 1966 event is particularly interesting in that the flare is assumed to have taken place at about West 90 degrees. X-ray data are not available, but the radio emission dates the flare to between 1027 and 1037 U.T. The indications of bulk particle arrival began at about 1040, and the arrival of the relativistic electrons was statistically clear as early as 1050, indicating that the energetic particles arrived promptly, with less delay than that observed on 7 July. Moreover, the electrons and medium-energy (16- to 80-MeV) protons arrived and increased in intensity essentially simultaneously, quite unlike the 7 July event when velocity dispersion separated these groups by nearly an hour.

Finally, the time history is seen to be erratic, rather than smoothly following a typical diffusion curve, and to be much longer-lasting than that of the July event, as seen in Fugure 8. Chronologically, this was only the second event to clearly contain relativistic electrons, and the evidence for their presence is similar to that of 7 July except for the fact that their arrival did not precede that of the protons. The energy spectrum of the two events are compared in Figure 6 in which the statistical accuracy is sufficient only to indicate their similarity.

The 28 January 1967 event is even more unusual than the 14 September 1966 event in the sense that all indications point toward its location as on the back of the sun, presumably beyond the west limb since intense proton emission was found at both high and low energies. Studies of sea-level neutron monitor responses (J. A. Lockwood, 1967), as well as the absence of an observed x-ray burst after 0730 U.T. (Cline, Holt and Hones, unpublished), an hour before the high-energy particles arrived, indicate that the flare did not take place on the observable disk of the sun. An interesting feature of this particle event which is apparently becoming more common than was formerly supposed (McDonald and Kinsey, 1967), is the presence of a proton precursor. It began about 5 hours ahead of the great intensity increase at about 0830 U.T. The low-energy proton precursor was considerably more intense than that associated with the 24 March 1966 event, but since the main event was also more intense we assume the two cases are phenomenologically similar. The relativistic electron increase on 28 January 1967, shown in Figure 9, was observed for less than one hour until about 0920 when the detector became non-linear due to the high intensity of incident particles; the time history could not be monitored thereafter. The

energy spectrum of the electrons observed during the onset is of greatly reduced statistical accuracy, but its slope is consistent with those of the other cases. The peak counting rates of both the 28 January 1967 and 2 September 1966 solar proton events were too intense for the detector. However, the September event was followed, after detector recovery, by a long proton intensity decay in which no significant increase of electrons was found, whereas the January event was followed by a series of additional superimposed proton events in which the electron intensity was measurable over several days. These are discussed in the next section.

Several additional solar events of medium size took place, well separated in time, after the 28 January and early February group but before the end of the useful life of IMP-III in May 1967. (One of these, the 14 February event, was at W10 degrees, such that a measurable electron intensity might be expected, but was not a sufficiently large proton event to produce an electron component observable over background). The 27 February and 11 March events, on the other hand, definitely contained relativistic electrons and have time histories, shown in Figure 10 and 11, not dissimilar from that of the 7 July prototype.

The 27 February event can be definitely related to a flare at N27 and E01 due to a medium-size hard x-ray burst observed on OGO-3 (Cline, Holt and Hones, unpublished). The 11 March event is puzzling to the extent that the electron intensity is sufficient to be associated with a high-intensity hard x-ray burst, but none was observed. A very soft burst was observed quite early at around 1700 U.T., and at that time plage 8711 was at the west limb. Qualitatively the event does resemble a west limb or back-side event, but the absence of a flare patrol or related report precludes the absolute identification.

In addition to these more recent events, the 5 February 1965 event can be illustrated at this point. This event was not only a relatively small proton event which occurred relatively early in the present solar cycle, but took place a few degrees east of central meridian. However, as shown in Figure 12, the response observed with IMP-II was indicative of a barely measurable electron intensity with better statistics than, for example, the 28 August 1966 event (which was a larger event at approximately the same longitude). The 5 February 1965 electron data are not as convincing as in those events including and following that of 7 July 1966, but are sufficient, taken together with those events of Spring 1967, to indicate that a longitude correlation of flares with preferential relativistic solar electron production may be premature.

6. The 1 February and 1 April 1967 Events

The very intense 28 January solar proton event was followed by additional proton events on 1 and 3 February, yielding an interplanetary condition which the medium-energy proton intensity was several decades above background for a few weeks throughout early February. During that time a detectable relativistic electron intensity increase was observed with reduced accuracy. Figure 13 shows the electron intensity in early February for which the electron fraction of stopping particles was not predominant, so that the statistical errors are large even though the absolute intensity becomes comparable with that of the 7 July event. The origins of these increases are not clear: solar proton increases began early on 1 February and later on 2 February (J. Kinsey, private communication), the first of which may be due to a flare at 0150 U.T. at E62, (A. Masely, private communication), but there is no clear relationship to the

electron increase. Also, an electron intensity spike at 1500 U.T. on 2 February is followed, several hours later, by a new low-energy proton increase, showing the expected velocity dispersion in the fashion of the 7 July event. Due to the superimposition of the various intensities and the high solar activity in general, it seems we cannot reliably establish the solar connection at present. This, fortunately, is not the case for the majority of the events we observe.

The 1 April event was caught only in the decay phase, as shown in Figure 14. The data therefore do not exist to determine its onset characteristics and identity; it is, however, the only electron event observed between 15 March and 11 May 1967.

7. Conclusions

Two of the general considerations that relate to the data presented above are the problem of the origin of the relativistic solar electrons and the problem of their propagation in interplanetary space. These questions bear directly on the problem of the relation of the interplanetary electrons to the flare electrons responsible for the solar radio and x-ray emissions; these two questions are also naturally related since a determination of the particle number at the source depends on knowledge of the manner of travel to the point of observation.

It is well known that fitting solar-particle data to the standard diffusion-theory picture does not show that interplanetary diffusion takes place; the particles could just as well have spent 10 A.U. in travel in tight spirals close to the sun and then have flown freely out along the interplanetary spiral lines, for example. However, the diffusion treatments employed here are useful since

they show that for at least one noteworthy event the relativistic electrons and the medium-energy protons propagate in a manner consistent with a simple diffusion picture. Also, the similarity between the 7 July prototype and, for example, the 28 September 1961 event, for which this velocity-correction treatment was first devised (Bryant et al., 1965) is quite striking. We thus can conclude, first, that at least for those events appropriately situated in solar longitude, electrons and protons both obey simple diffusion through a velocity transformation to a rigidity- and energy-independent picture over several decades of energy and of rigidity.

Further, this diffusion fit is sensitive to the zero of time used. Figure 15 shows diffusion plots for four different events, similar to that of Figure 4 but varied as a function of injection time, with an 8.3 minute time difference from graph to graph. It is seen that the zero of propagation can in each case be experimentally determined within a few minutes. The time at which it is fixed, in each of those two cases for which the flare x-ray time is known, is just that time of x-ray maximum, adjusted for the 8.3 minute propagation delay. This result is of interest since it implies that the interplanetary electrons are produced and injected into their region of diffusion at that moment when the flare electrons are accelerated, producing the x-ray and microwave radio emissions. Such a picture can be contrasted with the picture of a delayed interplanetary production occurring some tens of minutes later when longer wavelength radio emissions are most intense: Figure 16 shows the dynamic radio spectrum of the 7 July 1966 event (Y. Hakura, private communication) in which the 1000 MHz radio emission is seen to maximize between 0100 and 0200

U.T., during which time the interplanetary electron intensity does build up. One thus might be tempted to associate the interplanetary electrons with this source. The diffusion fit to the (0037 U.T. — 8 minutes) microwave maximum is, however, self-consistent: the electrons could not both have been emitted from the sun at, or after, the later time of 0100 U.T. and have been propagated in a simple diffusion manner. We thus conclude, second, that the interplanetary electrons are created simultaneously with the flare electrons which cause the microwave and x-ray bursts and are probably a sample of that same flare electron population.

As was mentioned earlier in this paper, the total number of interplanetary electrons from a flare cannot be accurately determined. The 7 July 1966 diffusion fit estimate did yield, however, a number that was in agreement with the lower limit to, or perhaps two orders of magnitude below, the number of x-ray and microwave-producing electrons at the flare site estimated from those data. One can conclude, third, that probably a small fraction of flare electrons escape into interplanetary space.

It is also possible to compare the relative spectra and total numbers of interplanetary protons and relativistic electrons produced by a given flare. Since all the observed particles propagating from the 7 July 1966 event were shown to obey a velocity transformation (Figure 5) to yield the same distribution in path lengths, it is possible, in the manner described by Bryant et al. (1965), to define the source spectra of solar protons and electrons, that is, the spectrum at injection into the diffusion medium. These can then be compared so as to determine the relative production of interplanetary particles of these two kinds. Using the data displayed in Figure 5, it is found that the 7 July protons have a

source spectrum with a slope of about -2.±0.4, again similar to the 28 September 1961 event. On a kinetic-energy basis, the > 3-MeV electron source differential intensity is plotted about two decades below the proton curve, whereas on a kinetic energy per unit mass (or γ -1) basis, converting to a function of velocity alone, it falls at least a decade above. This result can be compared with that obtained by Brunstein and Cline (1966) in an investigation of the relative velocity spectra of cosmic-ray electrons and protons. In that category, it was found that in the same interval (of 3- to 12-MeV electrons) the differential intensity vs. γ plots of electrons and protons are essentially the same. We can therefore conclude, fourth, that in events like that of 7 July the sun may be more effective in producing relativistic interplanetary electrons, relative to that effectiveness for proton production, than is the galactic source of cosmic rays (in spite of the fact that probably only a fraction of the solar electrons escape).

It is curious that the 7 July 1966 event was nearly solely responsible for all the above conclusions; the question of its uniqueness is therefore worth investigating. As we mentioned earlier, the detector was sensitive to a band in the sky of relatively fixed position; this region included the ecliptic plane at 45 to 60 degrees west of the sun only during certain seasons of the year. This sensitive orientation was at maximum during months when no events were monitored, and at minimum for some of the electron events observed. We therefore do not believe our event selection was an instrumental effect correlated with extreme anisotropies in the electron beam, but was rather a property of the solar and interplanetary conditions and the earth's orientation. We can thus conclude, fifth, that only a sample of the electron events obey simple diffusion (similar to the observation of Bryant et al. (1965) that not all solar proton events do) and that

only some electron events can be directly and quantitatively related to the solar radio and x-ray observations.

Finally, we may compare the considerations discussed above with those results found for > 40 KeV solar electrons by Anderson and Lin (1966), that the low-energy electrons were collimated and anisotropic with a net out-flow of particles from the sun, and (Lin and Anderson, 1967), that the categorization of events is either simple, in which the earth is close to intercepting the Archimedes-spiral solar field line from the west-longitude flare region, or complex, in which the flare region is usually near, or east of, central meridian. Although our sample of events is much smaller in number, due to the higher-energy threshold of observation, their general picture seems to have some validity at these higher energies; however, there exist too many exceptions to allow one to generalize: (a) both the 28 August 1966 and 27 February 1967 flares had the same east-central longitude but differed in their electron productions, (b) both the 24 March 1966 and 7 July 1966 flares were west longitude but were quite different, and (c) at least two of the relatively intense events could not be identified with visible flares: (28 January and 11 March 1967), and probably originated in active regions behind the west limb. We thus conclude, sixth, that although nearly all solar particle events of reasonable size are now seen to produce interplanetary relativistic electrons, one cannot correlate their production and propagation to solar conditions with a simple model based on solar longitude alone.

Acknowledgements

We would like to thank J. Kinsey for supplying us with the 7 July 1966 proton data prior to publication.

REFERENCES

Anderson, K. A., and Lin, R. P.: 1966, 'Observations on the propagation of solar flare electrons in interplanetary space,' Phys. Rev. Letters 16, 1121-1124.

Boischot, A., and Denisse, J. F.: 1957, 'Les emissions de type IV et l'origine des rayons cosmiques associes aux eruptions chromospherique,' Compt. Rend. 245, 2194-2197.

Bryant, D. A., Cline, T. L., Desai, U.D., and McDonald, F. B.: 1965, 'Studies of solar protons with Explorers XII and XIV,' Ap. J. 141, 478-499.

Brunstein, K. A., and Cline, T. L.: 1967, 'Possible spectral neutrality of cosmic radiation,' Nature 209, 1186-1188.

Cline, T. L., Holt, S. S., and Hones, E. W., Jr.: 1968, 'High-energy x-rays from the solar flare of July 7, 1966,' J. Geophys Res. 73, 434.

Cline, T. L., Ludwig, G. H., and McDonald, F. B.: 1964, 'Detection of interplanetary 3- to 12- MeV electrons,' Phys. Rev. Letters 13, 786-789.

Guss, D.: 1964, 'Distribution in heliographic longitude of flares which produce energetic solar particles,' Phys. Rev. Letters 13, 363-364.

Holt, S. S., and Cline, T. L.: 1968, 'On the generation of synchrotem and x-ray emission from electrons with energy below mc^2 in solar flares,' Ap. J., in press.

Lin, R. P., and Anderson, K. A.: 1967, 'Electrons > 40 KeV and Protons > 500 KeV of solar origin,' Solar Physics 1, 446-464.

Lin, R. P., Kahler, S. W., and Roelof, E. C.: 1967, 'Solar flare injection and propagation of 0.5 - 20 MeV protons and $\gtrsim$ 45 KeV electrons deduced from large spatial flux gradients observed on 7-9 July, 1966,' Solar Physics (in press).

Lockwood, J. A.: 1967, 'Cosmic-Ray solar flare effect on 28 January 1967 as recorded by neutron monitors,' Bull. Am. Phys. Soc. 12, 1068.

McDonald, F. B., and Kinsey, J. H.: 1967, 'Cosmic-ray observations over solar minimum,' Bull. Am. Phys. Soc, 12, 1067-1068.

Meyer, P. and Vogt, R.: 1962, 'High-Energy electrons of solar origin,' Phys. Rev. Letters 8, 387-389.

Takakura, T.: 'Theory of Solar bursts,' Solar Physics 1, 304-353.

Van Allen, J. A., and Krimigis, S. M.: 1965, 'Impulsive emission of $\sim$ 40 KeV electrons from the sun,' J. Geophys. Res. 70, 5737-5751.

Wild, J. P.: 1962, 'The radio emission from solar flares,' J. Phys. Soc. Japan 17, Suppl. A-II, part II, 249-258.

FIGURE CAPTIONS

Figure 1. Energy loss vs. energy vs. intensity patterns observed with the IMP-III cosmic-ray detector (a) during solar quiet times, indicating the cosmic-ray protons and electrons, and the cosmic-ray induced background, and (b), during most of the peak intensity and decay portions of the solar particle event of 7 July 1966 in which the solar protons dominate the pattern.

Figure 2. The intensity patterns observed during several time intervals in the onset of the 7 July 1966 event when an early group of electrons is gradually superceded by 16- to 80-MeV protons. The points in these four patterns represent about 1/600, 1/1000, 1/1300 and 1/1500 of the total numbers of stopping particles detected in the periods shown, respectively.

Figure 3. The time history of $>$ 3-MeV solar electrons, contrasted with the 16- to 80-MeV solar-proton time history, for the 7 July 1966 event. The electrons are seen to be well towards maximum intensity before the lower-velocity protons begin to arrive.

Figure 4. A plot of ln $(I\, t^{1.5})$ vs $t^{-1.}$ for the 7 July event, showing the straight-line fit to a standard diffusion equation. Here $t = T - T_o$ in which the zero of time was chosen to be 8.3 minutes (the transit time across 1 A.U.) before the observed 0037.5 U.T. maximum of energetic x-rays. The slope yields a mean free path of 0.027 R and the intercept is 5×10^{31} particles in the energy range observed.

Figure 5. (a) Profiles of the observed intensity of 16 to 38 MeV, 38 to 59 MeV, 59 to 80 MeV protons, and > 3. MeV electrons plotted against time; (b) profiles of each relative intensity, I/I_{max}, plotted against distance travelled, $x = vt$, where v is the mean velocity for each energy group. The fit to a common curve is clearly seen. The velocities of the protons are between 0.18 and 0.4 that of the electrons ($\approx c$), but the rigidities of the protons (175 to 400 MV) are up to two orders of magnitude higher than those of the electrons (>3.5 MV).

Figure 6. Differential energy spectra of the observed electron events comparing onset and decay portions wherever statistically meaningful. In most cases a slope of -3. to -3.5 is a reasonable fit, although some steepening of the spectrum with time may be indicated.

Figure 7. The 28 August 1966 solar-proton time history, in which the relativistic electrons were relatively absent (in contrast to the 7 July event) at least to the extent that the upper limits to the electron intensity are well below comparable figures in the 7 July event.

Figure 8. The 14 September 1966 event, in which the electrons and low-energy protons arrive more nearly simultaneously than in the 7 July event.

Figure 9. The intense 28 January 1967 event, in which a proton precursor is followed by an abrupt, large intensity increase which quickly becomes impossible to monitor, but in which some electron response is briefly indicated.

Figure 10. The 27 February 1967 electron event. Although this was due to a central meridian flare, the electron intensity is definitely measurable, unlike that for the earlier east-central event of 28 August 1966.

Figure 11. The 11 March 1967 event. This particle event is very similar to that following the 7 July 1966 west-longitude flare, but the flare in this case cannot be identified. It is reasonable to conjecture that it may be over the west limb, similar to that of 28 January 1967.

Figure 12. The 5 February 1965 event. This 9-degree east-longitude flare event occurred early in the present cycle, yet, as shown here, presented a barely observable electron intensity. These data alone might be insufficient to establish the presence of relativistic electrons in such an event, but the similarity between this time history and several of the others is convincing in retrospect.

Figure 13. The early February series electron time history, seen on an hourly basis. Most of the electron data were obtained by subtraction in the presence of a high-intensity proton background, and hence are not as clean as in other events, but the presence of electrons is definitely indicated. This event is close to one solar rotation prior to the 27 February event, also an electron emitter.

Figure 14. Hourly averages for the time history of the 1 April 1967 event. There is no known solar proton event to correlate with these electron data.

Figure 15. Diffusion plots of ln $[I(T-T_o)^{1.5}]$ vs. $(T-T_o)^{-1.}$ for the electron events of 7 July and 14 September 1966, and 27 February and 11 March 1967, in which the T_o was varied by 8.33 minutes from graph to graph. The best fits in the two events for which high-energy x-ray data exist, 7 July 1966 and 27 February 1967, very closely coincide with the times of x-ray maximum intensity at the sun.

Figure 16. The dynamic radio spectrum of 7 July 1966 (Y. Hakura, private communication) in which the observed time of peak microwave intensity is seen to be 0037 U.T., coincident with the time of $\approx$ 100 keV x-ray intensity maximum (Cline, Holt, and Hones, 1968).

This time is 0029 at the sun, that time seen in Figure 15 to be the best fit for the T_o of the electron propagation assuming simple diffusion.

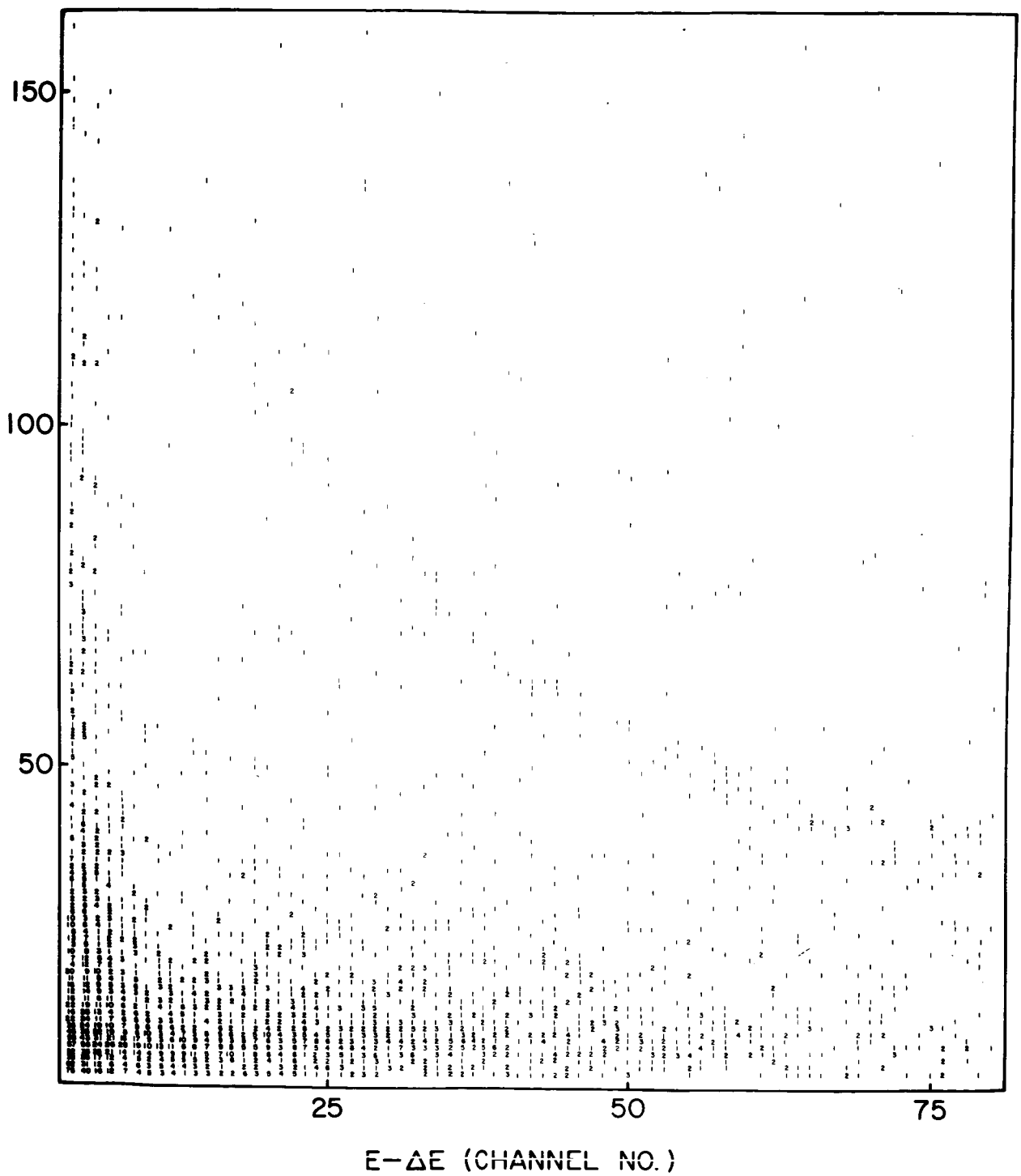

Fig. 1a

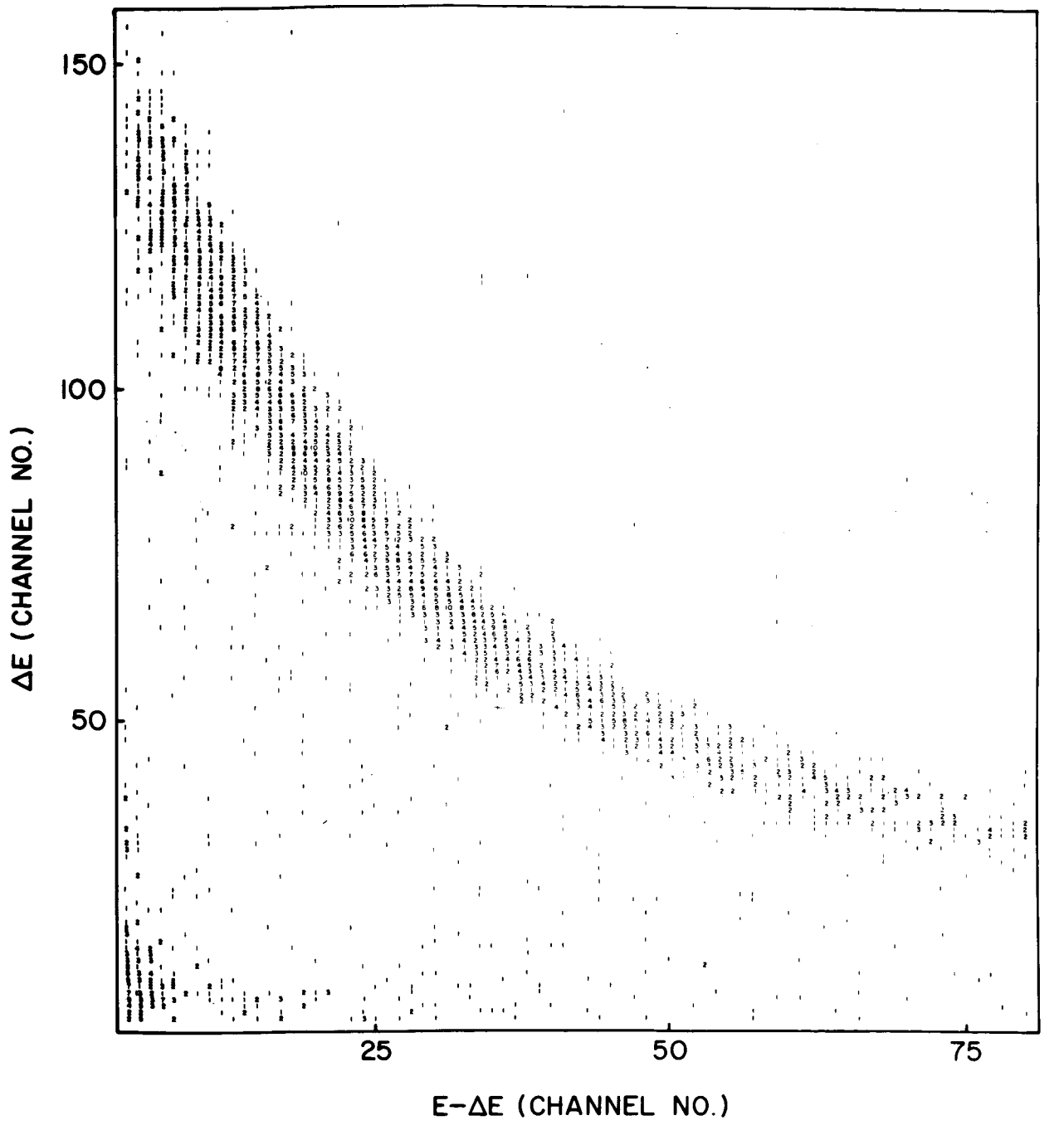

Fig. 1b

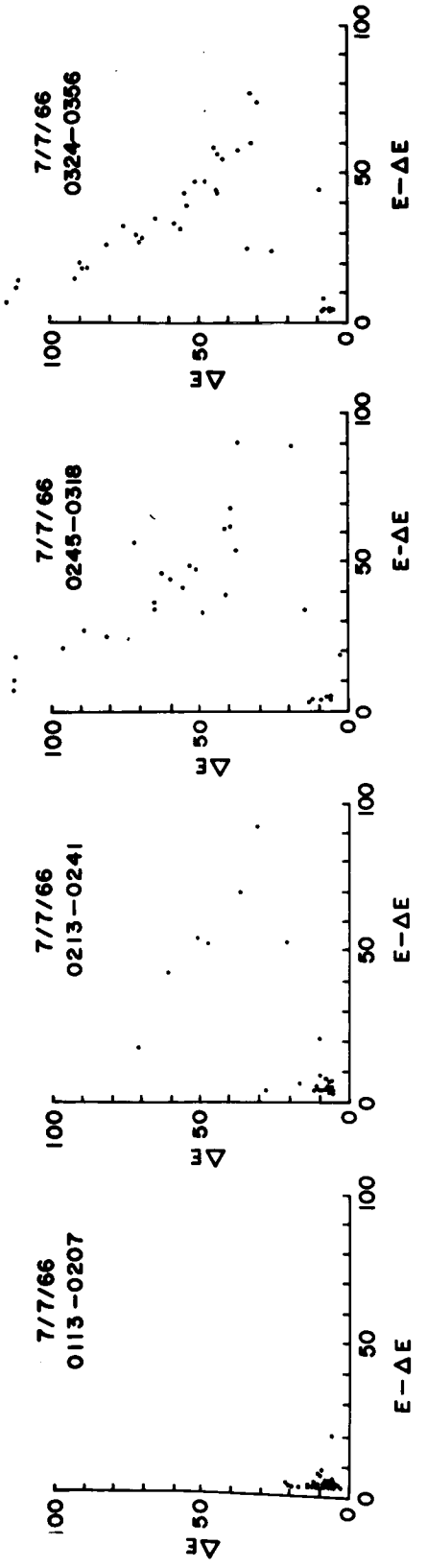
7/7/66
0113-0207
7/7/66
0213-0241
7/7/66
0245-0318
7/7/66
0324-0356
ΔE
E-ΔE
0
50
100

Fig. 2

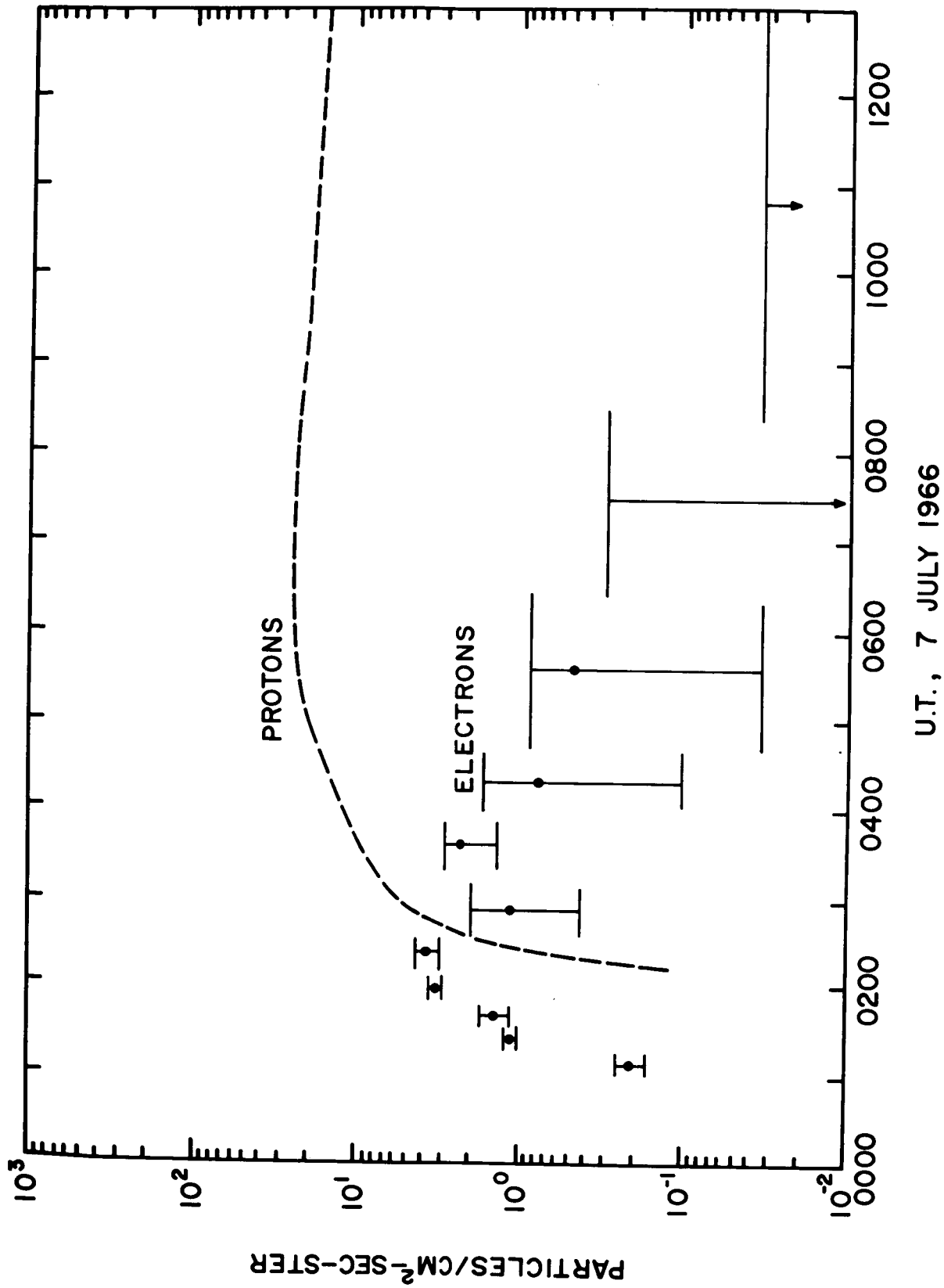
PROTONS
ELECTRONS
PARTICLES/CM²-SEC-STER
U.T., 7 JULY 1966
10³
10²
10¹
10⁰
10⁻¹
10⁻²
0000
0200
0400
0600
0800
1000
1200

Fig. 3

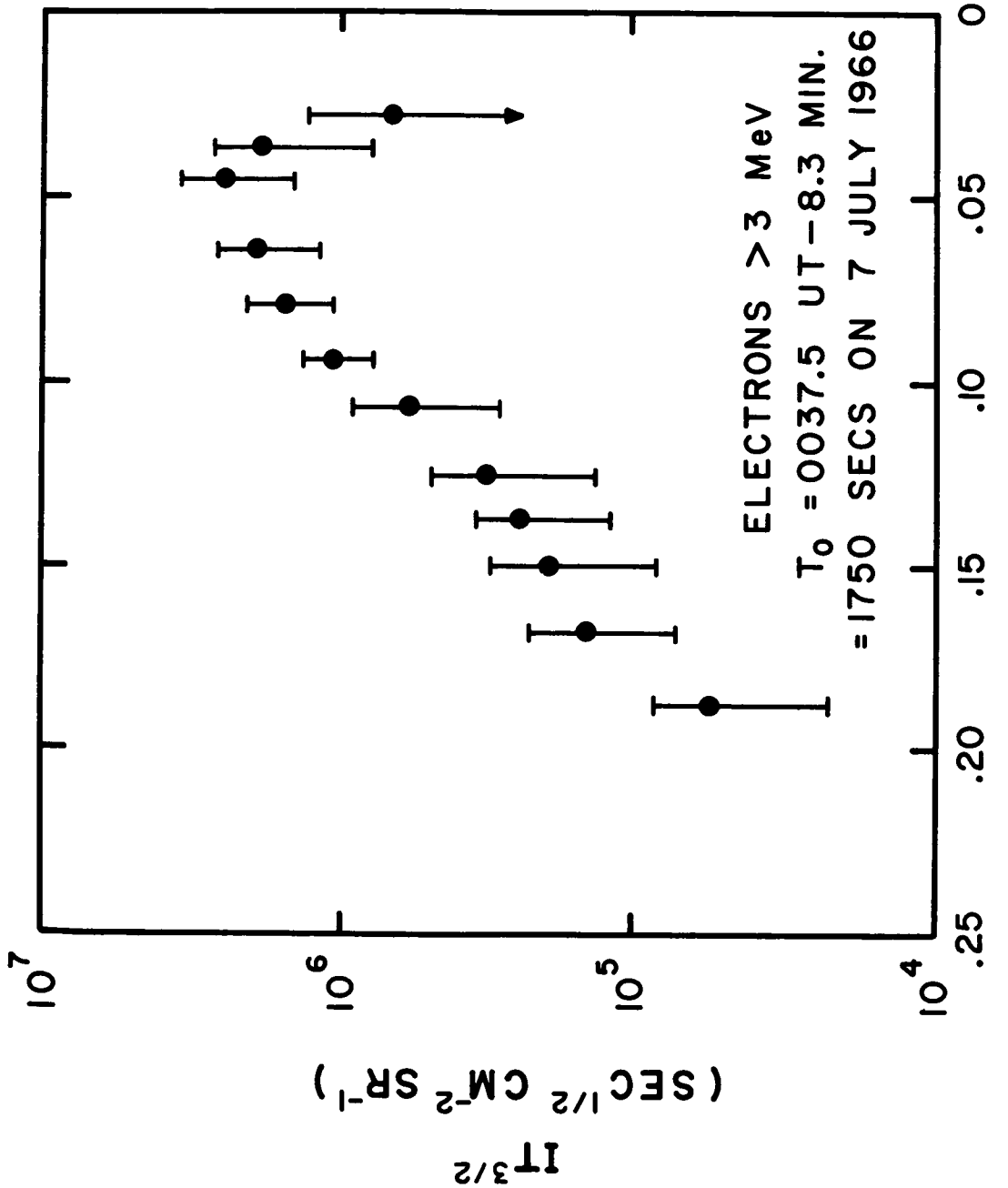
ELECTRONS >3 MeV
T_0 = 0037.5 UT − 8.3 MIN.
= 1750 SECS ON 7 JULY 1966
R / CT
0
.05
.10
.15
.20
.25
10^7
10^6
10^5
10^4
$IT^{3/2}$
(SEC$^{1/2}$ CM^{-2} SR^{-1})

Fig. 4

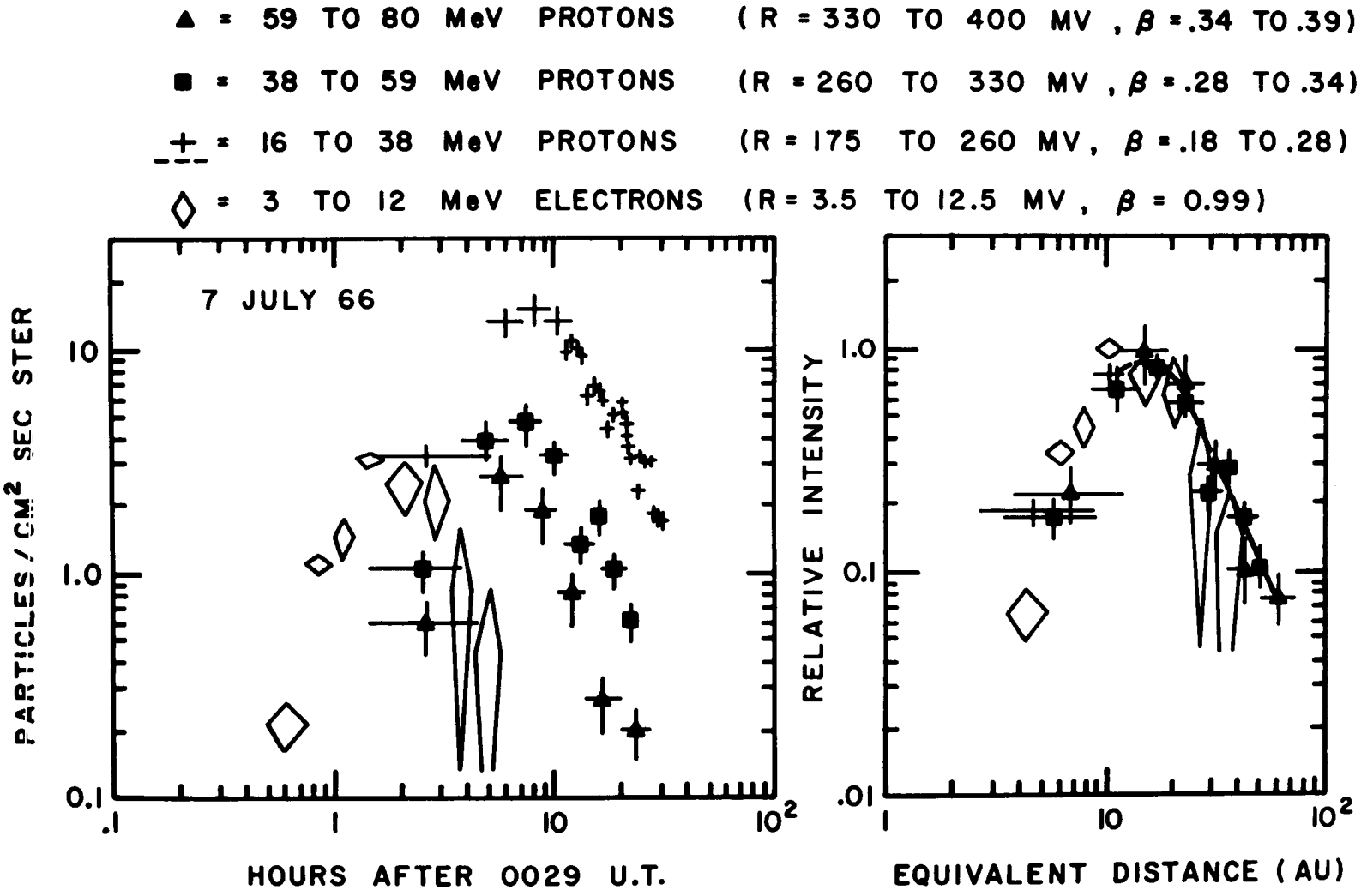
▲ = 59 TO 80 MeV PROTONS (R = 330 TO 400 MV, β = .34 TO .39)
■ = 38 TO 59 MeV PROTONS (R = 260 TO 330 MV, β = .28 TO .34)
+ = 16 TO 38 MeV PROTONS (R = 175 TO 260 MV, β = .18 TO .28)
◇ = 3 TO 12 MeV ELECTRONS (R = 3.5 TO 12.5 MV, β = 0.99)
7 JULY 66
PARTICLES / CM² SEC STER
10
1.0
0.1
.1
1
10
10²
HOURS AFTER 0029 U.T.
RELATIVE INTENSITY
1.0
0.1
.01
1
10
10²
EQUIVALENT DISTANCE (AU)

Fig. 5

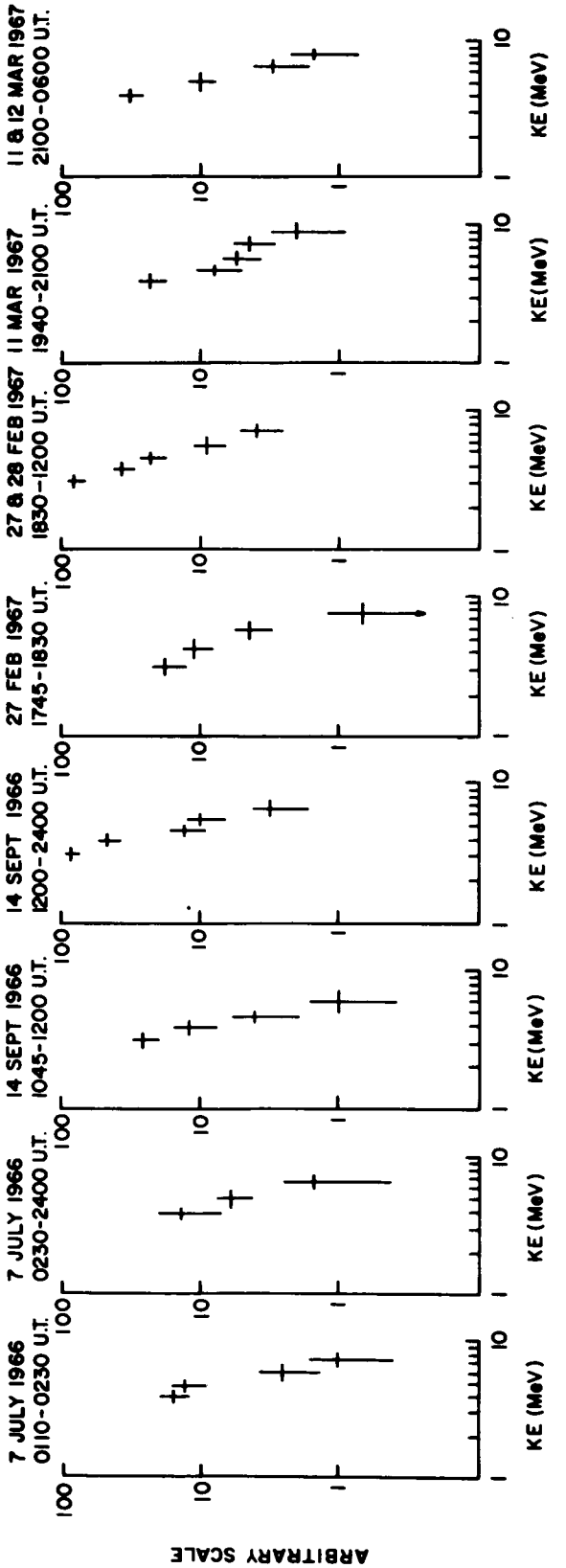
7 JULY 1966
0110-0230 U.T.
7 JULY 1966
0230-2400 U.T.
14 SEPT 1966
1045-1200 U.T.
14 SEPT 1966
1200-2400 U.T.
27 FEB 1967
1745-1830 U.T.
27 & 28 FEB 1967
1830-1200 U.T.
11 MAR 1967
1940-2100 U.T.
11 & 12 MAR 1967
2100-0600 U.T.
KE (MeV)
ARBITRARY SCALE

Fig. 6

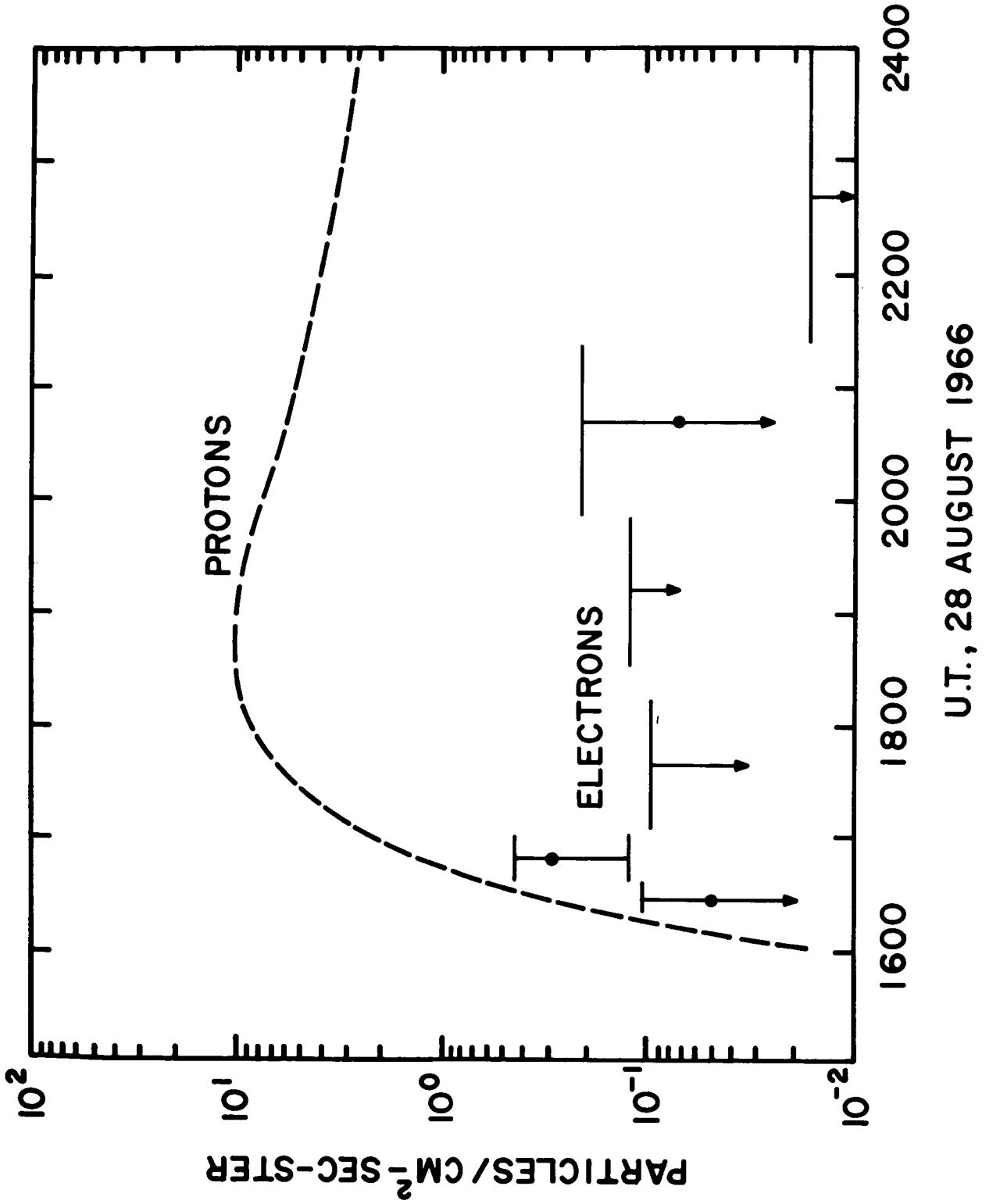
PROTONS
ELECTRONS
PARTICLES/CM²-SEC-STER
10²
10¹
10⁰
10⁻¹
10⁻²
1600
1800
2000
2200
2400
U.T., 28 AUGUST 1966

Fig. 7

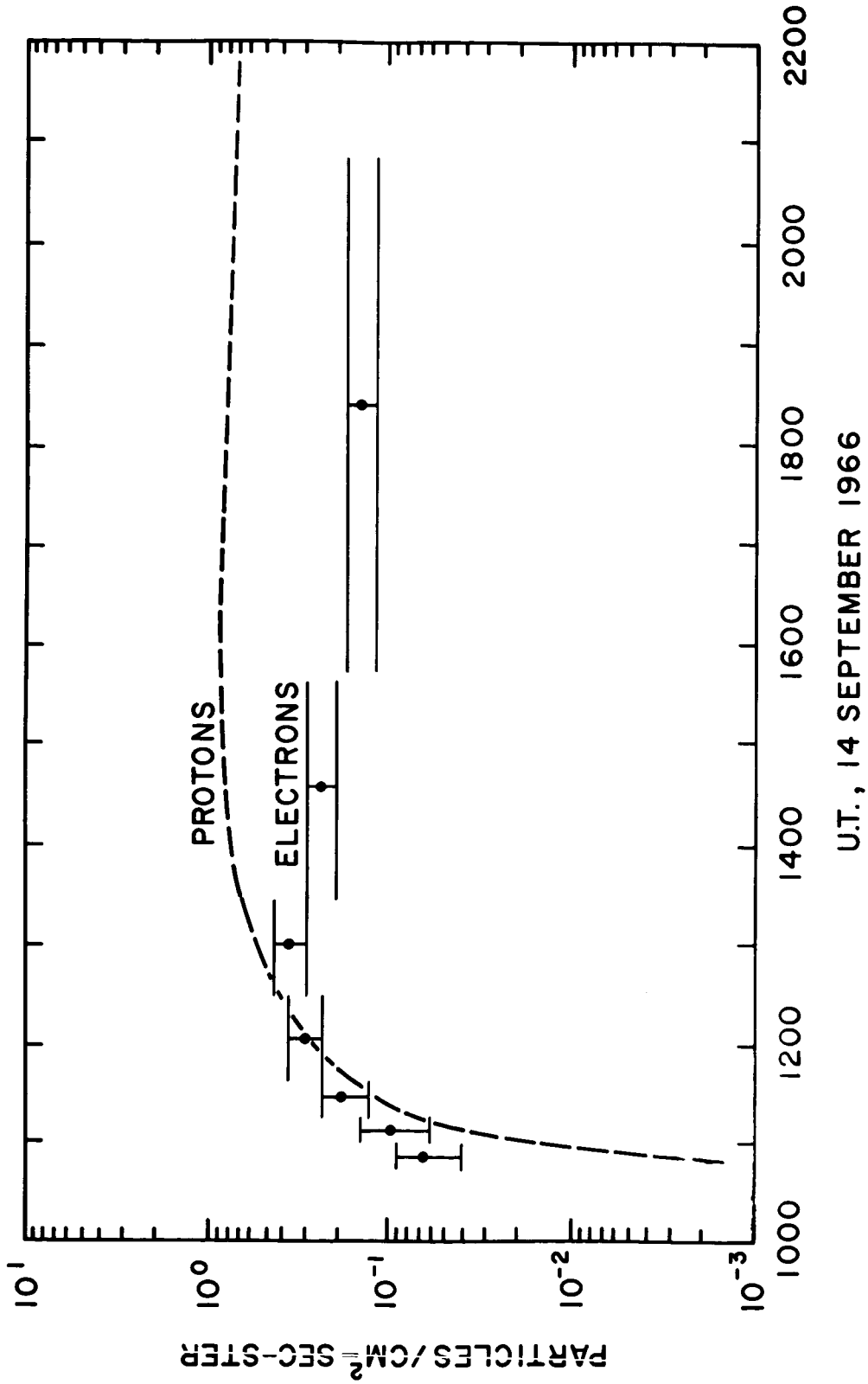
PROTONS
ELECTRONS
PARTICLES/CM²-SEC-STER
10⁻¹
10⁰
10⁻¹
10⁻²
10⁻³
1000
1200
1400
1600
1800
2000
2200
U.T., 14 SEPTEMBER 1966

Fig. 8

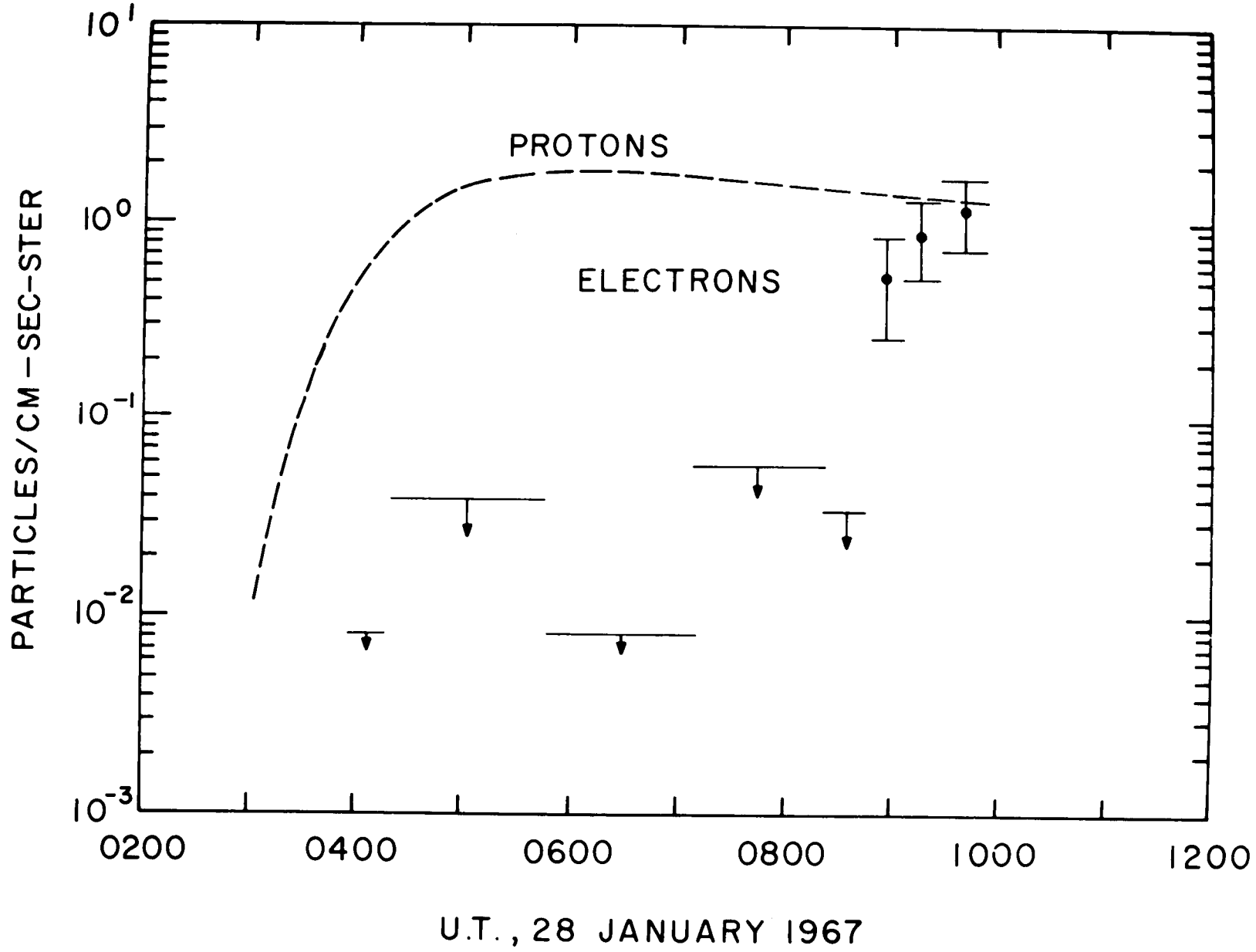
PROTONS
ELECTRONS
PARTICLES/CM-SEC-STER
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0200
0400
0600
0800
1000
1200
U.T., 28 JANUARY 1967

Fig. 9

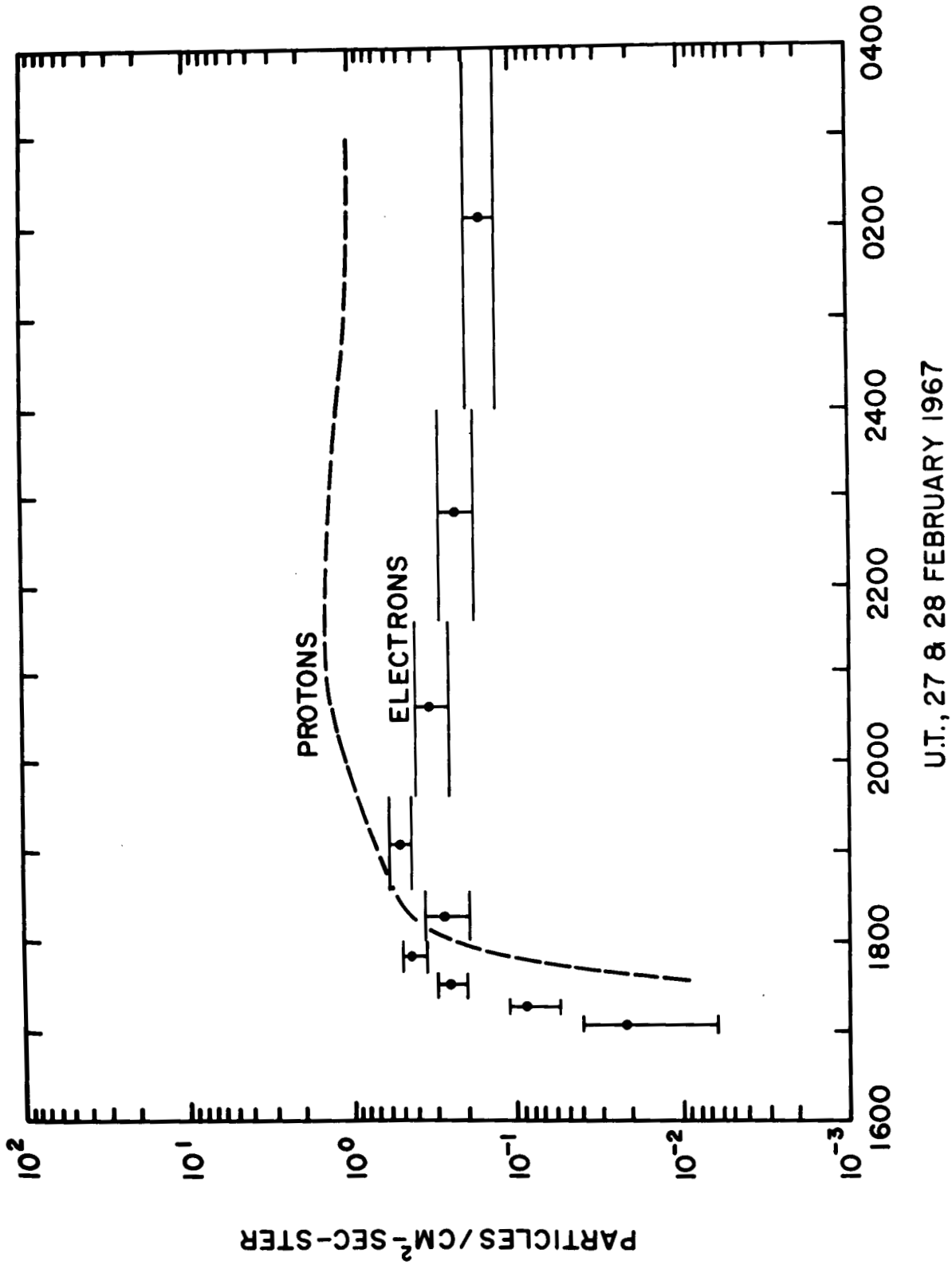
PROTONS
ELECTRONS
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
PARTICLES/CM^{2}-SEC-STER
1600
1800
2000
2200
2400
0200
0400
U.T., 27 & 28 FEBRUARY 1967

Fig. 10

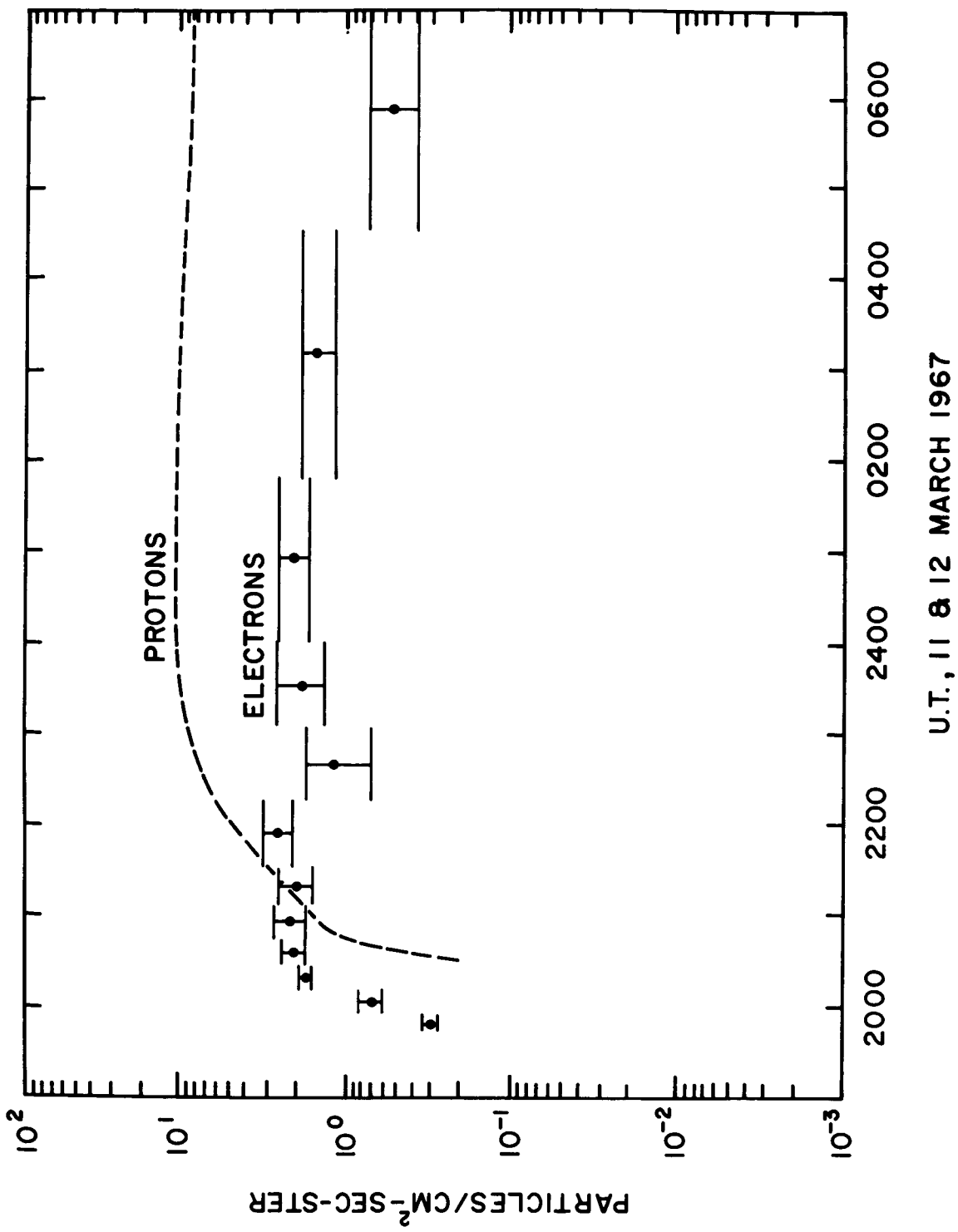
PROTONS
ELECTRONS
PARTICLES/CM²-SEC-STER
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
2000
2200
2400
0200
0400
0600
U.T., 11 & 12 MARCH 1967

Fig. 11

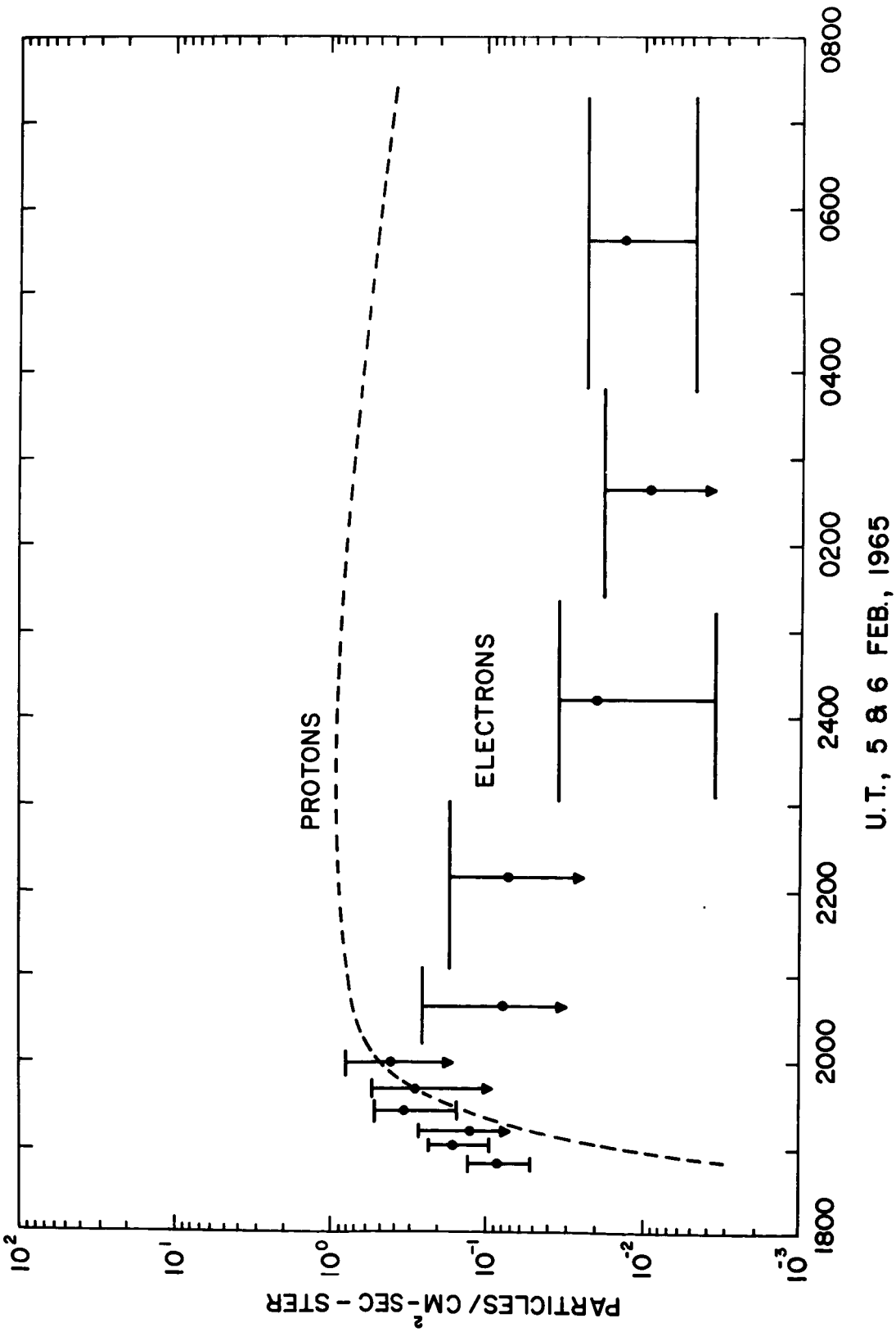
PROTONS
ELECTRONS
PARTICLES/ CM²-SEC - STER
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
1800
2000
2200
2400
0200
0400
0600
0800
U.T., 5 & 6 FEB., 1965

Fig. 12

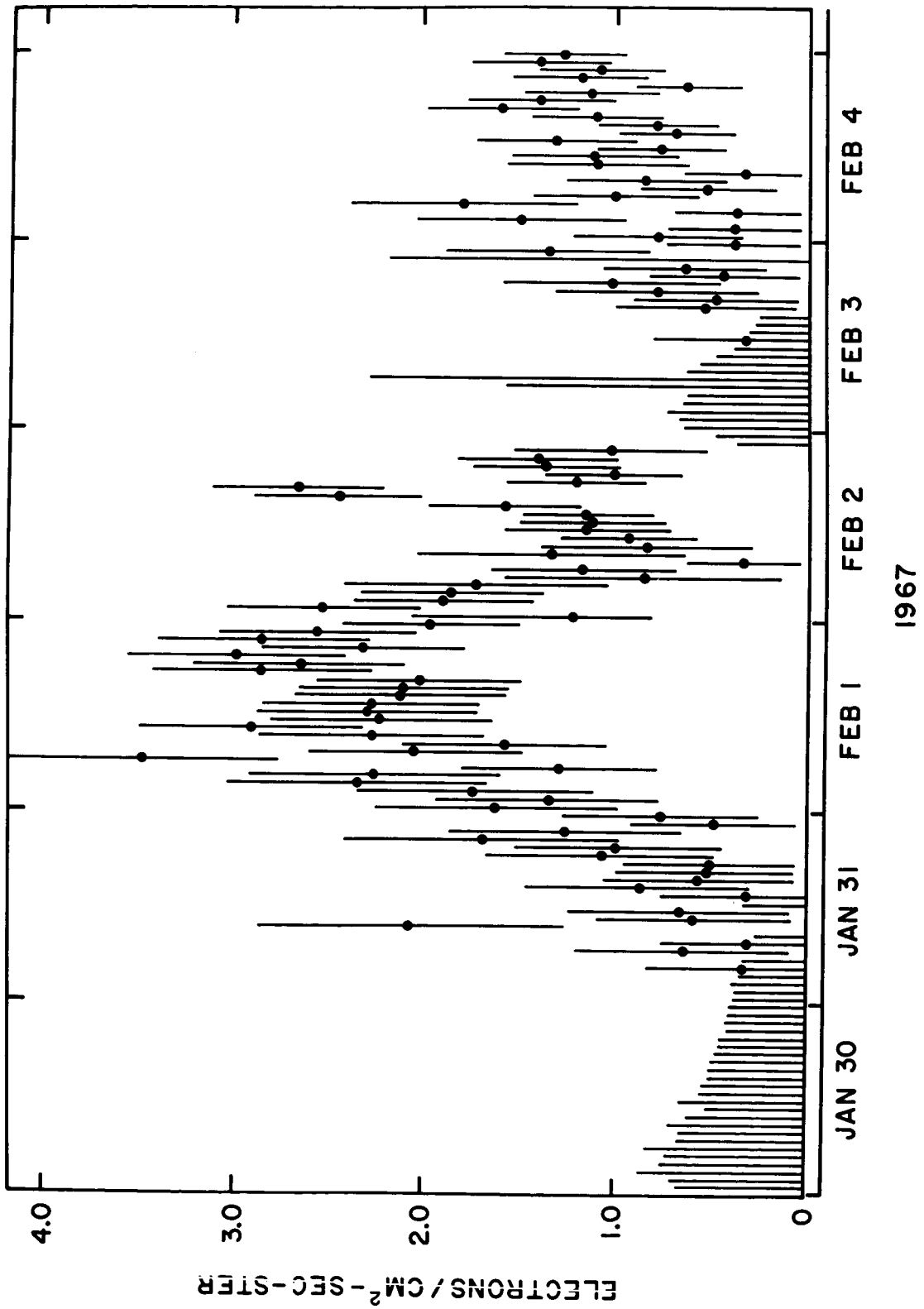
ELECTRONS / CM^2-SEC-STER
4.0
3.0
2.0
1.0
0
JAN 30
JAN 31
FEB 1
FEB 2
FEB 3
FEB 4
1967

Fig. 13

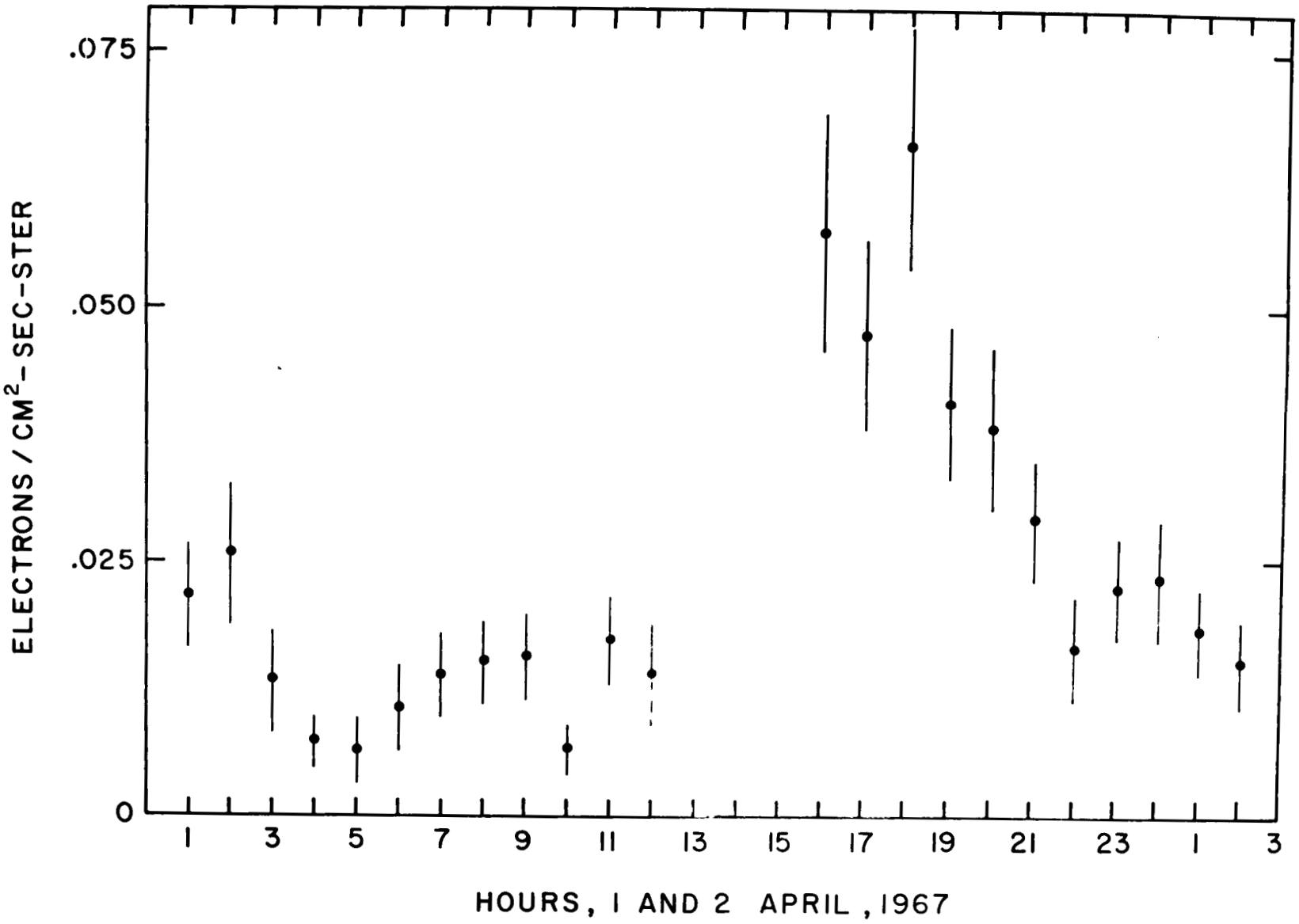
.075
.050
.025
0
ELECTRONS / CM²-SEC-STER
1
3
5
7
9
11
13
15
17
19
21
23
1
3
HOURS, 1 AND 2 APRIL, 1967

Fig. 14

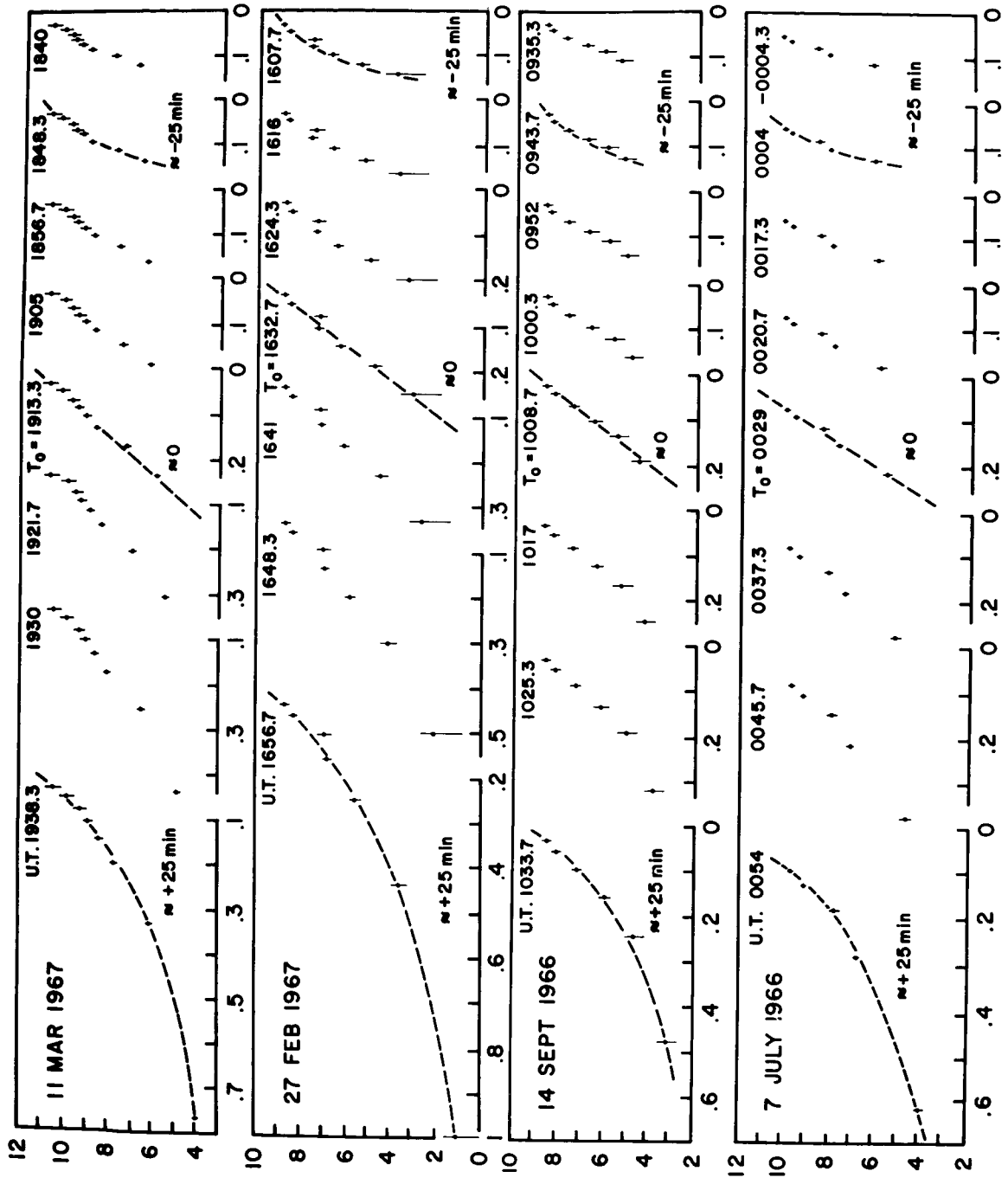
11 MAR 1967
U.T. 1938.3
1930
1921.7
T₀ = 1913.3
1905
1856.7
1848.3
1840
≈ +25 min
≈0
≈ -25 min
27 FEB 1967
U.T. 1656.7
1648.3
1641
T₀ = 1632.7
1624.3
1616
1607.7
≈ +25 min
≈0
≈ -25 min
14 SEPT 1966
U.T. 1033.7
1025.3
1017
T₀ = 1008.7
1000.3
0952
0943.7
0935.3
≈ +25 min
≈0
≈ -25 min
7 JULY 1966
U.T. 0054
0045.7
0037.3
T₀ = 0029
0020.7
0017.3
0004
-0004.3
≈ +25 min
≈0
≈ -25 min
Ln [I (T−T₀)^1.8] (ARBITRARY UNITS)
R / C(T−T₀)

Fig. 15

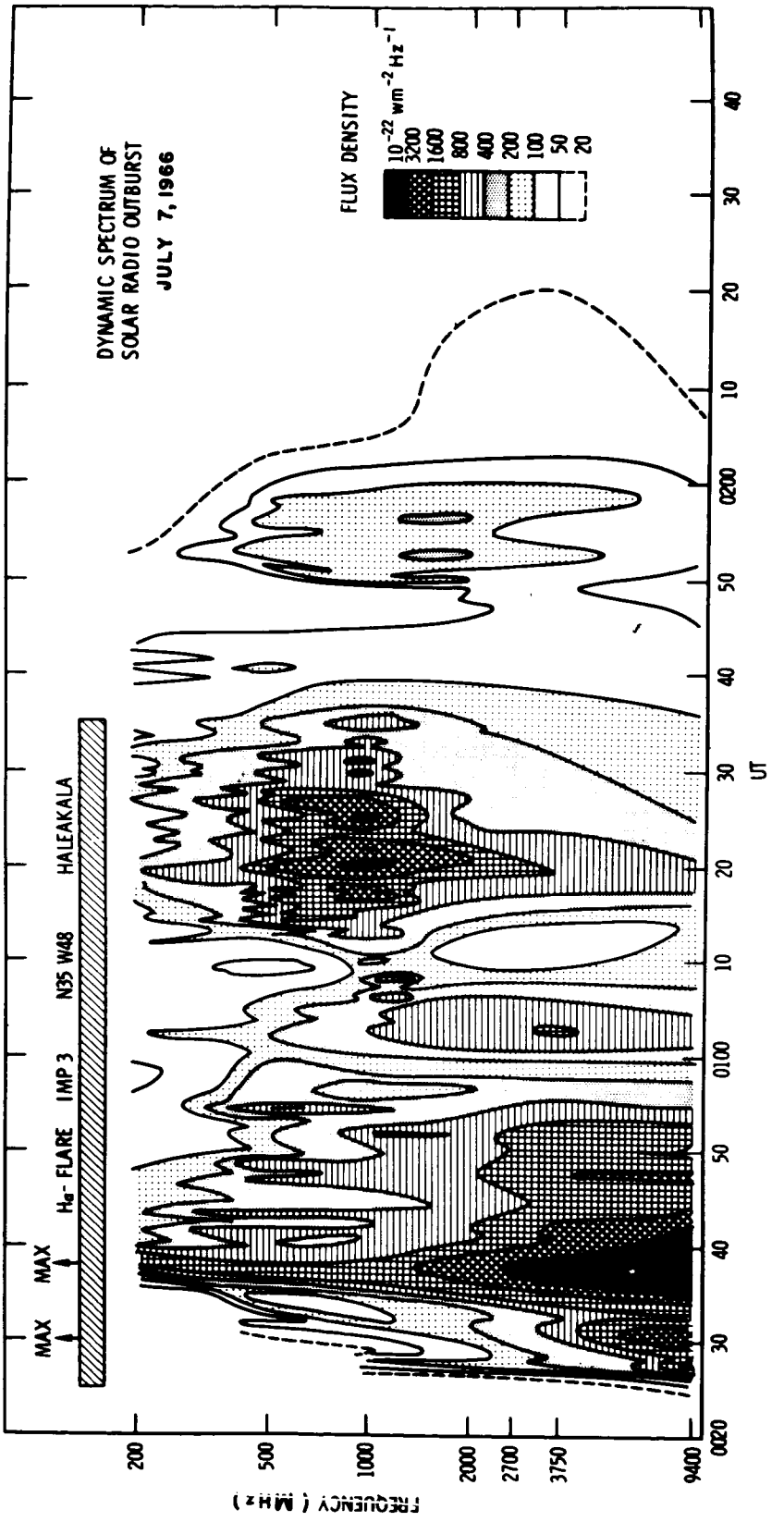
DYNAMIC SPECTRUM OF
SOLAR RADIO OUTBURST
JULY 7, 1966
FLUX DENSITY
10^{-22} wm^{-2}Hz^{-1}
3200
1600
800
400
200
100
50
20
MAX
MAX
Hα- FLARE
IMP 3
N35 W48
HALEAKALA
200
500
1000
2000
2700
3750
9400
0020
30
40
50
0100
10
20
30
40
50
0200
10
20
30
40
UT
FREQUENCY (MHz)

Fig. 16