U. of Iowa 65-28

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .50

ff 653 July 65

FACILITY FORM 602

N66-15352

(ACCESSION NUMBER)

(THRU)

51

(PAGES)

1

(CODE)

CR 69350

(NASA CR OR TMX OR AD NUMBER)

29

(CATEGORY)

Department of Physics and Astronomy

THE UNIVERSITY OF IOWA

Iowa City, Iowa

U. of Iowa 65-28

Impulsive Emission of ~ 40 keV Electrons from the Sun

by

J. A. Van Allen and S. M. Krimigis*

Department of Physics and Astronomy
University of Iowa
Iowa City, Iowa

July 1965

*Graduate Trainee of National Aeronautics and Space Administration.

ABSTRACT

Using data from a system of three thin-window Geiger tubes and one thin silicon surface barrier detector on the Mars-bound spacecraft Mariner IV, we have observed three interplanetary particle events on May 25-28, June 5-7, and June 13-14, 1965. The particles are identified conclusively as electrons of energy $E_e \gtrsim 40$ keV with steeply falling energy spectrums and with approximately isotropic angular distributions. The maximum unidirectional intensities are 80, 58, and 5 $(\text{cm}^2 \text{ sec sterad})^{-1}$, respectively. The time profiles of intensity exhibit abrupt onsets, increases to maximum values in times of the order of several hours, and gradual declines over periods of the order of a day. It appears that these bursts of interplanetary electrons are emitted impulsively from the sun at approximately the same time as are bursts of radio noise and x-rays observed by others with terrestrial equipment. The interplanetary diffusion of electrons is discussed and it is estimated that about 10^{34} electrons $E_e > 40$ keV are emitted on May 25 and on June 5 and about 10^{33} on June 13. The solar emission of non-thermal electrons has been suggested previously but not observed in such a clear way. Such electrons constitute a new tool for study of the structure of the interplanetary magnetic field and for discussion of the physics of solar flares.

Introduction

We report herein three clear-cut cases of the impulsive emission of ~ 40 keV electrons from the sun and their diffusive propagation through the interplanetary medium. The observations were obtained with equipment on the Mars-bound spacecraft Mariner IV at positions in space quite remote from any celestial body.

By means of a single thin-window Geiger tube on the Venus fly-by spacecraft Mariner II [Van Allen and Frank, 1962] [Van Allen, Frank, and Venkatesan, 1964] we observed some 13 distinct interplanetary particle "events" during the period August 29 to October 30 and November 9 to December 29, 1962. The threshold of the detector was ~ 40 keV for electrons, 0.5 MeV for protons, 1.8 MeV for alpha particles, etc. Using simultaneous data from two other radiation detectors on Mariner II, a large Geiger tube and an ionization chamber [Anderson, 1965], it was possible to show that four of the events were probably due to protons having a steeply falling spectrum between 0.5 and 10 MeV. The identification of the particles in the other events was inconclusive.

Early, though marginal, evidence for interplanetary electrons $E_e \sim$ tens of keV was obtained by Arnoldy, Hoffman, and Winckler [1960] with Pioneer V during the late March --early April 1960 solar proton events. Hoffman, Davis, and Williamson [1962] reported a brief (~ 15 minute) burst of ~ 20 keV electrons at the time of an SC during the solar proton event of September 30, 1961. Their instruments were on Explorer XII, at a geocentric radial distance of 11.9 R_E (earth radii) on the sunward side of the magnetosphere. In view of subsequent extensive studies of this region [Frank and Van Allen, 1964] with electron detectors, it appears quite likely that the electrons observed by Hoffman et al. were associated with phenomena in the magnetospheric transition region.

Frank [his figure 33, 1965] observed a clearer example of an electron ($40 < E_e < 230$ keV) event associated with a small solar proton event on April 15, 1963 with Explorer XIV at ~ 90,000 km in the evening fringe of the magnetosphere. The particle identification was conclusive and the unidirectional intensity j ($E_e > 40$ keV) was $\sim 10^4$ $(cm^2 \text{ sec sterad})^{-1}$. But again, there was the question of magnetospheric influence and the author [Frank, private communication] did not feel justified in regarding the observed electrons as "interplanetary".

Other studies of non-solar-wind electrons in interplanetary space have been concerned with those having energies greater than a few MeV. Meyer and Vogt [1962] suggested the solar emission of electrons in the energy range 100 to 1000 MeV, such electrons having been observed with balloon equipment on July 22, 1961 and not on August 1, 1961. Detailed studies of interplanetary electrons $3 < E_e < 12$ MeV have been made with satellite equipment over the period December 1963--May 1964 by Cline, Ludwig, and McDonald [1964]. The latter authors favor a "cosmic" origin for electrons which they observe but consider it conceivable that they might be emitted from the sun.

Using our new Mariner IV observations of electron events in interplanetary space, we develop, in a subsequent section, the observational association between interplanetary electrons in the tens of keV energy range and solar x-ray and radio noise flares. The literature on the latter subject is extensive [see reviews by Kundu, 1963; Dolan and Fazio, 1965; Wild, 1962] and it has been supposed that energetic electrons in the solar atmosphere are the essential agents for generation of both x-ray and radio noise bursts. Most authors have assumed, either explicitly or implicitly, that the electrons themselves do not escape from the sun. We shall show that this assumption is, at least in part, false.

Interplanetary electrons in the MeV range may or may not share the same origin as those which are the subject of the present paper.

For discussion of the propagation of electrons in the interplanetary medium, we employ a model which has been developed over the years to describe the corresponding phenomenon for protons and other heavy particles which are emitted impulsively from the sun [Parker, 1963; Krimigis, 1965].

Apparatus

The U. of Iowa package of low energy particle detectors on Mariner IV comprises three end-window Geiger-Mueller tubes (EON Type 6213), designated A, B, and C, respectively; and one thin (35 micron) surface barrier solid state detector (Nuclear Diodes, Inc.) having two discrimination levels, designated D_1 and D_2. Each of the four detectors has a conical collimator with a full vertex angle of 60° (nominal). The axes of the collimators of B, C, and D are parallel to each other and at an angle of 70° to the roll axis of the spacecraft, and the axis of the collimator of A is at an angle of 135°. The roll axis of the spacecraft is directed continuously at the sun with an error of less than one degree; rotation of the spacecraft about this axis is controlled in such a way as to point the axis of a spacecraft-fixed, directional antenna approximately toward the earth. Thus, detectors B, C, and D receive particles moving generally outward from the sun and at angles to the sun-to-probe vector of $70 \pm 30°$. The detectors themselves and the complete inner walls of their collimators are shielded from direct light and x-rays from the sun. Detector A receives particles moving generally inward toward the sun at angles to the sun-to-probe vector of $135 \pm 30°$. The sidewall shielding of all detectors has a minimum thickness corresponding to the range of ~ 50 MeV protons. Both discrimination levels of the solid state detector, D_1 and D_2, are insensitive to electrons of any energy in the intensities found in the present series of experiments. This insensitivity is designed into the system (thin detector, high bias level, and 200 nanosecond delay-line pulse-clipping) and is demonstrated in thorough pre-flight testing. It is further confirmed during traversal of the magnetosphere in the early phase of the flight of Mariner IV [Krimigis and Armstrong, 1965]. Detector channels D_1 and D_2 are also insensitive to galactic cosmic rays. In order to have direct observational knowledge of the proper operation of these channels during interplanetary flight, the solid state detector is equipped with an $_{95}Am^{241}$ source of ~ 5.5 MeV alpha particles which provides in-flight counting rates of 0.071 and 0.059 $(sec)^{-1}$ on D_1 and D_2, respectively--rates which are accurately identical to their pre-launch values.

The counting rate of each of the three Geiger tubes is the sum of the rates due to galactic cosmic rays (about 0.6 counts/sec); to electrons, x-rays, protons, alpha particles, etc., which pass through their collimators; and, in some cases, to sidewall penetrations.

Further details concerning the detectors are given in Table I. It is clear that combinations of the data from this simple system of detectors provide information on absolute intensities, particle identification, energy spectra, and angular distributions. In favorable cases particle identification is conclusive.

The five U. of Iowa data channels are part of a commutated sequence of eight as follows: E, B, D_1, D_2, E, B, A, C (where E represents the data channel from another experiment). The basic frame of telemetry during the "cruise mode" (8.33 bits/sec for entire spacecraft), which was employed throughout the period

Table I

Characteristics of Detectors

Detector	Unidirectional Geometric Factor	Omnidirectional Geometric Factor	Particles to Which Sensitive	Dynamic Range
	cm^2 sterad	cm^2		
A	0.044 ± 0.005	~ 0.15	Electrons: $E_e \gtrsim$ 45 keV Protons: $E_p >$ 670 ± 30 keV	From galactic cosmic ray rate of 0.6 counts/sec to 10^7 counts/sec
B	0.055 ± 0.005	~ 0.15	Electrons: $E_e \gtrsim$ 40 keV Protons: $E_p >$ 550 ± 20 keV	"
C	0.050 ± 0.005	~ 0.15	Electrons: $E_e \gtrsim$ 150 keV Protons: $E_p >$ 3.1 MeV	"
D_1	0.065 ± 0.003	---	Electrons: None Protons: $0.50 \leq E_p \leq 11$ MeV	From in-flight source rate to 10^6 counts/sec
D_2	0.065 ± 0.003	---	Electrons: None Protons: $0.88 \leq E_p \leq 4.0$ MeV	"

of the present study, is of 50.4 seconds duration. Unscaled counts from each of the detectors corresponding to the above eight channels are gated in turn into a shift register of 19 bits plus two overflow bits for a 45.0 second period and are read out through the spacecraft telemetry system during the subsequent 5.4 seconds. A complete cycle of eight detectors is completed each 8 x 50.4 = 403.2 sec. Thus the "duty cycle" of each of the four channels A, C, D_1, and D_2 is 11.2% and that of channel B is 22.3%.

Notes on the Trajectory of Mariner IV

The spacecraft Mariner IV of the National Aeronautics and Space Administration/Jet Propulsion Laboratory was launched successfully at 14:22 UT on November 28, 1964 and placed on a trajectory calculated to produce a close approach to the planet Mars on July 15, 1965. During the period of time of interest in the present paper the spacecraft was quite remote from the sun and from all planets and its heliocentric radial distance was less than that of Mars. Some relevant parameters of the trajectory are given in Table II.

Table II

Parameters of Trajectory of Probe Mariner IV
at 01:00 U.T.S.C. (Spacecraft Time) on Dates Shown
[Reference J.P.L./IBSYS-JPTRAJ-SFPRO-111464 of Dec. 15, 1964]

Date	May 26	June 6	June 13
Sun-Probe Distance	1.480	1.502	1.514 A.U.*
Sun-Probe Signal Time for E.M. waves	739	750	756 sec
Probe-Earth Distance	0.962	1.069	1.138 A.U.
Probe-Earth Signal Time for E.M. Waves	480	533	568 sec
Sun-Earth Distance	1.013	1.015	1.016
Sun-Earth Signal Time for E.M. Waves	505	506	507 sec
Earth-Sun-Probe Angle**	40.2	45.4	48.7 deg

*1 A.U. = 1.495985×10^{8} km.

**The trajectory of the probe is approximately in the ecliptic plane. During the period covered here the probe is lagging behind the earth; i.e., clockwise in a heliocentric coordinate system as viewed from the north ecliptic pole.

The J.P.L. convention is to label telemetered data with the Greenwich Mean Time of reception of the signals at the earth (called U.T.E. or simply U.T. herein) and to label entries in the ephemeris of the spacecraft with Greenwich Mean Time as it would be recorded by a clock on the spacecraft (called U.T.S.C. herein). Further, it is general practice to label the occurrence of an optical or radio event on the sun with the Greenwich Mean Time of its observation on the earth (U.T. or U.T.E.). We designate herein the times of solar events either by U.T. (or U.T.E.) or, as appropriate, by the Greenwich Mean Time as it would be recorded by a clock on the sun, U.T. Sun. It is necessary to distinguish among these three systems of time in considerations involving time delays of the order of the signal delay times or less. Thus on May 26 (Table II)

(a) U.T.E. = U.T.S.C. + 480 sec
for an event occurring at U.T.S.C. at the spacecraft;

(b) U.T.E. = U.T. Sun + 505 sec
for a solar event occurring at U.T. Sun and observed by means of an electromagnetic signal at the earth; and

(c) U.T.E. = U.T. Sun + Sun-Probe Propagation Time + 480 sec
for a solar event occurring at U.T. Sun, observed at the spacecraft at U.T.S.C., and reported by a radio telemetric signal which reaches the earth at U.T.E. The sun-probe propagation time is 739 sec for electromagnetic waves and a greater value for particles.

Solar Electron Event of May 25-28, 1965

The observed counting rates of detectors C, A, B, D_1, and D_2 are shown in Figure 1 as a function of earth time for the period 22:00 U.T.E./May 25 to 12:00 U.T.E./May 29. Enlarged plots of the counting rates of A and B during the early portion of the event are given in Figures 2 and 3. The "apparent" onset time is 23:20 ($\pm$ 5) U.T.E. on May 25 (see, however, subsequent detailed discussion of time delays and of diffusive propagation). From this time to about 07:30 U.T.E. on May 26 the observed particle beam consists exclusively of electrons having $40 \leq E_e \leq 150$ keV. This conclusive identification proceeds as follows:

(a) There is a major effect detected by A and B but no comparable effect is observed by C, D_1, or D_2, all of which have similar geometric factors to those of A and B. Also B, C, D_1, and D_2 receive particles from the same directions in space.

(b) The absence of an effect in C means that the particles received by B (and very likely by A also) must be <u>either</u> electrons $40 \leq E_e \leq 150$ keV or protons $0.55 \leq E_p \leq 3.1$ MeV.

(c) The absence of an effect in D_1 means that the intensity of protons $0.50 \leq E_p \leq 11$ MeV (an energy range which completely encompasses that of the B-C difference of (b) above) is negligible, by at least a factor of 200.

(d) Hence the particles received by B must be <u>electrons</u> $40 \leq E_e \leq 150$ keV.

(e) Even though A receives particles from different directions in space and has a slightly higher threshold than does B, it is supposed henceforward that the foregoing identification is applicable to its output also, on the primary ground that the time histories of the counting rates of A and B are quite similar.

(f) It may be noted that the alpha particle sensitivities of the several detectors are as follows: A, $E_\alpha > 2.20$ MeV; B, $E_\alpha > 1.90$ MeV; C, $E_\alpha > 12.4$ MeV; D_1, $0.8 \leq E_\alpha \leq 120$ MeV; and D_2, $1.15 \leq E_\alpha \leq 50$ MeV. Hence an argument similar to that just given also conclusively eliminates alpha particles (as well as heavier nuclear particles) on the basis of direct experimental knowledge.

(g) D_1 has a detection efficiency of less than 6×10^{-7} for ~ 40 keV electrons.

(h) As remarked in the description of the apparatus, neither direct x-rays nor light from the sun can illuminate any part of the inner collimators or the windows of detectors A and B.

Also, no part of the spacecraft lies within the field of view of the collimators. Scattering of such electromagnetic radiations from interplanetary gas, interplanetary dust, and from planets is easily demonstrated to reduce their intensity by many orders of magnitude below that inferred from observations with similar detectors pointed directly at the sun [Van Allen et al., 1965]. Also the time profile of x-ray flares is quite different than that of the events reported herein. The Jet Propulsion Laboratory's data on the alignment of the axis of the spacecraft with the probe-sun line assure that the nominal orientation of the detectors is maintained during the flight periods of interest. Thus, there appears to be no possibility that the responses of A and B can be attributed to solar x-rays or ultraviolet light.

Later in the event, 07:30 to 11:00 U.T.E./May 26, a relatively small intensity of protons appears clearly on D_1 and less clearly on D_2 and corresponding enhancements of the rates of B and A are observed. There is no effect on C. Hence these protons are in the energy range 0.5 to 11 MeV and mainly toward the lower end of this range. A subsequent, gradual reappearance of such protons begins at about

00:00 U.T.E./May 27, and they continue to be present for at least a day.

The presence of these protons is of subsidiary interest but the principal emphasis of the present paper is on the electrons.

A detectable intensity of electrons $E_e > 40$ keV persisted to ~ 18:00 U.T.E./28 May.

Solar Electron Event of June 5-7, 1965

In Figure 4 are shown the counting rates of C, A, B, and D_1 during the period 18:00 U.T.E./June 5 to 06:00 U.T.E./June 7. The general run of data is similar to that of the May 25-28 event. Again, the response of B is attributed conclusively to electrons $40 \leq E_e \leq 150$ keV. As before, it is supposed that the same identification argument is applicable to A. There is no evidence for protons $E_p > 0.5$ MeV at any stage of the June 5-7 event. An enlarged plot of the counting rates of A and B early in the event is given in Figure 5. The empirically apparent onset time is 19:10 ($\pm$ 8) U.T.E. on June 5.

Solar Electron Event of
June 13-14, 1965

Data for a third interplanetary electron event are shown in Figure 6. The apparent onset time is 05:20 U.T.E. on June 13; the maximum unidirectional intensity of electrons, at about 14:00 U.T.E. on June 13, is $j\ (E_e > 40\ \text{keV}) = 5.4\ (\text{cm}^2\ \text{sec sterad})^{-1}$. The electron event is superimposed on a proton event which begins at ~ 10:00 U.T.E. on June 12, reaches a maximum in mid-day on June 16, and declines into the background on June 19. The electron and proton events appear to be unrelated.

Qualitative Considerations

In general, detectable "events" in interplanetary space are presumed to have a direct solar origin (e.g., x-rays or protons) or an indirect one (e.g., shock waves, changes in plasma flow, and structure of the magnetic field) on the simple but persuasive ground that no other celestial object either within or outside of the solar system appears to have a comparable capability (selective observations of specific objects excluded!). On this consideration alone, we attribute the above electron events to the sun. Further, we will show in a later section that consideration of preliminary data on other types of solar and geophysical activity and of detailed time sequences and propagation mechanisms leads to the working hypothesis that the ~ 40 keV electrons of the May 25-28, June 5-7, and June 13-14 events are emitted directly from the sun and are not incidental to interplanetary shock waves, etc.

It may be noted that some features of our Mariner IV data on the February 5-13, 1965 solar proton event [Van Allen, Krimigis, and Frank, 1965] are explained most naturally as being due to an admixture of electrons, though the evidence for electrons is less persuasive than that for the three later events just described and no detailed discussion of the February 1965 event is included herein.

We are now disposed to believe that mixed proton-electron events and pure electron events may be quite common, having escaped identification heretofore due to inadequate observational arrangements. The observed nature of an event is, of course, different for every different experimental configuration. For example, our Mariner IV apparatus is insensitive to protons having the same energy (~ 40 keV) as the electrons which we find; also 40 keV protons move through interplanetary space at a very much slower rate than electrons of the same energy, having a reciprocal rectilinear velocity of 5.40×10^4 sec/A.U.

to be compared to 1.334×10^3 sec/A.U. for electrons. Thus it is doubly clear that our experiment provides no information whatever on the presence or absence of such protons. Even protons at the threshold energy of our detectors, 0.5 MeV, have a reciprocal rectilinear velocity of 1.53×10^4 sec/A.U.

Thus, although the evidence of the preceding sections establishes the presence and time history of the intensity of interplanetary electrons $E_e \sim 40$ keV, it is quite inadequate to establish the full nature of the primary solar emission.

Intensities, Energy Spectrums, and Angular Distributions

At the peak of the May 25-28 event (~ 01:30 U.T.E./May 26) the absolute unidirectional intensities of electrons are as follows:

(a) From A, $j\ (E_e > 45 \text{ keV}) = 48\ (\text{cm}^2 \text{ sec sterad})^{-1}$

(b) From B, $j\ (E_e > 40 \text{ keV}) = 80$

(c) From C, $j\ (E_e > 150 \text{ keV}) \leq 2$

The quoted intensities in the above summary are obtained simply by dividing the net counting rates (actual minus galactic cosmic ray background) by the unidirectional geometric factors of Table I. The indicated energies are, however, those for which the absolute efficiency is about 1/e. It is recognized that this convention is inaccurate, but calculations using measured efficiency versus electron energy curves for thin window Geiger tubes and various steeply falling energy spectra show that a more refined procedure yields improvements which are relatively trivial for the present purposes. (The proton thresholds of A, B, C, D_1, and D_2 are, in contrast, known with precision since the efficiency rises rapidly from zero to essentially unity at the quoted energies).

By means of pre-flight alpha particle calibrations, it is found that the window of A is about 5 keV thicker for electrons than the window of B. Also the geometric factors are determined to an absolute accuracy of about 10% and to a relative accuracy of about 3%. The raw ratio of j from B to j from A is 1.67 and, since the energy threshold of B is lower than that from A, this ratio is clearly an upper limit to an index of anisotropy. Furthermore, this ratio is more-or-less constant throughout the event, beginning with the earliest time at which its value is statistically significant. Hence, we are inclined to assume essential isotropy and to use the B/A intensity ratio to find a crude energy spectrum.

Assuming $dj/dE_e = \exp(-E_e/E_o)$, we find $E_o \sim 10$ keV, a result which is consistent with the upper limit of the C/B intensity ratio derived from the tabulation at the beginning of this section. Note that B and C receive particles from the same directions in space, whereas A and B do not.

Assuming $dj/dE_e = E^{-\gamma}$, we find $\gamma \sim 5$, and again consistency with the upper limit of the C/B intensity ratio.

The above analysis permits the reasonably firm conclusions (a) that the angular distribution of solar electrons on May 25-28 at the spacecraft at ~ 1.5 A.U. from the sun does not depart markedly from isotropy, even near the onset of the event; and (b) that their energy spectrum is steeply falling above 40 keV with $E_o \sim 10$ keV or $\gamma \sim 5$.

Corresponding analysis of the June 5-7 event yields similar conclusions, though the electron spectrum may be somewhat steeper than during the May 25-28 event.

The intensities during the June 13-14 event are not sufficient to permit an analysis of comparable significance but the observations do not suggest any contradiction.

Interplanetary Propagation of Solar Electrons

The time profiles of intensity of solar electrons during the May 25-28 (Figures 1, 2, and 3) and June 5-7 (Figures 4 and 5) events have a striking general similarity to corresponding time profiles for ~ 20 MeV solar proton events--specifically

(a) A sharp onset;

(b) An increase to a maximum value in a time of the order of several hours; and

(c) A gradual decline over a period of the order of a day or two.

Hence, we are encouraged to treat the interplanetary propagation of solar electrons by a similar analytical model. The specific model is the one of Parker [1963] as further developed by Krimigis [1965], viz.:

(a) N electrons per unit solid angle are emitted impulsively and isotropically from a point source at the position of the sun.

(b) The interplanetary medium is of infinite radial extent and is comprised of fixed, isotropically-scattering centers, whose density may be dependent on heliocentric distance r but not on heliographic latitude or longitude.

(c) Each monoenergetic component of the electron spectrum diffuses without change of energy in a spherically symmetric manner independent of every other component.

(d) The diffusion coefficient $D = M r^{\beta}$, where M and β are parameters independent of r but possibly dependent on electron energy.

For a monoenergetic component, the solution of the partial differential equation which describes the diffusive propagation of particles in the above interplanetary model is essentially:

$$j\,(r,\,t) \sim \frac{1}{t^{3/(2-\beta)}} \exp\left[-\frac{r^{2-\beta}}{M(2-\beta)^2}\,\frac{1}{t}\right]. \qquad (1)$$

The solution exists only for $\beta < 2$.

The application of equation (1) to experimental data consists of plotting $\ln\,[j\,t^{3/(2-\beta)}]$ against t^{-1}, using observed values of j and t and seeking by trial and error to find an assigned value of β that yields a straight line. The time t in equation (1) is measured from the moment t_o at which j departs from zero, however slightly. In the framework of diffusion theory, this moment is the one at which an unscattered electron arrives from the source at the point of observation. Hence, there is a different zero time t_o for every r. Zero time never occurs earlier than r/v after the moment of emission at the sun, where v is the rectilinear velocity of the particle. The delay is increased if an unscattered electron is constrained to follow a curved path.

In working with experimental data the rising side of the counting rate versus time curve is extrapolated into the background to get an "apparent" zero time t_o' (cf. Figures 2 and 5). Then a value of β is found, as described above, ignoring departures from linearity at early times (i.e., at large values of t^{-1}). Such a value of β is insensitive to an error in t_o' of a few tens of minutes. Finally, using the chosen value of β, t_o' is taken as a parameter and its value is chosen so as to straighten the plot of $\ln [j\ t^{3/(2-\beta)}]$ vs t^{-1} at early times. The "true" zero time as so determined is always earlier than the "empirically apparent" value. The reason for this is evident from Figure 7 which shows the essential nature of the right hand side of equation (1) for a particular r and for $\beta = 0$. Plots for other β are of the same general nature. Under practical experimental conditions the early toe of the curve may be unobservable. Some idea of the magnitude of $(t_o - t_o')$ can be gained from Figure 7. In that plot $t_o = 0$, the maximum intensity occurs at $t_{max} = 0.667$, and the extrapolated onset as it would be derived from experimental data occurs at $t_o' = 0.149$. Thus

$$\frac{(t_{max} - t_o)}{(t_{max} - t_o')} = \frac{0.667}{0.518} = 1.29 \ .$$

For the May 25-28 event, $(t_{max} - t_o') = 130$ minutes (approx.). Hence $(t_{max} - t_o)$ may be expected to be 168 minutes and $(t_o - t_o')$, to be about minus 38 minutes, if equation (1) gives a valid description of the diffusive process.

Inasmuch as M and β may be energy-dependent [Krimigis, 1965], intensity data from integral detectors are not properly analyzed, in general, according to equation (1). But in the present case, it has been shown that the electron energy spectrum is quite steep. Hence the responses of detectors A and B are due dominantly to a narrow band of energies ($\Delta E_e \sim 15$ keV) near their thresholds, and the monoenergetic approximation is probably satisfactory.

Using the fully detailed diffusion solution [Krimigis, 1965], of which our equation (1) is an abridgment, it is possible to determine absolute values of M and of the impulsive source strength N from the observed data at a given position in space. Such results are, of course, valid only to the extent that the assumed model is valid.

The raw data for the May 25-28 event (Fig. 1) exhibit multiple structure beyond ~ 6 hours after onset and those for the June 5-7 event (Figure 4), beyond ~ 10 hours after onset. Restricting an analysis of the above described nature to the periods before multiple structure becomes apparent we find:

(a) For the early portion of the May 25-28 event

$\beta = 0 \ (\pm\ 0.2)$ for both A and B

$t_o = 22{:}45 \ \left(\begin{smallmatrix}+10\\-5\end{smallmatrix}\right)$ U.T.E./May 25
for both A and B

$N_A \sim 0.7 \times 10^{33}$ electrons/sterad

$N_B \sim 1.1 \times 10^{33}$ electrons/sterad

$D_A \sim D_B \sim 8 \times 10^{21}\ cm^2/sec$

(b) For the early portion of the June 5-7 event

$\beta = 0 \ (\pm\ 0.2)$ for both A and B

$t_o = 18{:}55 \ \left(\begin{smallmatrix}+10\\-5\end{smallmatrix}\right)$ U.T.E./June 5
for both A and B

$N_A \sim 4.5 \times 10^{32}$ electrons/sterad

$N_B \sim 8 \times 10^{32}$ electrons/sterad

$D_A \sim D_B \sim 1.3 \times 10^{22}\ cm^2/sec$

The value $\beta = 0$ corresponds to the case of the effective diffusion coefficient being independent of r. This is a distinctively different result than that obtained by Krimigis [1965] for solar proton events during 1961-1963.

An important physical distinction between electrons and protons is their markedly different radii of gyration in the interplanetary magnetic field. Table III illustrates the fact that the radius of gyration of a 40 keV electron is $\sim 10^{-3}$ of that of protons in the energy range usually studied in solar events, and is of the order of 10^{-6} A.U. in the interplanetary medium. Hence, it appears that solar electrons constitute a valuable new tool for the study of the structure of the interplanetary magnetic field. For example, the elementary scattering encounter with a magnetic inhomogeneity whose scale is, say, 10^{-4} A.U. is of a quite different nature for a 40 keV electron than for a 20 MeV proton.

TABLE III

Particle	Kinetic Energy	Magnetic Rigidity	Radius of Gyration in B = 5 Gamma Field
Electron	40 keV	4.60×10^{-6} γ-A.U.	0.9×10^{-6} A.U.
Proton	1 MeV	0.97×10^{-3}	0.2×10^{-3}
	10 MeV	3.05×10^{-3}	0.6×10^{-3}
	100 MeV	9.66×10^{-3}	1.9×10^{-3}
	1000 MeV	30.54×10^{-3}	6.1×10^{-3}

Association of Electron Events with Other Solar and Geophysical Phenomena

At the date of writing a full compilation of potentially significant observations of other solar and geophysical phenomena has not been completed. Principal reliance has been placed on the weekly "Preliminary Report of Solar Activity" of the High Altitude Observatory at Boulder, Colorado for a preliminary discussion. Table IV excerpts solar and geophysical data which appear to be pertinent to our three solar electron events from H.A.O./TR No. 717 of May 28, 1965, H.A.O./TR No. 719 of June 11, 1965, and H.A.O./TR No. 720 of June 18, 1965.

Terrestrial atmospheric effects of types attributable to the absorption of solar x-rays in the D-region are observed at times of apparent interest on May 25, June 5, and June 13.

On May 25, the onset times of noteworthy solar radio noise, of a Sudden Short Wave Fade, and of a Sudden Cosmic Noise Absorption are all about 22:42 U.T.E. or 22:34 U.T. Sun. The empirically apparent onset time of the May 25-28 solar electron event is 23:20 U.T.E. If one subtracts 8 minutes for spacecraft-to-earth signal time (Table II) and further subtracts 33 minutes for the rectilinear travel time of a 40 keV electron from the sun to the spacecraft, one finds 22:39 U.T. Sun

TABLE IV

Excerpts from H.A.O. Weekly Reports Nos. 717, 719, and 720

Date 1965	Flares and Subflares					H.A.O. Radio Spectra	Radio Bursts	SSWF-GSWF-slow	Other Events
	IMP	BEG	MAX	END	PLAGE	Type/UT/mc	Type/UT/mc	UT/IMP	Type/UT/IMP or Plage No.
May 25						cont 22:41-22:50/08-41 III 22:42-22:44/08-41	major 22:41-22:44/200 major 22:42-22:44/500 simple 22:42-22:44/2800	S 22:42-22:52/1-	SCNA 22:41-23:30/07%/1-
June 5	1-	18:07	18:13	18:34	42	III 18:12-18:16/ 8-41 II 18:18-18:37/15-41 III 18:21-18:25/ 8-41 IV 18:25-18:32/21-41		S 18:10-18:55/2+	SCNA 18:09-18:38/1+/26% SEA 18:10-18:19/1+
June 13	2	02:57	03:15	05:00	47			G 03:00-04:35/1+ S 03:08-04:47/2	SPA 03:06-04:31/1

Note: All times in this table are Greenwich Mean Times of observation at the earth (U.T.E.).

as the latest possible moment at which such "onset" electrons could have been emitted from the sun. This time is in remarkably good agreement with that of the radio and x-ray emission. It is tempting to regard this evidence as showing that the emission of electrons and radio noise and x-rays occurs simultaneously. The simple appeal of this conclusion is attenuated somewhat by reference to the previous section of this paper entitled "Interplanetary Propagation of Solar Electrons", in which it is inferred that the "true" onset time of the electron event is 22:45 U.T.E. or 22:04 U.T. Sun--an emission time about 30 minutes before that of the x-rays. In view of the unknown validity of many features of the assumed diffusion model, however, we are inclined to regard the toe of the curve of Figure 7 as of doubtful validity and to give greater weight to the simple-minded derivation of latest physically possible emission time.

On June 5, the apparent emission time of radio noise and x-rays is about 18:02 U.T. Sun, the latest possible empirically-inferred emission time of "onset" solar electrons is 18:28 U.T.Sun, and the emission time implicit in the diffusion analysis is 18:13 U.T. Sun. The foregoing dilemma is not apparent here; nonetheless, we regard 18:28 as a more valid estimate of emission time.

On June 13, the corresponding three times are 02:55 U.T. Sun, and very approximately 04:35 U.T. Sun and 04:10 U.T. Sun. The cross identification of phenomena in this case is assessed as weak.

Returning to the events on May 25, there is further evidence of interest. A solar x-ray event was observed directly by one of the Vela satellites. We are indebted to Dr. J. P. Conner of the Los Alamos Scientific Laboratory for the following provisional summary:

No x-rays evident at	22:41:01 U.T.E./May 25
First clear x-ray signal	22:41:33 U.T.E.
Rise time to peak intensity	~ 2 minutes
Duration of approximately constant peak intensity	~ 1 minute
Middle of peak	22:44:20 U.T.E.
Latest time of detectable x-rays	22:55:22 U.T.E.
Maximum energy flux (0.5 to 15 A°)	~ 10^{-2} erg/cm^2 sec
Apparent Planck color temperature	~ 5 x 10^6 °K

These observations support the belief that soft solar x-rays are the causative agent of the SSWF and SCNA noted in Table IV, and provide quantitative energy flux data of importance.

Conner characterizes the May 25 x-ray event as "not particularly noteworthy in any respect" for the current era of solar activity and as considerably weaker than a number of events observed in 1963 by the same technique.

Our detectors A and B have a measurable efficiency for (non-penetrating) electrons down to a few keV in energy. For example, the efficiency is $\sim 10^{-6}$ at 5 keV. It may be thought possible that the responses of A and B on May 25, for example, are due to an emission of $\sim 10^{40}$ electrons having $E_e \sim 5$ keV. The rectilinear flight time of such electrons from the sun to the spacecraft is, however, much too great to be consistent with the cross-identification of phenomena which has been outlined above. By the same token, the observed electrons can not be attributed to an interplanetary shock wave or to any other indirect mechanism which requires a sun-to-spacecraft propagation delay of more than about 0.5 hour.

Conclusion

We believe that the electrons reported in the present paper are associated most plausibly with the solar flare x-ray spectrum above 20 keV as observed and discussed by Chubb, Friedman, and Kreplin [1960], Vette and Casal [1961], Anderson and Winckler [1962[, and Frost (1964].

Representative fluxes in such energetic x-ray events ($E_{h\nu} > 20$ keV) are of the order of 2×10^{-6} erg $(cm^2 \ sec)^{-1}$ for periods of the order of 100 seconds. The time integrated energy emission in the form of such x-rays is some 5×10^{23} ergs.

If comparable x-ray data are found to exist for May 25, June 5, or June 13, 1965, it will be possible to use our electron data to estimate the fraction of causative electrons which escapes from the sun.

The scheme of a crude estimate is as follows. The total energetic efficiency for the production of bremsstrahlung by 40 keV electrons stopped in a 10/1 hydrogen-helium target is about 10^{-4}. The estimated 10^{34} electrons emitted from the sun on May 25 would, if stopped in such a target, yield some 6×10^{22} ergs of x-rays, about 0.25 of which are of photon energy above 20 keV. Thus, we suggest that a significant fraction (0.01 to 0.1) of the electrons which are responsible for energetic x-ray flares does, indeed, escape from the sun before being stopped. If this is true the site of x-ray generation would lie not deeper than $\sim 10^{-3}$ g $(cm)^{-2}$ in the solar atmosphere.

Acknowledgements

Development, construction, and preflight testing of the U. of Iowa equipment was supported by subcontract 950613 with the Jet Propulsion Laboratory. Analysis and publication have been performed in part under National Aeronautics and Space Administration Grant NsG 233-62. We are indebted to Dr. L. A. Frank and Messrs. H. K. Hills, T. P. Armstrong, D. L. Chinburg, and D. C. Enemark of the University of Iowa and to Dr. H. R. Anderson and Messrs. R. K. Sloan, R. A. Lockhart, and D. Schofield of the Jet Propulsion Laboratory for various aspects of the work. The flight data used herein are from the J.P.L. preliminary, though substantially complete, "users programs", which have been received promptly.

REFERENCES

Anderson, H. R., Ionizing radiation measured between Earth and Venus by Mariner 2, pp. 521-543, Space Research V, edited by P. Muller, North-Holland Publishing Co., Amsterdam, 1965.

Anderson, K. A., and J. R. Winckler, Solar flare x-ray burst on September 28, 1961, J. Geophys. Res., 67, 4103-4117, 1962.

Arnoldy, R. L., R. A. Hoffman, and J. R. Winckler, Solar cosmic rays and soft radiation observed at 5,000,000 kilometers from earth, J. Geophys. Res., 65, 3004-3007, 1960.

Chubb, T. A., H. Friedman, and R. W. Kreplin, Measurements made of high-energy x rays accompanying three class 2+ solar flares, J. Geophys. Res., 65, 1831-1832, 1960 (Ltr.).

Cline, T. L., G. H. Ludwig, and F. B. McDonald, Detection of interplanetary 3- to 12-MeV electrons, Phys. Rev. Letters, 13, 786-789, 1964.

Dolan, J. F., and G. G. Fazio, The gamma-ray spectrum of the sun, Rev. Geophysics, 3, 319-343, 1965.

Frank, L. A., A survey of electrons $E > 40$ MeV beyond 5 earth radii with Explorer 14, J. Geophys. Res., 70, 1593-1626, 1965.

Frank, L. A., and J. A. Van Allen, Measurements of energetic electrons in the vicinity of the sunward magnetospheric boundary with Explorer 14, J. Geophys. Res., 69, 4923-4932, 1964.

Frost, K. J., Comments on high energy x-ray bursts observed with OSO I, AAS-NASA Symposium on the Physics of Solar Flares, U. S. Government Printing Office pp. 139-143, NASA SP-50, edited by W. N. Hess, 1964.

Hoffman, R. A., L. R. Davis, and J. M. Williamson, Protons of 0.1 to 5 MeV and electrons of 20 keV at 12 earth radii during sudden commencement on September 30, 1961, J. Geophys. Res., 67, 5001-5005, 1962.

Krimigis, S. M., Interplanetary diffusion model for the time behavior of intensity in a solar cosmic ray event, J. Geophys. Res., 70, 2943-2960, 1965.

Krimigis, S. M., and T. P. Armstrong, Observations of protons in the magnetosphere with Mariner 4, Trans., American Geophysical Union, 46, 113, 1965 (Abstract).

Kundu, M. R., Centimeter-wave radio and x-ray emission from the sun, Space Science Reviews, 2, 438-469, 1963.

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

Parker, E. N., Interplanetary dynamical processes, Interscience, 272 pp., 1963.

Van Allen, J. A., and L. A. Frank, The Iowa radiation experiment in the Mariner II Venus probe, Science, Vol. 138, No. 3545, pp. 1097-1098, 7 December 1962.

Van Allen, J. A., L. A. Frank, B. Maehlum, and L. W. Acton, Solar x-ray observations by Injun 1, J. Geophys. Res., 70, 1639-1645, 1965.

Van Allen, J. A., L. A. Frank, and D. Venkatesan, Small solar cosmic-ray events observed with Mariner 2, Trans. American Geophysical Union, 45, 80, 1964 (Abstract).

Van Allen, J. A., S. M. Krimigis, and L. A. Frank, Observations with University of Iowa equipment on Mariner IV, November 1964--February 1965 (Preliminary Report), U. of Iowa 65-5, February 1965.

Vette, J. I., and F. G. Casal, High energy x-rays during solar flares, Phys. Rev. Letters, 6, 334-336, 1961.

Wild, J. P., The radio emission from solar flares, J. Phys. Soc. Japan, 17, Supplement A-II, Part II, 249-258, 1962.

CAPTIONS FOR FIGURES

Figure 1. (A) Comprehensive plot of data from all detectors for the major portion of the May 25-28, 1965 solar electron event.

(B) Continuation showing disappearance of detectable electrons on May 28.

Figure 2. An expanded plot of the early portion of the May 25-28 event.

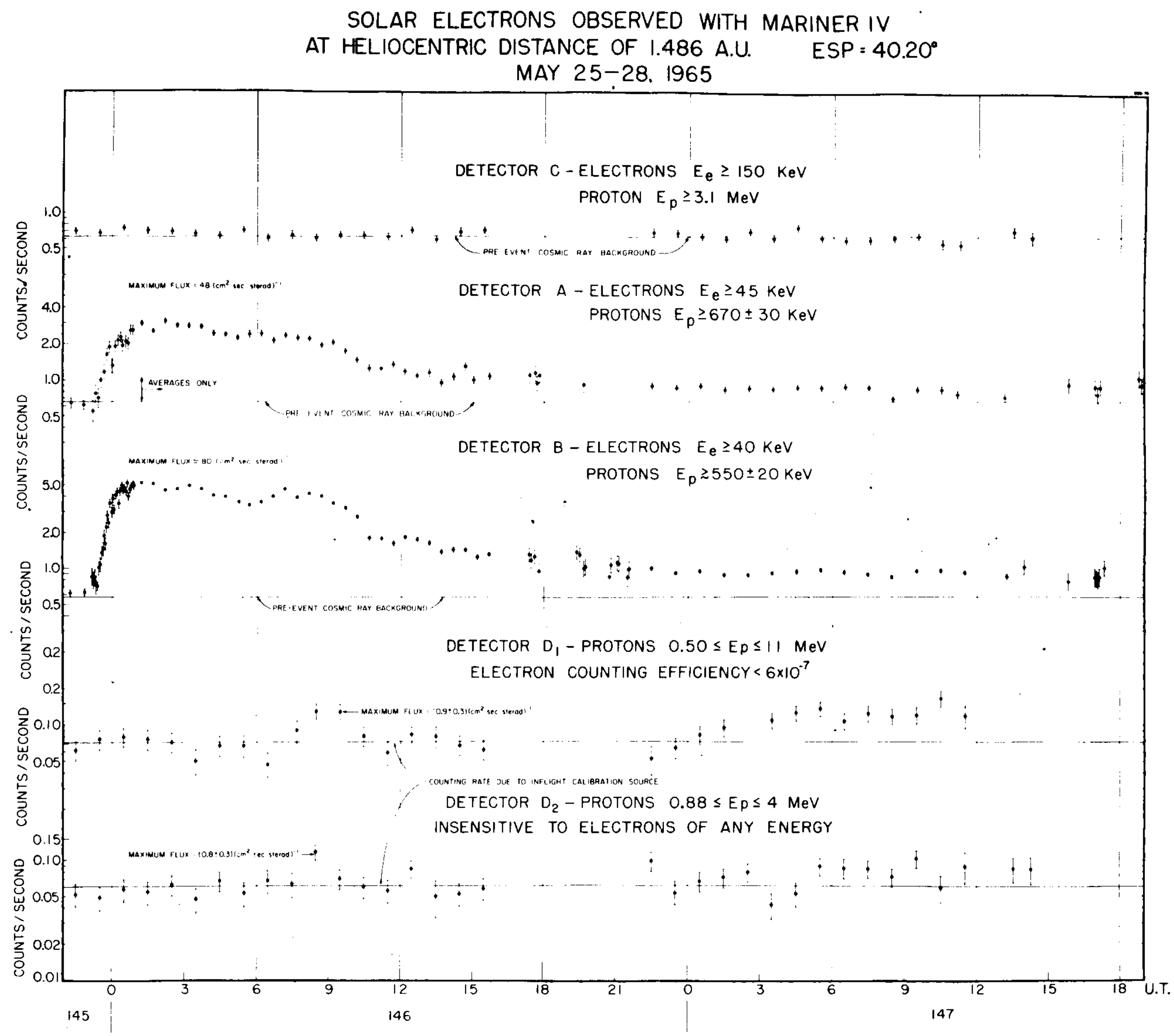
Figure 3. An alternative plot of the early portion of May 25-28 event showing net counting rates due to solar electrons.

Figure 4. Comprehensive plot of data from all relevant detectors for the June 5-7, 1965 solar electron event.

Figure 5. An expanded plot of the early portion of the June 5-7 event.

Figure 6. Plot of data from all relevant detectors for the June 13-14, 1965 solar electron event.

Figure 7. A plot of the function $f = \exp\left(-\frac{1}{t}\right)/t^{3/2}$ which represents the right hand side of equation (1) for $\beta = 0$ and for a particular r. The positions of the maximum ($f' = 0$) and of the two inflection points ($f'' = 0$) are shown. The straight line through the first inflection point is the calculated tangent line through that point and is taken to represent the procedure for determining the apparent onset time of an event using observational data.



SOLAR ELECTRONS OBSERVED WITH MARINER IV
AT HELIOCENTRIC DISTANCE OF 1.486 A.U. ESP = 40.20°
MAY 25–28, 1965
DETECTOR C - ELECTRONS $E_e \geq 150$ KeV
PROTON $E_p \geq 3.1$ MeV
PRE EVENT COSMIC RAY BACKGROUND
DETECTOR A - ELECTRONS $E_e \geq 45$ KeV
PROTONS $E_p \geq 670 \pm 30$ KeV
AVERAGES ONLY
PRE EVENT COSMIC RAY BACKGROUND
DETECTOR B - ELECTRONS $E_e \geq 40$ KeV
PROTONS $E_p \geq 550 \pm 20$ KeV
PRE-EVENT COSMIC RAY BACKGROUND
DETECTOR D_1 - PROTONS $0.50 \leq E_p \leq 11$ MeV
ELECTRON COUNTING EFFICIENCY $< 6 \times 10^{-7}$
COUNTING RATE DUE TO INFLIGHT CALIBRATION SOURCE
DETECTOR D_2 - PROTONS $0.88 \leq E_p \leq 4$ MeV
INSENSITIVE TO ELECTRONS OF ANY ENERGY
COUNTS/SECOND
U.T.
145
146
147

Figure 1A

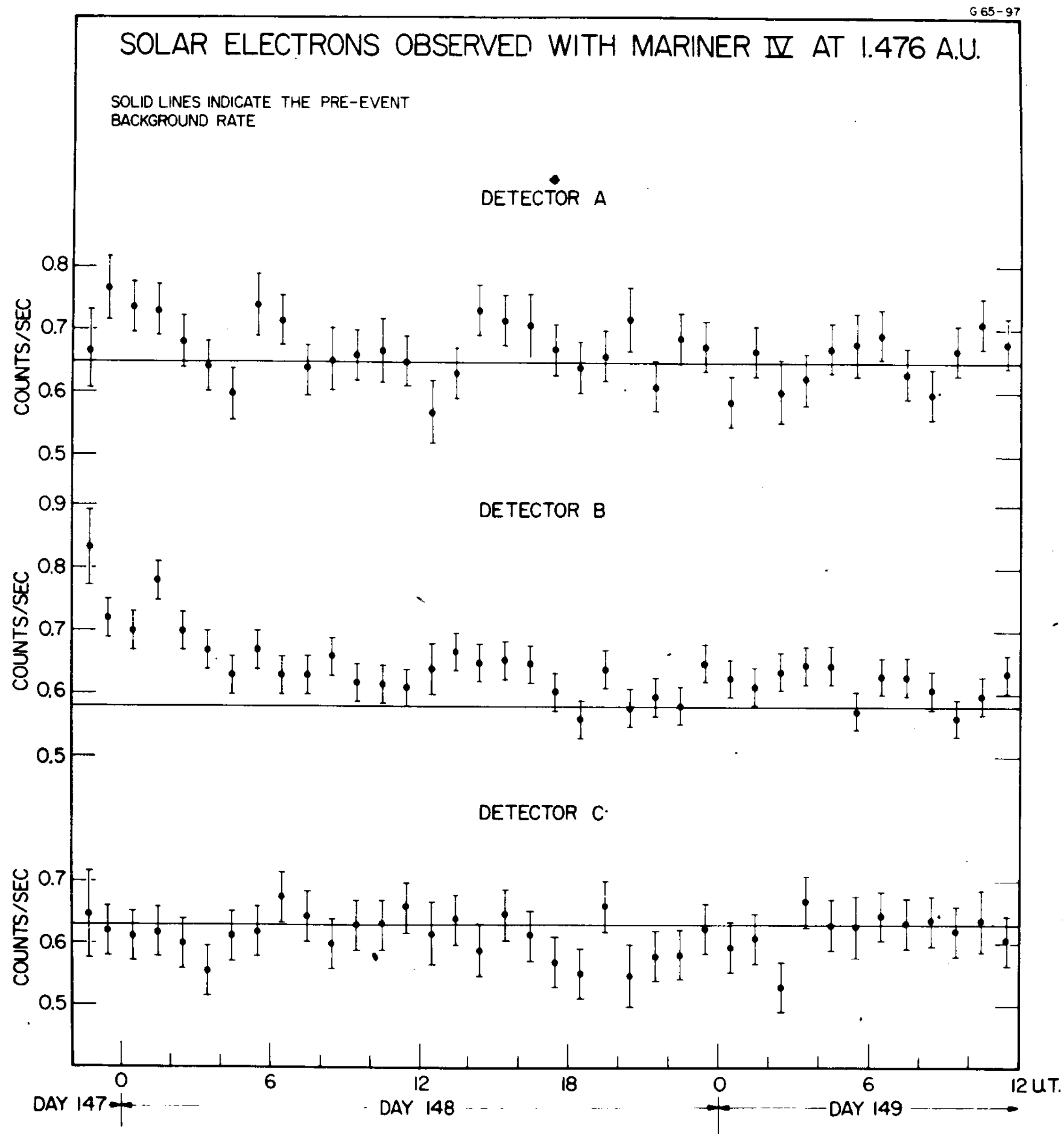

G 65-97
SOLAR ELECTRONS OBSERVED WITH MARINER IV AT 1.476 A.U.
SOLID LINES INDICATE THE PRE-EVENT BACKGROUND RATE
DETECTOR A
DETECTOR B
DETECTOR C
COUNTS/SEC
0.9
0.8
0.7
0.6
0.5
0
6
12
18
0
6
12 U.T.
DAY 147
DAY 148
DAY 149

Figure 1B

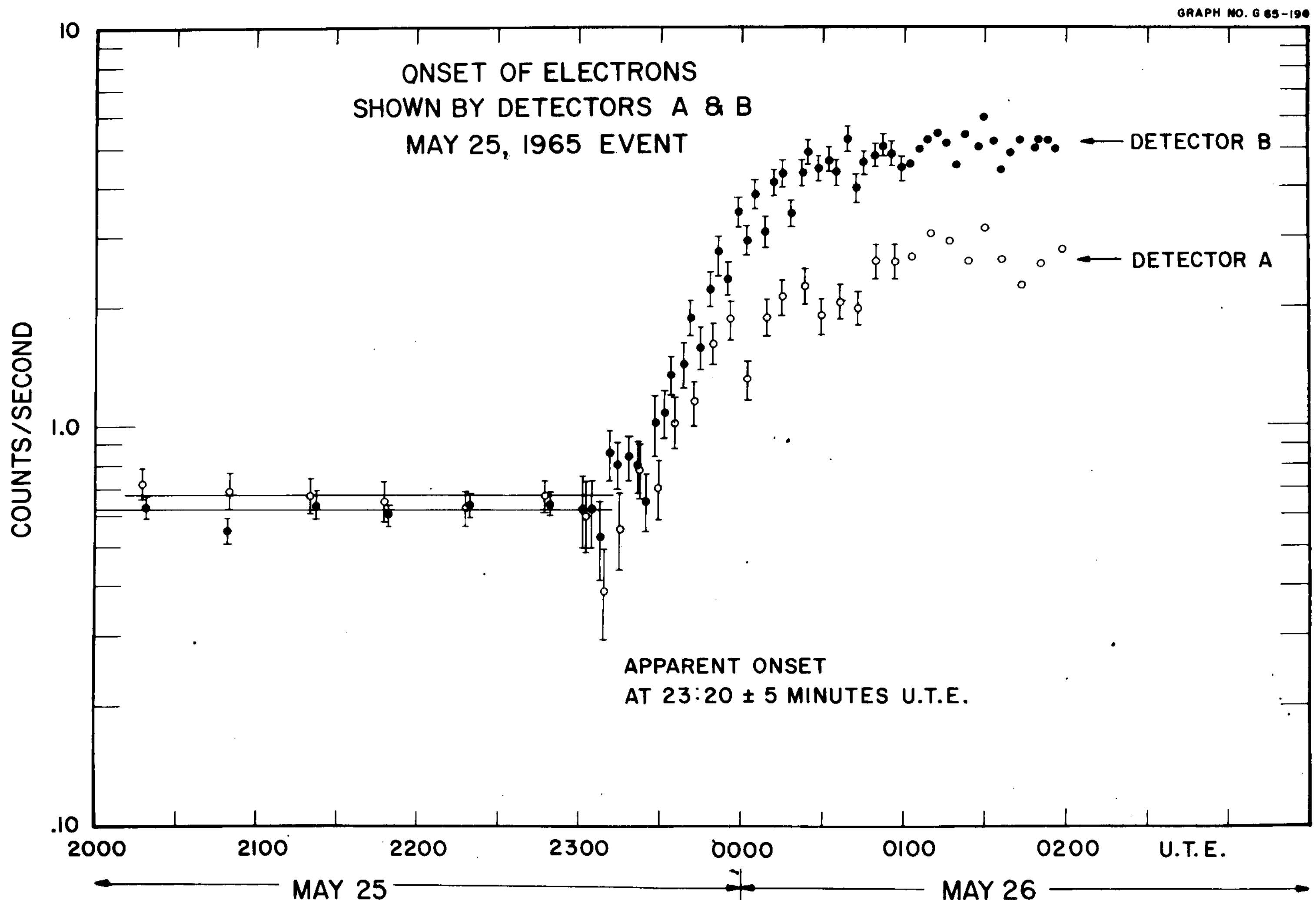

GRAPH NO. G 65-190
ONSET OF ELECTRONS
SHOWN BY DETECTORS A & B
MAY 25, 1965 EVENT
DETECTOR B
DETECTOR A
APPARENT ONSET
AT 23:20 ± 5 MINUTES U.T.E.
COUNTS/SECOND
10
1.0
.10
2000
2100
2200
2300
0000
0100
0200
U.T.E.
MAY 25
MAY 26

Figure 2

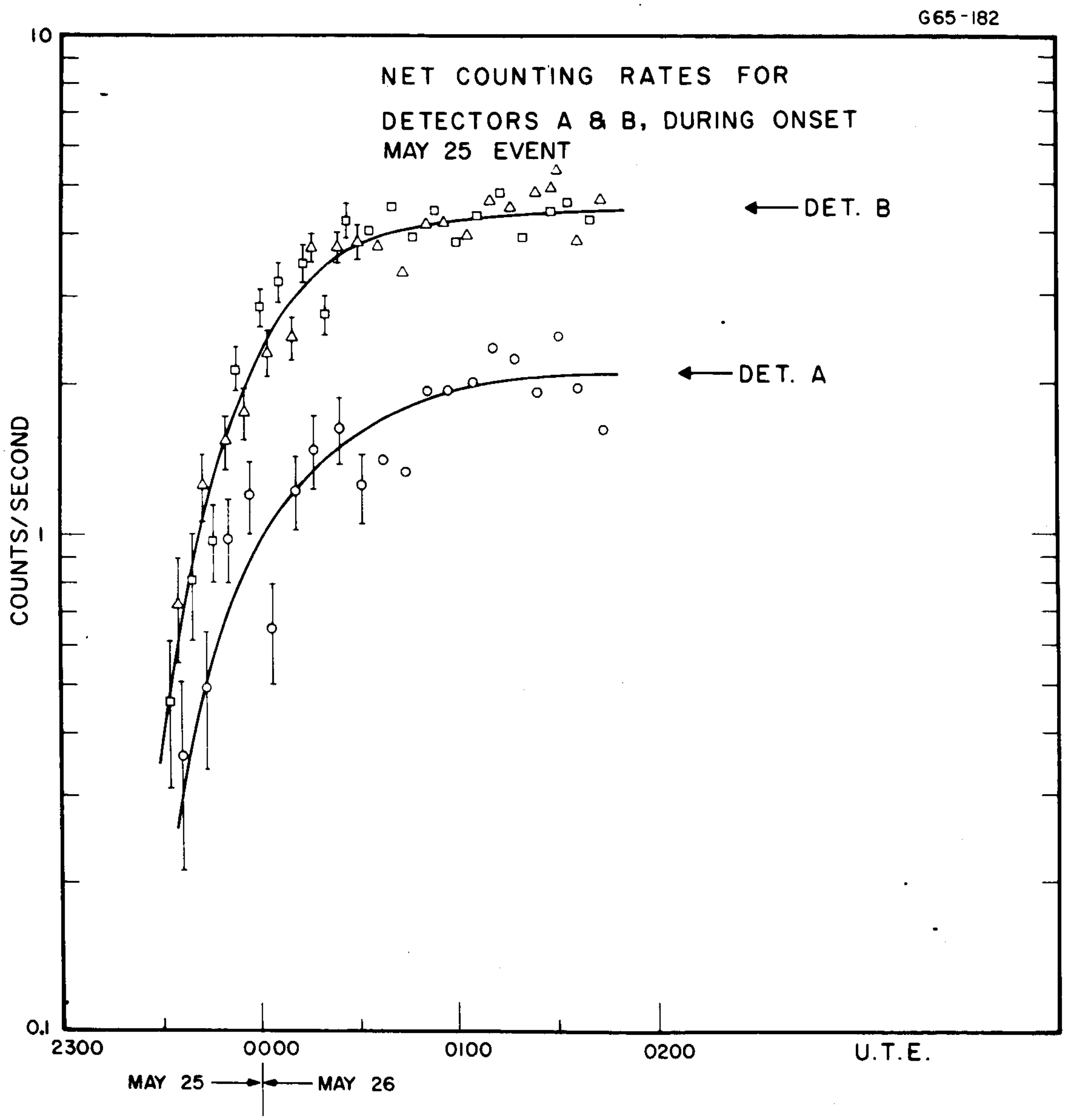

G65-182
NET COUNTING RATES FOR
DETECTORS A & B, DURING ONSET
MAY 25 EVENT
DET. B
DET. A
COUNTS/SECOND
10
1
0.1
2300
0000
0100
0200
U.T.E.
MAY 25
MAY 26

Figure 3

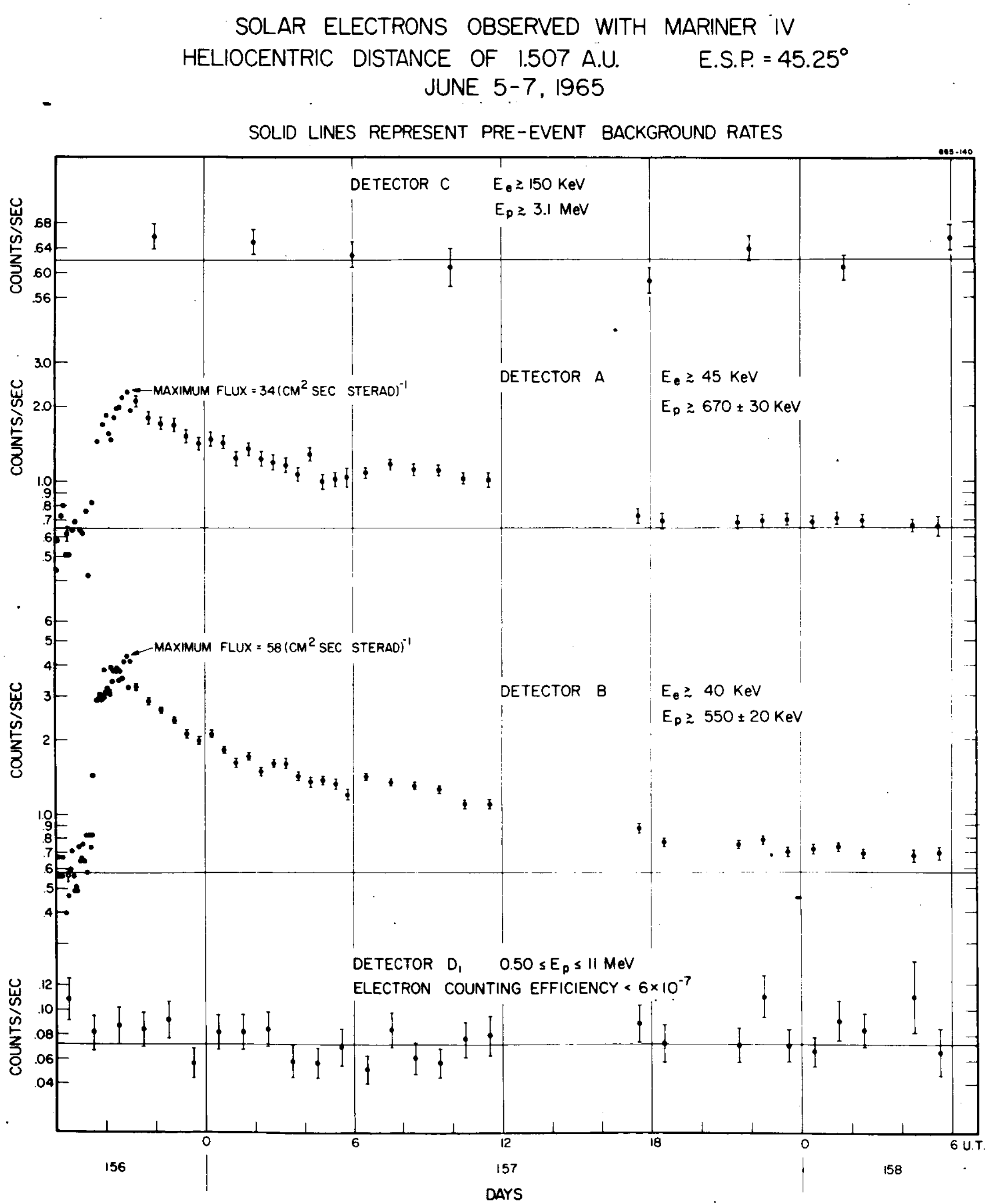

SOLAR ELECTRONS OBSERVED WITH MARINER IV
HELIOCENTRIC DISTANCE OF 1.507 A.U. E.S.P. = 45.25°
JUNE 5-7, 1965
SOLID LINES REPRESENT PRE-EVENT BACKGROUND RATES
DETECTOR C $E_e \geq 150$ KeV $E_p \geq 3.1$ MeV
COUNTS/SEC
.68
.64
.60
.56
DETECTOR A $E_e \geq 45$ KeV $E_p \geq 670 \pm 30$ KeV
MAXIMUM FLUX = 34 $(\mathrm{CM}^2\ \mathrm{SEC\ STERAD})^{-1}$
3.0
2.0
1.0
DETECTOR B $E_e \geq 40$ KeV $E_p \geq 550 \pm 20$ KeV
MAXIMUM FLUX = 58 $(\mathrm{CM}^2\ \mathrm{SEC\ STERAD})^{-1}$
DETECTOR D_1 $0.50 \leq E_p \leq 11$ MeV
ELECTRON COUNTING EFFICIENCY < 6×10^{-7}
.12
.10
.08
.06
.04
0
6
12
18
0
6 U.T.
156
157
158
DAYS

Figure 4

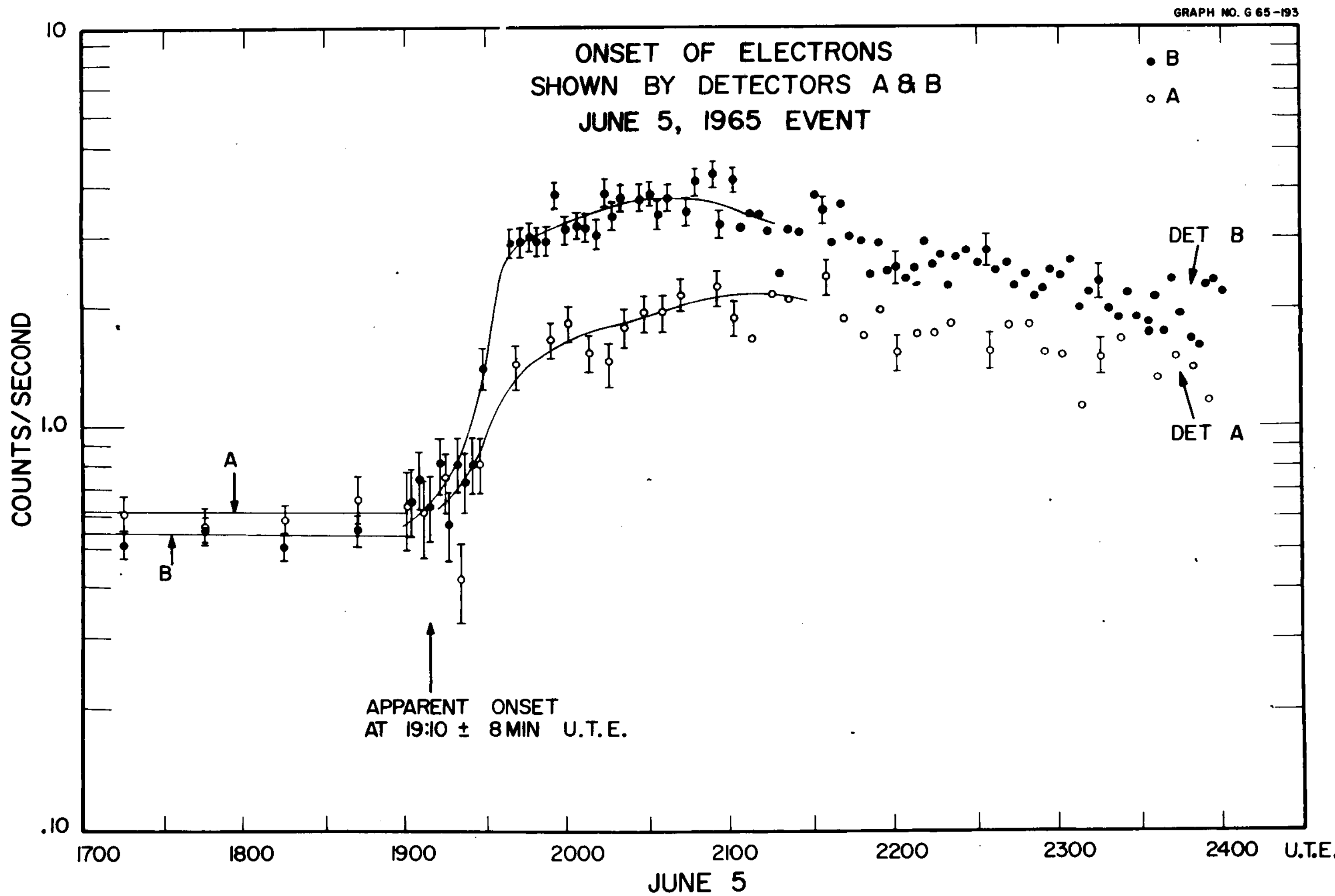

GRAPH NO. G 65-193
ONSET OF ELECTRONS
SHOWN BY DETECTORS A & B
JUNE 5, 1965 EVENT
• B
○ A
DET B
DET A
A
B
APPARENT ONSET
AT 19:10 ± 8 MIN U.T.E.
COUNTS/SECOND
10
1.0
.10
1700
1800
1900
2000
2100
2200
2300
2400
U.T.E.
JUNE 5

Figure 5

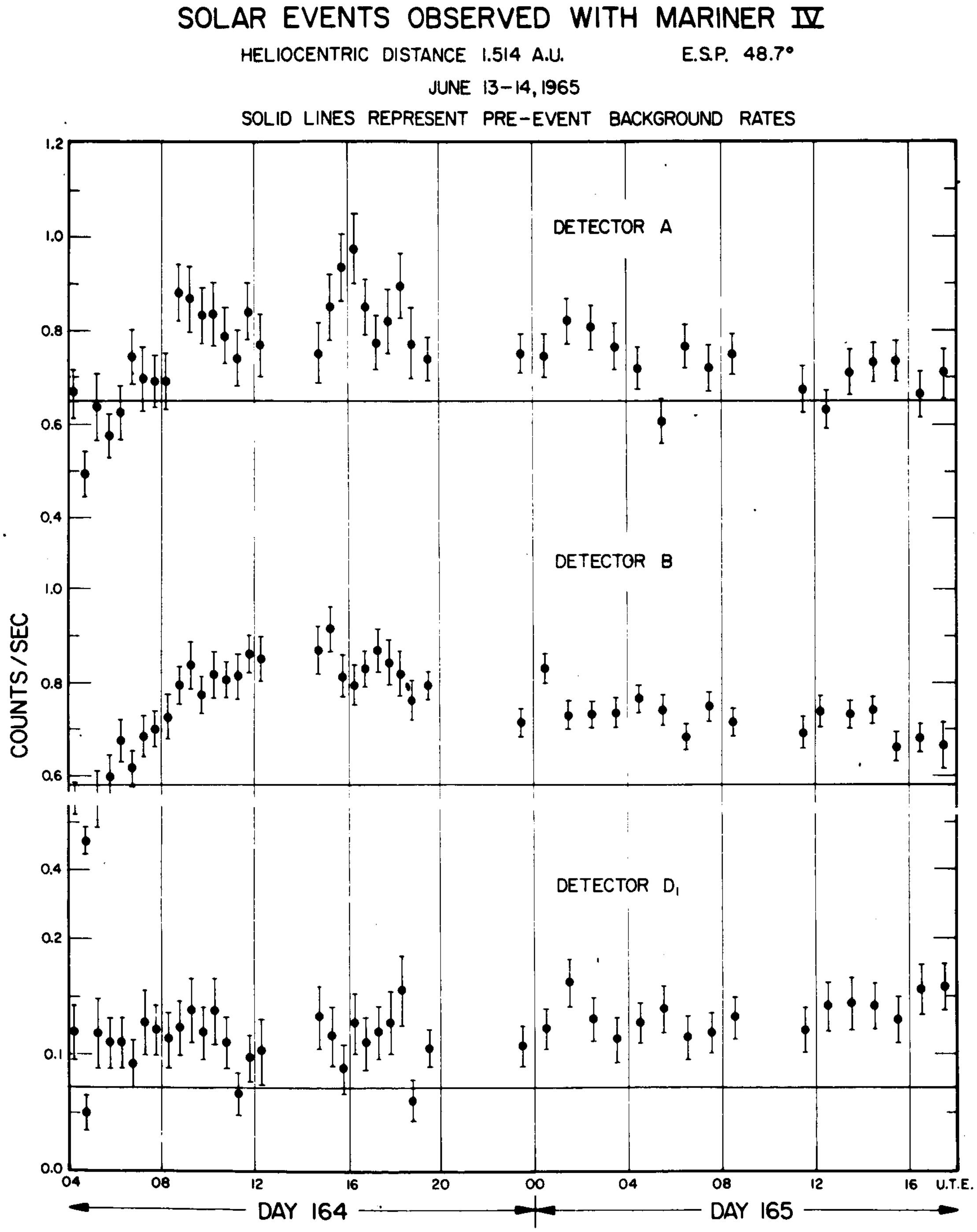
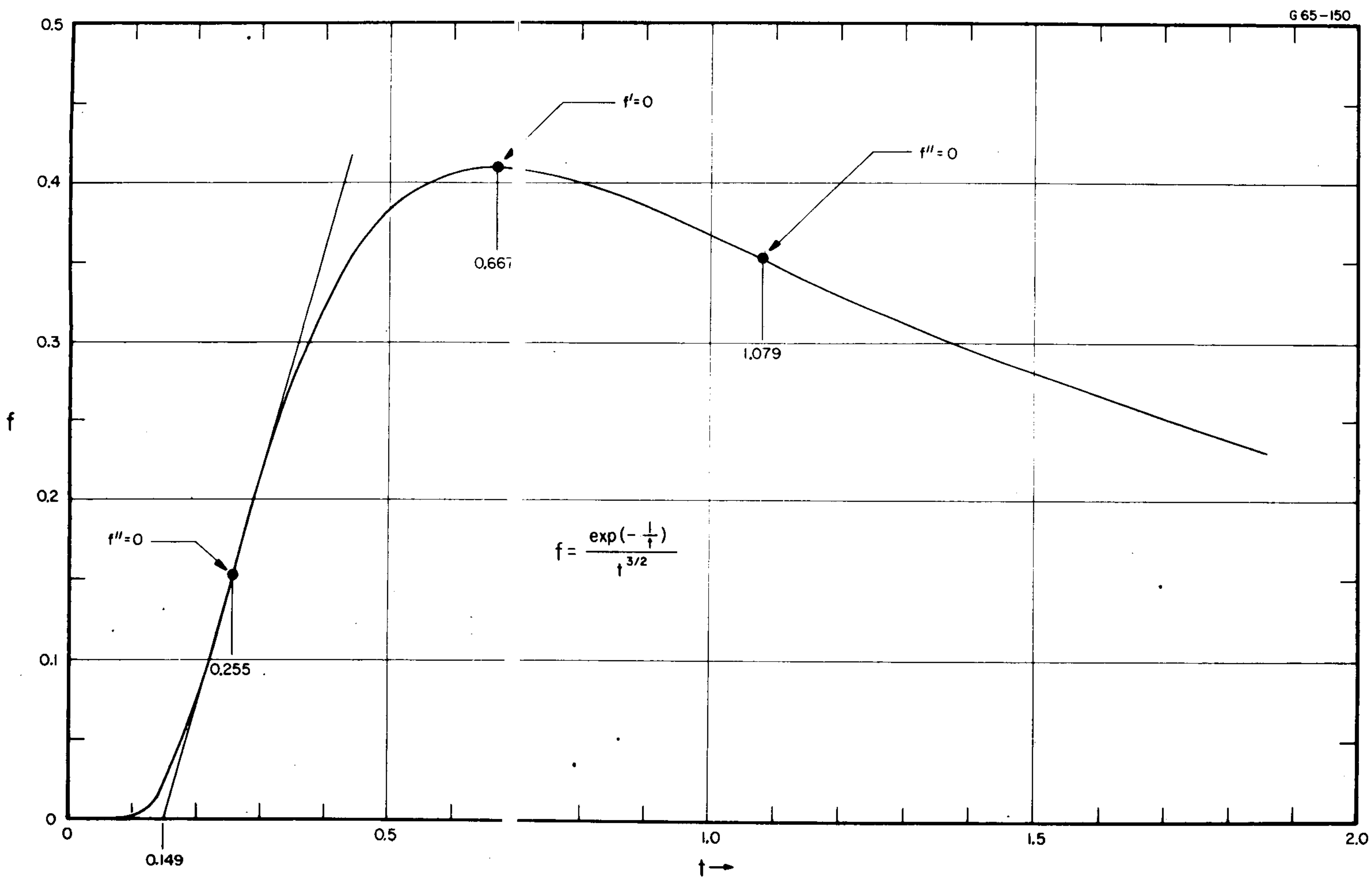

SOLAR EVENTS OBSERVED WITH MARINER IV
HELIOCENTRIC DISTANCE 1.514 A.U.
E.S.P. 48.7°
JUNE 13-14, 1965
SOLID LINES REPRESENT PRE-EVENT BACKGROUND RATES
DETECTOR A
DETECTOR B
DETECTOR D1
COUNTS/SEC
1.2
1.0
0.8
0.6
0.4
0.2
0.1
0.0
04
08
12
16
20
00
U.T.E.
DAY 164
DAY 165

Figure 6



G 65-150
f
0.5
0.4
0.3
0.2
0.1
0
0.5
1.0
1.5
2.0
t→
0.149
0.255
0.667
1.079
f″=0
f′=0
f″=0
$f = \frac{\exp(-\frac{1}{t})}{t^{3/2}}$

Figure 7