U. of Iowa 66-12

The Temporal Variations of Electron Intensities at Low Altitudes in the Outer Radiation Zone as Observed with Satellite Injun 3*

by

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NsG. 87-6

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April 1966

*Research supported in part by the Office of Naval Research under contracts Nonr-1509(06) and N9onr 93803.

**Graduate Research Fellow of the National Aeronautics and Space Administration.

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ABSTRACT

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Temporal variations of the intensities of electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) trapped in the outer radiation zone in the region $3.0 \leq L \leq 6.0$ and mirroring at altitudes of ~ 1500 km have been studied during a seven-month period from January 1 to July 31, 1963, by means of three Geiger-Mueller tubes on-board the U. of Iowa/Office of Naval Research research satellite Injun 3. From observations during some twenty geomagnetically disturbed periods, it is shown that the largest intensity variations occur at the onset of such disturbances and that subsequent behavior is dependent on the magnitudes of the disturbances as measured by the maximum daily sums of the planetary magnetic disturbance parameter, K_p. The time histories of these intensity variations are compared with those of 3-hour averages of the horizontal component of the geomagnetic field at College, Alaska ($L = 5.5$), for several disturbed periods.

Nearly simultaneous measurements of the directional intensities of electrons ($E > 40$ keV), which mirror at low altitudes, with Injun 3, and omnidirectional intensities of these electrons near the geomagnetic equatorial plane, with Explorer 14,

indicate similar temporal behavior at $L \sim 4$. The highest observed intensities of trapped electrons ($E > 40$ keV) in the outer zone at low altitudes appear to occur under a condition of approximate isotropy and equal omnidirectional intensities $\lesssim 10^8$ $(cm^2\text{-sec})^{-1}$ along a magnetic field line at all altitudes above several hundreds of kilometers.

During four periods of post-disturbance geomagnetic calm, the intensities of electrons ($E > 40$ keV) were observed by Injun 3 to decrease exponentially in time with decay constants $\tau = 12 \pm 3$ days at $L = 3.0$, and $\tau = 4 \pm 2$ days in the region $3.5 \leq L \leq 6.0$. Simultaneously measured values of the decay constants for these electron intensities near the geomagnetic equatorial plane at $L \sim 4$ agree, within observational error. Long-term exponential decays in the intensities of artificially injected electrons ($E > 1.6$ MeV) were observed by Injun 3 to be characterized by $\tau = 40 \pm 5$ and 45 ± 5 days at $L = 3.0$ and 3.5, respectively.

Further evidence for the diffusion of electrons ($E > 1.6$ MeV) is presented.

I. Introduction

The observations of a quasi-thermalized plasma with omnidirectional intensities of electrons ($E > 100$ eV) of the order of 2×10^{8} $(\text{cm}^{2}\text{-sec})^{-1}$ [Serbu, 1965], some tens of ergs $(\text{cm}^{2}\text{-sec})^{-1}$ of electrons ($E \sim 1$ keV) [Freeman, Van Allen, and Cahill, 1963] and frequent isolated "spikes" of electrons ($40 < E < 200$ keV) with intensities below $\sim 10^{5}$ $(\text{cm}^{2}\text{-sec})^{-1}$ [Frank and Van Allen, 1964] at the sunward boundary of the magnetosphere within the magnetosheath, or transition region, and the observations of an abrupt decrease in the intensities of electrons ($E > 100$ eV) at the shock boundary [Serbu, 1965] and the infrequent solar emission of observable intensities of electrons ($E > 40$ keV) [Van Allen and Krimigis, 1965] demonstrate the heating and partial confinement of the low energy electron component of the solar plasma. The observations of high intensities of electrons ($E > 40$ keV) throughout the magnetosphere (J_o ($E > 40$ keV) $\sim 10^{5-8}$ $(\text{cm}^{2}\text{-sec})^{-1}$) and intensities of electrons ($E > 230$ keV, > 1.6 MeV) which in the heart of the outer radiation zone reach levels of $J_o(E > 230 \text{ keV}) \sim 5 \times 10^{6}$ $(\text{cm}^{2}\text{-sec})^{-1}$ and $J_o(E > 1.6 \text{ MeV}) \sim 10^{6}$ $(\text{cm}^{2}\text{-sec})^{-1}$ [Frank, Van Allen, Whelpley, and Craven, 1963] demonstrate that mechanisms of particle acceleration and propagation must exist within the magnetosphere, which energize and distribute the lower energy particles found within the transition and magnetospheric tail regions, to produce the observed distributions of particle intensities. The initial observations of large scale temporal variations in the intensities of electrons (E > 1.2 MeV) in the outer radiation zone with the low altitude satellite Explorer 7 [Forbush, Venkatesan, and McIlwain, 1961; Forbush, Pizzella, and Venkatesan, 1962] as well as small scale variations in the inner radiation zone particle intensities [Pizzella, McIlwain, and Van Allen, 1962], and subsequent observations of these temporal variations in the intensities of electrons (E > 40 keV, > 230 keV, > 1.6 MeV) in the outer zone near the geomagnetic equatorial plane [Frank, Van Allen, and Hills, 1964], trapped electrons (E > 280 keV, > 1.2 MeV) mirroring at low altitudes in the outer zone [Williams and Smith, 1965] and precipitating electrons (E > 40 keV) from the outer zone [O'Brien, 1964] further require that such acceleration mechanisms operate over a large dynamic range and be capable of operating effectively within times of the order of minutes to hours.

Current candidates for such "local" acceleration mechanisms are magnetospheric electric fields [e.g., Axford, 1962; Speiser, 1965; Taylor and Hones, 1965] and adiabatic trans-L diffusion

[Kellogg, 1959; Parker, 1960; Herlofson, 1960; Davis and Chang, 1962; Nakada, Dungey, and Hess, 1964]. The theoretical computations indicate that electric fields may exist with sufficient strength to accelerate electrons to energies of several tens of kiloelectron volts. The observations of the apparent radial diffusion of electrons ($E > 1.6$ MeV) at $L \sim 3\text{-}5$ by Frank [1965b] and of protons ($40 > E > 110$ MeV) at $L \sim 2.2$ by McIlwain [1965] are suggestive of such processes.

The present paper presents the results of an investigation of the temporal variations of the intensities of electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) trapped in the outer radiation zone and mirroring at low altitudes as observed by the U. of Iowa/ONR research satellite Injun 3 during the period January 1 to July 31, 1963.

II. Description of the Experiment

The University of Iowa research satellite Injun 3 (1962 beta-tau) was launched on December 13, 1962, into an orbit whose initial parameters were an apogee altitude of 2785 km, a perigee altitude of 237 km, an orbital inclination of 70.4° and a period of 116 minutes. The satellite was oriented with respect to the local geomagnetic field vector, $\vec{B}$, by an on-board permanent magnet. Throughout its useful lifetime of some nine months, data pertaining to the orientation [Fritz, 1965] and the operating voltages and temperatures were routinely monitored. A system of on-board solar aspect sensors indicated those times when data from directional detectors sensitive to light and/or solar x-rays were being contaminated. A description of the complete Injun 3 satellite is given by O'Brien, Laughlin, and Gurnett [1964].

This paper is concerned with data obtained from three Geiger-Mueller tubes which were part of the Injun 3 radiation experiment. They are: 213A, a thin-windowed (~ 1.2 mg cm^{-2} mica) Anton 213 G.M. tube, whose 13° half angle conical field of view is centered on a line normal to $\vec{B}$, when the satellite is properly oriented; 213B, a G.M. tube which is identical to 213A with the exception of an additional 48 mg cm^{-2} of aluminum over the viewing window; 302, an Anton 302 G.M. tube surrounded by 265 mg cm^{-2} of magnesium. The physical parameters associated with these instruments are tabulated in Table I.

The true versus apparent (R vs r) counting rate calibrations of these instruments were performed by doing a series of overlapping inverse-square calibrations, utilizing a Westinghouse Quadrocondex x-ray machine. The dynamic ranges of the G.M. tube counting rates were greater than 3×10^6. Allowing for the temperature and voltage coefficients of the instruments, the R vs r curves are considered accurate to within 20% for 302 when $r < 10^4$ counts $(sec)^{-1}$ and for 213A and 213B when $r < 5 \times 10^3$ counts $(sec)^{-1}$, the higher counting rates being the least accurate. The accuracies of the curves decrease at higher counting rates, being ~ 50% for 302 when $r \sim 2 \times 10^4$ counts $(sec)^{-1}$, for 213A when $r \sim 1.3 \times 10^4$ counts $(sec)^{-1}$ and for 213B when $r \sim 8 \times 10^3$ counts $(sec)^{-1}$.

The efficiencies of G.M. tubes for the detection of non-penetrating electrons have been studied in detail by this laboratory [e.g., Frank, 1962], and a summary of such work, for several of the G.M. tubes of the type used on Injun 3, is presented in Figure 1.

From this data, nominal threshold energies and geometric factors have been obtained by numerically evaluating an integral of the form

$$\int \epsilon(E) g \frac{dj}{dE} \, dE ,$$

where $\epsilon(E)$ is the empirically determined efficiency, in counts $(\text{electron})^{-1}$, g is the directional geometric factor for penetrating electrons and dj/dE is the directional differential intensity spectrum assumed. For the 302, corresponding omnidirectional quantities are used. The quantity

$$\alpha(E,\gamma) = \frac{\int_E^\infty \epsilon(E) g \frac{dj}{dE} \, dE}{\int_0^\infty \epsilon(E) g \frac{dj}{dE} \, dE}$$

which is the relative contribution to the total counting of the G.M. tube, due to electrons of energy greater than E when the differential intensity spectrum is of the form $AE^{-\gamma}$, has been computed for a selection of spectra. From these results, which are summarized in Table II, and the forms of the observed energy spectra, the following conclusions have been made for all events observed during this study: (1) 213A is responding primarily to electrons with $E > 40$ keV and has an effective ϵg of 4×10^{-3} count-cm^2-sr (electron)$^{-1}$, and (2) 302 is responding primarily to electrons with $E > 1.6$ MeV and has an effective ϵG_o of 0.1 count-cm^2 (electron)$^{-1}$.

A revaluation of the efficiencies of 213B-type Geiger tubes is in progress, but the results are not expected to differ in any important way from those previously known, that in the outer zone the 213B responds primarily to electrons with $E > 230$ keV with an effective ϵg of 4×10^{-3} count-cm^2-sr(electron)$^{-1}$.

Identification of the charged particles observed by the three G.M. tubes was made by comparing their intensities with those measured with complementary experiments on-board Injun 3. The p-n junction experiments, which measured the energy spectrum and directional intensities of protons (700 keV $< E <$ 100 MeV) (data the courtesy of C. Bostrom and G. Pieper, The Applied Physics Laboratory, Johns Hopkins University) indicate that for any reasonable proton spectra there are no important contributions to the responses of 213A and 213B due to protons ($E > 500$ keV) and ($E > 4$ MeV), respectively, in the region $L \geq 3$ for the data used in the present investigation. These results, plus the data obtained from the nearly omnidirectional pulse scintillator experiment which responded to protons ($E > 40$ MeV) (data the courtesy of C. McIlwain, Department of Physics, University of California at San Diego, La Jolla, California) have shown that the 302 was responding primarily to electrons ($E > 1.6$ MeV).

III. Data Analysis

Data telemetered by the Injun 3 satellite were received by a large network of ground stations and recorded on magnetic tape along with oral time verifications and, when possible, WWV. These data tapes were then sent to the University of Iowa for decoding and merging with ephemerides computed by the Goddard Space Flight Center of NASA. A master data tape was then compiled which, with each eight second average of the experimental data, contained the following information: universal time, satellite clock time, geographic local time, geographic latitude, longitude and altitude, B and L, B/B_o, solar aspect and magnetic orientation data, revolution number, receiving station identification code and various housekeeping data. With this master data tape it was possible to sort and select the data in any desired manner.

For this study, the data were organized in several manners. First, in order to study the temporal variations of the electron intensities at fixed points in B-L space [McIlwain, 1961] (which is assumed to be an equally valid coordinate system during geomagnetically calm and disturbed times in the region $L \lesssim 7$) for the seven-month period under investigation, the data were sorted on

L and divided into non-overlapping blocks whose dimensions were 0.5 L and which were centered on integer and half-integer values of L. Each block of data was then sorted on B, with dimensions of 0.02 gauss, forming a data matrix in B and L, each element of which was then ordered in time. To study the variations for seven consecutive months, one datum per twelve hours at a selected value of L ± 0.1 and at the lowest value of B which was available was selected from the data matrix for each G.M. tube and plotted against time. During several periods of increased geomagnetic activity, observations of the temporal behavior of the electron intensities were made with a time resolution of several hours by selecting all available data at a fixed L ± 0.1 and plotting it against time. In these cases the dependence on B must be carefully studied.

The L dependence of the temporal variations of the outer zone electron intensities was further studied by choosing sets of nearly identical passes through the outer zone and comparing the day to day changes in those intensities. Any set of passes, which, for any given value of L in the outer zone, has the same value of B, to within ~ 0.01 gauss, are termed nearly identical. These passes occurred once every ~ 24 hours, and sets of 8-12 passes were typical.

Data were accepted only when the satellite was within 10° of alignment with the local geomagnetic field vector and data contaminated by solar x-rays were eliminated. Corrections due to changes in operating voltages and temperatures were not necessary.

A summary of the ground stations which were active in receiving telemetry from Injun 3, and a breakdown by month of the number of passes through the outer zone for which data exist has been published [Frank, Van Allen, and Craven, 1964]. In summary, it shows that ~ 90% of the data available for study were obtained when Injun 3 was over or near the North American Continent.

IV. Presentation of Data

1. The Temporal Variations of the Intensities of Electrons ($E > 40$ keV)

The temporal variations of the intensities of electrons ($E > 40$ keV) trapped in the outer radiation zone have been studied at low altitudes with the 213A G.M. tube on Injun 3 for the seven-month period from January 1 to July 31, 1963. The responses of 213A to these electrons are presented in Figure 2. The different ranges of B are indicated by appropriate symbols, which are defined therein. The values of L for which data were assembled were 3.0, 3.5, 4.0, 4.5, 5.0, and 6.0. Included are the corresponding daily sums of the planetary disturbance parameter, K_p [Lincoln, 1963], hereafter denoted by ΣK_p, which has been shown to be positively correlated with the intensities of electrons ($E > 40$ keV) near the geomagnetic equatorial plane [Frank, Van Allen, and Hills, 1964] and with the solar wind velocity [Snyder, Neugebauer, and Rao, 1963].

The striking parallel between periods of enhanced electron intensities and increased geomagnetic activity, as measured by ΣK_p, is self-evident: with each new geomagnetic disturbance, there occurs an abrupt increase in the intensities of electrons ($E > 40$ keV) trapped in the outer zone, followed by a monotonic decrease in the intensities as the disturbance subsides. The increases in intensities in the heart of the outer zone, i.e., $L \sim 4.5$, are typically $\sim 10^6$ $(\text{cm}^2\text{-sec-sr})^{-1}$, or a factor of $\sim$ 10-15 greater than the typical pre-disturbance intensities of $\sim 7\text{-}10 \times 10^4$ $(\text{cm}^2\text{-sec-sr})^{-1}$. At $L = 3.0$ the temporal variations of the intensities of trapped electrons ($E > 40$ keV) are found to be small in magnitude, with changes of a factor of ~ 2 being typical, and, unlike those occurring at higher L, are generally of a gradual nature, occurring over many days. Increases in intensities at $L = 3.0$ are observed only in association with the more intense geomagnetic disturbances (cf. March 7-14, 1963). During smaller disturbances the intensities appear to be gradually decreasing. The intensities of trapped electrons ($E > 40$ keV) at $L = 6.0$ display a temporal behavior which is similar to that observed in the heart of the outer zone at $L \sim 4.5$, although the intensities appear to be slightly more sensitive to variations in ΣK_p. The several "short-lived" decreases in the intensities of these electrons at $L = 6.0$ near the beginning of two geomagnetic disturbances in July, where the data are plentiful, are most curious. These observations are discussed in a later portion of this report.

A close study of Figure 2 reveals an interesting relation between the observed enhancements of the intensities of electrons ($E > 40$ keV) trapped in the outer zone and ΣK_p, as is demonstrated by the data at $L = 4.0$ for April, 1963. That is, the more intense a geomagnetic disturbance, as measured by the maximum ΣK_p observed during each such disturbance, and hereafter denoted by $MAX\Sigma K_p$, the greater the increase in the intensities of electrons ($E > 40$ keV) trapped in the outer zone at the onset of the disturbance. A study of this correlation at a specific L, say $L = 4.5 \pm 0.1$, indicates presence of the positive correlation, but a more clearly defined correlation, with a minimum of data scatter, is possible by taking, for each enhancement, the average increase in intensities in the region $3.5 \leq L \leq 5.0$, as measured by taking the average of the increases at $L = 3.5$, 4.0, 4.5, and 5.0, and associating this average with the corresponding $MAX\Sigma K_p$ for the disturbance.

These results are presented in Figure 3, where it can be seen that the temporal variations of the intensities of electrons

(E > 40 keV) are only marginally observable in the outer zone for geomagnetic disturbances characterized by MAX$\Sigma K_p \lesssim 15$, while for very intense events, MAX$\Sigma K_p \gtrsim 35$, the increases in intensities become only weakly dependent on MAXΣK_p, possibly indicating approach to some limiting value.

Although some 22 geomagnetic disturbances and the corresponding temporal behavior of the intensities of electrons (E > 40 keV) trapped in the outer zone were observed during the seven months under study, it was not always possible to determine the time rate of decay of these electron intensities at Injun 3 altitudes during periods of what might be termed "the quiet geomagnetic field", since new disturbances would introduce a supply of "fresh" electrons (E > 40 keV) and thus mask the decay which followed the previous enhancement. There were, however, several geomagnetic disturbances which were followed by extended periods of low K_p for which the time rate of decay of the intesities of electrons (E > 40 keV) have been measured at low altitudes in the outer zone. For these events, the intensities have been represented by

$$j_\perp (E > 40 \text{ keV}, t) = j_\perp (E > 40 \text{ keV}, 0)\ e(-t/\tau),$$

and the decay constant, τ, obtained for various values of L. The results are to be found in Figure 4, where it can be seen that the values of τ lie between 2 and 6.5 days for $3.5 \leq L \leq 6.0$, but increase rapidly at lesser L. The slightly larger values of τ obtained at L = 4.0 and 4.5 in March, and at 5.0 and 6.0 in February may be due to small injections of "fresh" electrons.

As Injun 3 only sampled the intensities of trapped outer zone electrons (E > 40 keV) which mirrored at low altitudes and whose equatorial pitch angles were $\lesssim 5°$, it was desirable to attempt to expand these results to include all equatorial pitch angles, by comparing point by point the Injun 3 data with simultaneous measurements by similar experiments in the outer zone and near the geomagnetic equatorial plane. The published Explorer 14 data of Frank [1965a], which gives the spin-averaged omnidirectional intensities of electrons (E > 40 keV) near the geomagnetic equatorial plane at L = 4.2 have been compared with the nearly simultaneous Injun 3 data at L = 4.0. The results are displayed in Figure 5. As this is considered only a preliminary study of the simultaneous measurement of the intensities of these electrons, the small difference in L is neglected, the measurements are simultaneous only to within ~ 24 hours and any local time dependence which might be present, due to the satellites being at different local times at the time of individual measurements, is neglected. It can be seen that while temporal variations corresponding to increases in intensities by factors of 15 have been observed, the scatter of the data is, with few exceptions, always less than a factor of 2 from the median. The medians of the ratios of the equatorial omnidirectional intensities to the low altitude unidirectional intensities were 32 and 14 for $j_{\perp}$ (E > 40 keV) = $7.4 \pm 2.5 \times 10^4$ and $12 \pm 4 \times 10^5$ $(cm^2\text{-sec-sr})^{-1}$, respectively.

From the same set of Explorer data, τ has been measured and is compared with the corresponding values measured at low altitudes in Table III. The agreement appears to strongly support the arguments for a close association between equatorial intensities of electrons (E > 40 keV) in the outer zone and the corresponding intensities at low altitudes.

2. The Temporal Variations of the Intensities of Electrons (E > 230 keV)

The responses of the 213B G.M. tube due to the intensities of electrons (E > 230 keV) trapped in the outer zone during the same period, and subject to the same method of analysis as for the 213A G.M. tube, are presented in Figure 6. As in the case of the intensities of electrons ($E > 40$ keV), the intensities of electrons ($E > 230$ keV) demonstrate characteristic temporal variations which can be correlated with the temporal behavior of ΣK_p. However, as these variations are not always clearly defined in Figure 6, as the time resolution of the data is, at times, comparable to the time scale of the variations being observed, and the allowed spread in L ($\pm$ 0.1) is too large for $L \leq 4.0$, where the intensities are changing rapidly with L, Figure 7 is included to more clearly define the variation in the regions of interest.

The morphology of these intensity variations, as shown in Figures 6 and 7, at $L \geq 4.5$, can typically be described as (1) a rapid initial decrease in the intensities of these electrons, which occurs in the early phase of a geomagnetic disturbance, when ΣK_p is typically $\gtrsim 20$, followed by (2) a recovery phase in which the intensities of these electrons increase to approximately those intensities which existed prior to the disturbance. The duration of the recovery is seen to vary between ~ 1-2 days and ~ 7-10 days, for various disturbances. The data for the last week of May are exceptions to this typical behavior in that a recovery is not observed at $L \sim 4$-4.5 while it is observed at $L > 4.5$.

Smaller geomagnetic disturbances, characterized by $\Sigma K_p < 20$, appear to be associated with gradual depletions of these electron intensities at $L \leq 4.5$, as is illustrated by the data for the latter parts of February and April. At $L = 6.0$, the depletion-recovery cycle is apparently still operative.

For $L \leq 4.0$, examples of no observable depletions are evident at the beginning of geomagnetic disturbances, particularly in Figure 7, where the spread in L is reduced (e.g., May 1 and June 6, 1963). The temporal variations in these few cases are quite similar to those observed for the intensities of electrons ($E > 40$ keV) in these regions of the outer zone.

During the first several months of observations, the 213B responses were significantly increased by the presence of artificially injected high energy electrons (see page 24 of the text). The primary mode of operation of the Injun 3 satellite during the first ~ 3 months of operation is responsible for the poor data sample obtained with this detector before ~ April 1, 1963.

3. The Temporal Variations of the Intensities of Electrons (E > 1.6 MeV)

In Figure 8 are displayed the responses of the 302 G.M. tube due to the intensities of electrons (E > 1.6 MeV) at low altitudes in the outer zone for the seven-month period under investigation. With the exception of the data for L = 3.0, and the general monotonic decrease in intensities superimposed on the regular temporal variations at L = 3.5, the temporal variations of the intensities of electrons (E > 1.6 MeV) trapped in the outer zone are of a form which vary in magnitude from 10 to 10^3, depending upon the particular geomagnetic disturbance and the value of L. Associated with each geomagnetic disturbance there is a rapid decrease in the intensities of electrons (E > 1.6 MeV) which takes place within several days, followed by a monotonic increase in the intensities which continues until either another depletion occurs in the outer zone or the rate of increase lessens and the intensities approach some "equilibrium" level (e.g., at L = 4.0 and 4.5 from ~ May 19 to May 25).

At L = 3.0 and 3.5, the 302 responded primarily to electrons (E > 1.6 MeV) artificially injected into the outer zone by the Soviet high altitude nuclear detonations of October and November, 1962 [Frank, Van Allen, and Hills, 1964]. On January 1, 1963, the intensities were J_o $(E > 1.6 \text{ MeV}) = 4 \pm 2 \times 10^5$ and $6 \pm 2 \times 10^4$ $(\text{cm}^2\text{-sec})^{-1}$ at $L = 3.0$ and 3.5, respectively, for $B = 0.20 \pm 0.02$ gauss. At $L = 3.0$ the intensities for $B = 0.27 \pm 0.02$ gauss were reduced by a factor of ~ 4. The intensities at $L = 3.0$ exhibited an exponential time behavior of the form $\exp(-t/\tau)$ until about June 6, 1963, for which $\tau = 40 \pm 5$ days, throughout the period. Until May 8, 1963, an exponential decay which was interrupted during several large geomagnetic disturbances was observed at $L = 3.5$ with $\tau = 45 \pm 5$ days.

Following a depletion, the time rate of change of the intensities of electrons $(E \geqslant 1.6 \text{ MeV})$ was observed to be constant in time when the response of the 302 G.M. tube was in the linear region, and to slowly decrease as the non-linear response region was encountered. Making the correction for the 302 G.M. tube dead-time, it has been found that until the "equilibrium" intensities are approached, the time rate of change of the counting rate of the 302 is a "constant of the geomagnetic disturbance", depending only on the $\text{MAX}\Sigma K_p$ for the disturbance and the strength of the magnetic field. That is,

$$\frac{dR_{302}}{dt} = f_L(B, \mathrm{MAX}\Sigma K_p)$$

following the initial depletion of the intensities of electrons ($E > 1.6$ MeV). This quantity has been measured for ten geomagnetic disturbances at $L = 4.0$ and $B = 0.2 \pm 0.2$ gauss and is presented in Figure 9. The datum for $\mathrm{MAX}\Sigma K_p = 48$ was obtained from the event of mid-September 1963. The dependence on B is weak for this region of the outer zone, with dR/dt decreasing by less than 25% for an increase in B of 0.1 gauss.

In Figure 10 the change in dR/dt with L is displayed for the event of early July where $\mathrm{MAX}\Sigma K_p = 25$. It can be seen that dR/dt increases very rapidly from ~ 0 to nearly its maximum value between $L = 3.0$ and 4.0, changes little in the heart of the zone, $L = 4.5 \pm 0.5$, and then decreases with increasing L, though at a slower rate than on the inward side of the zone. Notice that the counting rates of the 302 for $L \leq 4.5$, when extrapolated to intersection, meet on July 6 which is ~ 2 days sooner than the extrapolated counting rates for $L > 4.5$. These latter counting rates appear to be only slowly varying until that time. A preliminary survey of several other geomagnetic events indicates that the slope of the dR/dt vs $\mathrm{MAX}\Sigma K_p$ line is independent of L throughout the region under investigation.

Several cases of an apparent diffusion of electrons ($E > 1.6$ MeV) toward lower values of L have been observed in the Injun 3 302 data. A typical observation is illustrated by the data presented in the upper panels of Figure 11 where a set of nearly identical passes through the outer zone has been selected and the responses of the 302 plotted against L. Notice that prior to onset of the geomagnetic disturbance the peak in the intensity of electrons ($E > 1.6$ MeV) occurred at $L \sim 3.9$, whereas following the initial depletion and during the period in which the intensities were increasing, the maximum occurred at $L \sim 4.5 \pm 0.3$, being at higher L at first and progressively moving toward lower L. An observation of the outer zone intensity distribution in late April (see Figure 14), just prior to a new disturbance, shows that the peak in the intensities had progressed to $L \sim 4.1$, which is the same behavior exhibited during the previous month, pass 1 (March 31, revolution 1341) being the last of the previous series.

The motions of several secondary peaks in the outer zone electron ($E > 1.6$ MeV) intensities were observed by the Injun 3 302 G.M. tube on May 18-19, 1963. The responses of the 302 for all available outer zone passes during this period are plotted in

Figure 12. It can readily be seen that during two separate epochs (revolution 1943-1947 and 1949-1957) secondary peaks are moving towards lower L with nearly constant intensities $\sim 7 \times 10^3$ $(\text{cm}^2\text{-sec})^{-1}$, when resolved from the contribution of the quiescent outer zone intensities.

From these and other similar observations, the low altitude inward velocity of the intensity maxima of electrons ($E > 1.6$ MeV) has been obtained between an L of ~ 3.5 and 6.5, and are presented in Figure 13 along with the results of Frank [1965b] for the leading edge of the distribution of electrons ($E > 1.6$ MeV) observed near the geomagnetic equator. The upper limit of $\sim 2 \times 10^{-3}$ L $(\text{day})^{-1}$ at $L = 2.1$ was obtained from Explorer 4 measurements [Van Allen, McIlwain, and Ludwig, 1959] of electrons injected into the magnetosphere during the Argus project. The observed rates at $L = 4$ and 6 are $\sim 10^{-2}$ and ~ 2 L $(\text{day})^{-1}$, respectively. The order of magnitude difference between these results and those of Frank suggest that the leading edge of such a distribution, from which the data of Frank were obtained, moves at a larger velocity than the peak of the distribution, which is the region of interest in these observations.

4. Outer Zone Low Altitude Profiles

Return now to Figure 11, which presents the responses of 213A, 213B, and 302 for a set of nearly identical passes through the outer zone during the disturbance beginning April 4, 1963 ($\mathrm{MAX}\Sigma K_p = 33$ on April 5). As already discussed, the intensities of electrons ($E > 1.6$ MeV) were greatly reduced above $L \sim 3.5$ by April 5, and during the following six days were observed to steadily increase toward pre-disturbance intensities of $\sim 2 \times 10^4$ $(\mathrm{cm}^2\text{-sec})^{-1}$, the maximum in intensities moving progressively towards lower L. The intensities of electrons ($E > 230$ keV) decreased during a small disturbance on April 1, and were not greatly enhanced until after the April 4 onset at which time they increased rapidly. The intensities of electrons ($E > 40$ keV) displayed large spatial and temporal variations during April 4-6 when $\Sigma K_p > 20$ as compared to the intensities of April 2, which represents a quiet time profile. The sharp terminations of the intensities of electrons ($E > 40$ keV) at $L \sim 6.3$ and ~ 5.8 on April 4 and 6, respectively, indicate that high latitude trapping boundary for these electrons, which is typically above $L \sim 8$ [Frank, Van Allen, and Craven, 1964], is temporarily displaced towards lower latitudes during geomagnetically disturbed periods. The duration of the displacement and its maximum magnitude cannot be obtained from this data.

Another set of outer zone profiles is presented in Figure 14 for the period April 28 to May 4, 1963, during which a disturbance with $\mathrm{MAX}\Sigma K_p = 33$ (May 1) began on April 30. Of interest are the profiles of the low altitude outer zone intensities of electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) on May 1, 1963, at ~ 0239 U.T. as observed during the southbound portion of revolution 1726 over North America. It is readily seen that the intensities of these electrons are catastrophically depleted throughout the outer zone with the intensities of electrons ($E > 1.6$ MeV) being markedly depleted above $L \sim 3.5$, above $L \sim 4.0$ for electrons ($E > 230$ keV) and above $L \sim 4.6$ for electrons ($E > 40$ keV). The low altitude electron intensities at $L = 5.0$ on May 1, 1963, at ~ 0237 U.T. were

$$j_\perp\ (E > 40\ \mathrm{keV}) \sim 740\ (\mathrm{cm}^2\text{-sec-sr})^{-1}$$

$$j_\perp\ (E > 230\ \mathrm{keV}) < 250\ (\mathrm{cm}^2\text{-sec-sr})^{-1}$$

$$J_o\ (E > 1.6\ \mathrm{MeV}) \sim 20\ (\mathrm{cm}^2\text{-sec})^{-1}$$

The data from the northbound portion of revolution 1726 which passed through the outer zone at ~ 0225 U.T. indicate that the intensities of electrons ($E > 230$ keV, > 1.6 MeV) were greatly depleted down to $L \sim 4.4$ and $L \sim 4$, respectively, at low altitudes, and the intensities of electrons ($E > 40$ keV) were greater than $\sim 2 \times 10^4$ $(\mathrm{cm}^2\text{-sec-sr})^{-1}$ below $L \sim 7.5$ and then decreased abruptly by over two orders of magnitude. The displaced high latitude trapping boundary for electrons ($E > 40$ keV) was observed at a local time of ~ 1320 during the northbound pass and at ~ 1830 during the southbound pass. The corresponding median positions of the boundary [Frank et al., 1964], as defined by the value of L for which $j_{\perp}$ ($E > 40$ keV) decreases below 3×10^3 $(\mathrm{cm}^2\text{-sec-sr})^{-1}$ were ~ 18 and ~ 10, respectively, indicating that at ~ 1320 local time the boundary was displaced by $\Delta L \sim 10$ and at ~ 1830 by $\Delta L \sim 5.5$.

The hourly scalings of the horizontal component of the geomagnetic field at Sikta ($L \sim 4$) and College ($L \sim 5.5$), Alaska show abrupt increases of ~ 100 γ and ~ 200 γ, respectively, occurred during the hour 0200-0300 U.T. of May 1, 1963, as compared to the hourly scalings for the previous few hours.

On the southbound pass of revolution 1726, Injun 3 was at west longitude 127° when it crossed the $L = 5.5$ shell at an altitude of ~ 2000 km, thus being within ~ 20° of longitude of College. College riometer data [courtesy of R. Parthasarathy, Geophysical Institute, University of Alaska, College, Alaska] indicates that cosmic radio noise absorption at 27.6-Mc/s was minimum during the period 2200 U.T. April 30 to 0900 U.T. May 1, 1963, and was certainly never greater than 0.4 db above the quiet time background [Leinbach, private communication].

5. Maximum Resolution of Outer Zone Electron Intensities During Geomagnetic Disturbances

The observation of outer zone depletion of the intensities of electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) and the simultaneous increase in the horizontal component of the geomagnetic field suggests an attempt to correlate the time behavior of the geomagnetic field and the outer zone electron intensities on a scale of ~ 2 hours, that being the orbital period of Injun 3. For the periods of March 28-April 12 and June 4-10 all available data at $L = 4.0 \pm 0.1$ and $.17 \leq B \leq .37$ gauss have been plotted against time and are displayed in Figure 15, along with the corresponding 3-hour values of K_p and the 3-hour averages of the horizontal component of the geomagnetic field at College, Alaska. The temporal variations of the intensities of electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) are consistent with the heretofore presented data. The intensities of electrons ($E > 40$ keV), while not being observed to decrease at onset, do increase as expected, and appear to do so in association with each increase in the horizontal component of the order of 100 γ or greater. The intensities of electrons ($E > 230$ keV) are observed to gradually decrease near the onset of the April event and to be replenished within ~ 36 hours after maximum depletion. No depletion is observed in the June event, and the increase in intensities occurs within ~ 10 hours. The large depletions in the intensities of electrons ($E > 1.6$ MeV) are clearly defined, as are the steady increases in intensities following the depletion. The large depletions are observed to take place within 3-6 hours.

V. Discussion and Summary

The temporal variations of trapped outer zone electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) which mirror at low altitudes have been studied during the period from January 1 to July 31, 1963, with the U. of Iowa/ONR research satellite Injun 3. The unidirectional intensities of electrons ($E > 40$ keV) which mirror at low altitudes (~ 1500 km) have been directly compared with the omnidirectional intensities of these electrons near the geomagnetic equatorial plane [Frank, Van Allen, and Hills, 1964] at $L \sim 4$, and it has been found that, to within a factor of 2, the two are closely related throughout the range of observed intensities, regardless of geomagnetic conditions at the times of the measurements. The medians of the ratios of the equatorial omnidirectional intensities to the low altitude unidirectional intensities for $j_{\perp}$ ($E > 40$ keV) $\sim 7.5 \pm 2.5 \times 10^4$ and $12 \pm 4 \times 10^5$ (cm^2-sec-sr)$^{-1}$, are 32 and 14, respectively, indicating an approach to equal omnidirectional intensities along the field lines as the intensities approach $\sim 10^{7-8}$ (cm^2-sec)$^{-1}$. That the intensities at low altitudes (~ 1500 km) approach isotropy over at least $\sim 3\pi$ in this intensity limit is clearly demonstrated at L ~ 5.5 in Figure 4 of Parthasarathy, Bekery, and Venketesan [1965], in which Injun 3 data were used to compare the unidirectional intensities of electrons (E > 40 keV) mirroring at ~ 1500 km with those whose pitch angles at ~ 1500 km are < 40°, and hence a part of which are absorbed in the upper atmosphere [cf. O'Brien, 1964]. Equal omnidirectional intensities along a field line, extending from ~ 1500 km to the geomagnetic equatorial plane, and isotropy at ~ 1500 km follow from isotropy near the geomagnetic equatorial plane [Ray, 1959]. While the converse clearly need not follow, for field lines with only one minimum in B and an angular distribution which is well behaved along the field line, it is probably a good approximation.

The intensities of outer zone electrons (E > 40 keV) have been observed to change abruptly at the onset of geomagnetic disturbances [cf. Frank, Van Allen, and Hills, 1964]. Several events have been observed when the intensity changes occurred within the same 3-6 hour periods as the horizontal component of the geomagnetic field at College, Alaska (L ~ 5.5) increased by 100-200 γ. An observation of a catastrophic decrease in the intensities of these electrons in the outer zone down to L ~ 4.5 on May 1, 1963, at ~ 0230 U.T., during the same ~ 1 hour period in which the horizontal component at Sitka ($L \sim 4$) and College, Alaska, increased by $\sim 100\ \gamma$ and $\sim 200\ \gamma$, respectively, has been presented. At this time the intensities of electrons ($E > 40$ keV) were $\sim 740\ (\mathrm{cm}^2\text{-sec-sr})^{-1}$ at $L \sim 5$, which were a factor of ~ 1000 less than the quiet time intensities typically observed. This large scale depletion was also observed at the higher energies. Several similar types of depletion have since been found in the data, again occurring in the same time periods in which the horizontal component at College had increased by $> 100\ \gamma$ above the typical quiet time values. The durations of these depletions were certainly less than ~ 4-6 hours for electrons ($E > 40$ keV), as they were not observed during the next available transits through the outer zone. Further studies are required in order to ascertain whether or not this phenomenon occurs frequently at the beginning of geomagnetic disturbances.

It has been shown that during each geomagnetically disturbed period an enhancement in the intensities of electrons ($E > 40$ keV) takes place throughout the outer zone [cf. Frank et al., 1964], and that the increase, when averaged over the region $3.5 \leq L \leq 5.0$ is an increasing function of $\mathrm{MAX}\Sigma K_p$. For disturbances characterized by $\mathrm{MAX}\Sigma K_p \lesssim 15$, the changes in the intensities are only marginally observable, while for disturbances with $\mathrm{MAX}\Sigma K_p \gtrsim 35$ the increases become less sensitive to the parameter, indicating an asymptotic approach to an upper limit for the intensities of durably trapped electrons ($E > 40$ keV). This upper limit, J_o ($E > 40$ keV) $\sim 7 \pm 5 \times 10^7$ $(\mathrm{cm}^2\text{-sec})^{-1}$, is comparable to the intensities required for equal omnidirectional intensities along the field lines at $L \sim 4$ and compares favorably with the upper limits for durably trapped electrons ($E > 40$ keV) computed by Kennel and Petschek [1965] due to whistler mode noise diffusion of pitch angles for these electrons. These limits were J_o ($E > 40$ keV) $\sim 2 \times 10^8$ $(\mathrm{cm}^2\text{-sec})^{-1}$ at $L \sim 4$ and $\sim 4 \times 10^7$ $(\mathrm{cm}^2\text{-sec})^{-1}$ at $L \sim 6$, with an increasing diurnal effect occurring for $L \gtrsim 5$.

During periods of geomagnetic calm ($\Sigma K_p < 15$), which followed disturbed periods when large enhancements in the intensities of electrons ($E > 40$ keV) occurred, the intensities of these electrons were observed to decrease in approximately an exponential manner. For a representation proportional to $\exp(-t/\tau)$, τ has been found to vary between 2.0 and 6.5 days for $3.5 \leq L \leq 6.0$, with an average of 4.2 days, for four post-disturbance periods. At $L = 3.0$ the decay constant had increased significantly, to 12 ± 3 days. A comparison of Injun 3 and Explorer 14 measurements at $L \sim 4$, for the four periods, has shown the decay constants to be very similar at low altitudes and large radial distances, the average values of τ being 4 and 3.8 days, respectively.

The intensities of electrons ($E > 1.6$ MeV) have also been shown to vary greatly at the onset of geomagnetic disturbances [cf. Frank, Van Allen, and Hills, 1964]. During the few hours in which the intensities of electrons ($E > 40$ keV) were observed to change abruptly, the intensities of electrons ($E > 1.6$ MeV) were observed to decrease by factors of $10\text{-}10^3$ in the outer zone, and in the following 5-10 days to increase linearly with time, provided ΣK_p did not increase above ~ 10 during the recovery. The depth to which depletion occurred in the outer zone was dependent upon the intensity of the disturbance, as indicated by $\mathrm{MAX}\Sigma K_p$. For small disturbances ($\mathrm{MAX}\Sigma K_p < 20$), only depletions and/or an end to enhancements would occur below $L = 4.5$, but at higher L striking depletions were evident. Only the more intense disturbances, which were characterized by $\mathrm{MAX}\Sigma K_p \gtrsim 30$, produced large scale depletions at $L \lesssim 4.0$.

The rate of increase in the intensities of electrons ($E > 1.6$ MeV) following depletion was shown to be an increasing function of the MAXΣK_p, which characterizes the disturbance, and at $L = 4$ was 10^3 (cm^2-sec-day)$^{-1}$ and 7×10^4 (cm^2-sec-day)$^{-1}$ for MAXΣK_p = 23 and 48, respectively. It appears that the slope of this line is independent of L for the region under investigation. For a given MAXΣK_p, however, the magnitude of the rate of increase is a maximum in the heart of the outer zone, $L \sim 4$-4.5, and decreases at higher and lower L, the decrease being more rapid at lower L. Enhancement appears to begin earlier at lower L, with a time delay of as much as two days between $L \sim 4$ and $L = 5$-6. The observations of abnormally low intensities of electrons ($E > 1.6$ MeV) at low altitudes in the outer zone from mid-December, 1964 to early February, 1965 (typically $< 5 \times 10^2$ (cm^2-sec)$^{-1}$) as observed by Injun 4 [Frank, Van Allen, Craven, and Hills, 1965] are quite normal when considered in light of these Injun 3 observations, as some six small geomagnetic disturbances, for which $10 \leq$ MAX$\Sigma K_p \leq 25$, occurred in this period, but no large scale disturbances were observable.

Wentworth [1964] has reported that for some 25 geomagnetic disturbances which occurred between August 1, 1960, and June 16, 1963, for which $\text{MAX}\Sigma K_p \geq 30$ and for which no disturbances occurred in the preceding 7 days or in the following 11 days, hydromagnetic emissions were more likely to occur during the seven days after ΣK_p first went above 30 then during the geomagnetically quiet periods.

The observations of apparent inward diffusion of electrons ($E > 1.6$ MeV) and of protons ($40 < E < 110$ MeV) near the geomagnetic equatorial plane have been reported, respectively, by Frank [1965] at $L \sim 3$-5 and McIlwain [1965] at $L = 2.2$. Similar observations have been made at low altitudes for $3.5 < L < 6.5$ with Injun 3 yielding apparent diffusion rates of $\sim 10^{-2}$ L $(\text{day})^{-1}$ and ~ 2 L $(\text{day})^{-1}$ at $L = 4.0$ and 6.0, respectively, for electrons ($E > 1.6$ MeV). These rates are a factor of 10 lower than those observed near the geomagnetic equatorial plane by Frank, indicating that the leading edge of the distribution, from which the calculations of Frank were obtained, moves at a larger velocity than the peak of the distribution, which is the region of interest in these observations.

On January 1, 1963, the observed intensities of electrons ($E > 1.6$ MeV) which were artificially injected into the magnetosphere by the Soviet nuclear bursts in October and November, 1962 were J_o ($E > 1.6$ MeV) $= 4 \pm 2 \times 10^5$ and $6 \pm 2 \times 10^4$ $(\mathrm{cm}^2\text{-sec})^{-1}$ at $L = 3.0$ and 3.5, respectively, and $B = 0.2 \pm 0.02$ gauss. At $L = 3.0$ the intensities decreased exponentially with a decay constant $\tau = 40 \pm 5$ days until July 7, 1963. The intensities at $L = 3.5$ generally decreased with $\tau = 45 \pm 5$ days until May 8, 1963, but were greatly modulated several times during large geomagnetic disturbances. The intensities at $L = 3.0$ and $B = 0.27 \pm 0.02$ gauss were a factor of four less than those at $B = 0.20 \pm 0.02$ gauss. The values of these decay constants are in good agreement with those observed by Van Allen [1964] at these L values with Explorer 14.

The intensities of electrons ($E > 230$ keV) have been found to vary in a systematic manner, as did the heretofore discussed cases. For $L \geq 4.5$, it is typically observed that with each geomagnetically disturbed period the intensities of electrons ($E > 230$ keV) exhibit an initial decrease, followed by an enhancement phase which lasts from 1-2 to 7-10 days, during which near predisturbance intensities are re-established and further enhancement does not occur. For $L \lesssim 4$, weak disturbances $\mathrm{MAX}\Sigma K_p < 20$, generally cause only small depletions with no observable enhancements following, while at larger L these variations are discernible in the data. During several more intense disturbances, for which $\mathrm{MAX}\Sigma K_p \geq 28$, rapid increases in these electron intensities below $L \sim 4.5$ within 6-8 hours, with no observable depletions preceding the increases, were observed, which suggests that the mechanisms by which ~ 40 keV electrons are accelerated, may, during the more intense disturbances, be operative on such a scale as to energize electrons to energies of the order of ~ 300 keV. The more gradual enhancements, which are more characteristic of the intensities at $L > 4$, are similar in form to those observed for the intensities of electrons ($E > 1.6$ MeV).

Although the 27-day periodicity in outer zone electron ($E > 280$ keV, > 1.2 MeV) intensities recently discussed by Williams [1966] is clearly expected from earlier results [cf. Forbush et al., 1962; Frank, Van Allen, and Hills, 1964], its association with the passages of the interplanetary magnetic field sector boundaries [Ness and Wilcox, 1965] and several solar wind parameters is of great importance.

ACKNOWLEDGEMENTS

I wish to express my sincere thanks to Dr. L. A. Frank for the suggestions which prompted this work and for many valuable discussions during the course of the work. The continued interest and helpful suggestions offered by Dr. J. A. Van Allen are gratefully acknowledged. Mr. R. J. DeCoster's assistance with the numerical integrations and the graphing of the data was invaluable. The research was supported in large part by the Office of Naval Research under contracts N9onr 93803 and Nonr 1509(06).

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TABLE I

Physical Parameters of Several
Injun 3 Geiger-Mueller Tubes

Designation	213A	213B	302
Axis of Viewing Cone with Respect to $\vec{B}$	perpendicular		Omnidirectional over ~ 3π
Half-Angle of Viewing Cone	13°		
Shielding Window (mg-cm^{-2})	1.2 mica	1.2 mica 48 aluminum	---
Wall (g-cm^{-2})	2.2 lead 0.56 magnesium		0.4 stainless steel 0.265 magnesium
Minimum Penetration Energy (MeV) Window	$E_e \sim 0.04$ $E_p \sim 0.5$	$E_e \sim 0.23$ $E_p \sim 5$	---
Wall	$E_e \sim 8$ $E_p \sim 40$		$E_e \sim 1.6$ $E_p \sim 23$
Geometric Factor for Penetrating Particles Directional (cm^2-sr)	6×10^{-3}*	5×10^{-3}*	---
Omnidirectional (cm^2)	~ 0.2		0.6*

*See pages 8-10 of text.

TABLE II

Energies (MeV) Above Which the Relative Contributions to the Counting Rates of Several Injun 3 Geiger-Mueller Tubes are α, for a Differential Number-Energy Spectrum of the Form $AE^{-\gamma}$.

Detector Designation	α γ	1.0	0.9	0.7	0.5	0.3	0.1
213A 302	1	0.03 3	0.06 5	0.2 11	0.6 22	2 43	6 76
213A 302	2	0.03 2	0.05 3	0.07 5	0.1 7	0.2 12	0.5 26
213A 302	3	0.03 2	0.04 2.5	0.05 3	0.06 4	0.08 6	0.17 9
213A 302	4	0.03 0.07	0.04 0.2	0.05 2.5	0.06 3	0.07 4.5	0.09 6.5
213A 302	5	0.03 0.02	0.04 0.05	0.045 0.07	0.055 0.09	0.055 0.12	0.08 0.3
213A 302	6	0.03 0.02	0.035 0.05	0.045 0.06	0.05 0.07	0.055 0.08	0.07 0.13

TABLE III

Decay Constants for the Intensities
of Electrons ($E > 40$ keV) at $L \sim 4$

EPOCH (1963)	INJUN 3 $\tau \pm 1.0$ Days	EXPLORER 14 $\tau \pm 1.5$ Days
February 14-24	4.0	4.5
March 10-25	6.5	4.5
May 14-24	2.5	4.0
July 7-16	3.0	2.0
Average	4.0	3.75

FIGURE CAPTIONS

Figure 1. The efficiencies of several Injun 3 Geiger-Mueller tubes as a function of electron energy.

Figure 2. The responses of the Injun 3 213A G.M. tube due to the intensities of electrons ($E > 40$ keV) trapped in the outer radiation zone and mirroring at low altitudes, selected at $L = 3.0$, 3.5, 4.0, 4.5, 5.0, and 6.0 ± 0.1 to display the temporal variations during the period from January 1 to July 31, 1963. The values of B are defined therein.

Figure 3. The averaged increase in the intensities of electrons ($E > 40$ keV) trapped in the outer zone and mirroring at low altitudes at the onset of a geomagnetic disturbance as a function of the maximum ΣK_p occurring during the disturbance. The average is taken over the intensities measured by the Injun 3 213A G.M. tube at $L = 3.5$, 4.0, 4.5, and 5.0 ± 0.1.

Figure 4. The observed decay constants, τ, for the intensities of electrons ($E > 40$ keV) trapped in the outer zone and mirroring at low altitudes, as measured by the Injun 3 213A G.M. tube as a function of L, when the intensities are represented by $j\ (E > 40\ \text{keV}, t) = j\ (E > 40\ \text{keV}, t = 0)\ \exp\ (-t/\tau)$, for four periods of low K_p following geomagnetically disturbed periods.

Figure 5. The nearly simultaneous observations of the unidirectional intensities of electrons ($E > 40$ keV) trapped at low altitudes in the outer zone with Injun 3 at $L = 4.0 \pm 0.1$ and the corresponding omnidirectional intensities near the geomagnetic equatorial plane with Explorer 14 at $L = 4.2 \pm 0.05$. The measurements are simultaneous to within ~ 24 hours.

Figure 6. A continuation of Figure 2 for the responses of the 213B G.M. tube due to the intensities of electrons ($E > 230$ keV).

Figure 7. The responses of the Injun 3 213B G.M. tube due to the intensities of electrons ($E > 230$ keV) trapped in the outer radiation zone and mirroring at low altitudes, at $L = 5.0 \pm 0.1$ and 3.95 ± 0.05 during the period from May 1 to July 31, 1963. The different temporal behavior at the two values of L is clearly displayed.

Figure 8. A continuation of Figure 2 for the responses of the 302 G.M. tube due to the intensities of electrons ($E > 1.6$ MeV).

Figure 9. The time rate of change of the response of the Injun 3 302 G.M. tube due to the intensities of electrons ($E > 1.6$ MeV) at $L = 4.0 \pm 1.0$ following the depletion of intensities at the onset of a geomagnetic disturbance as a function of the maximum ΣK_p occurring during the disturbance.

Figure 10. An example of the linear increases in time of the responses of the 302 G.M. tube due to the intensities of electrons ($E > 1.6$ MeV) at low altitudes in the outer zone following the initial depletion phase. The disturbance was characterized by $\mathrm{MAX}\Sigma K_p = 25$.

Figure 11. A set of nearly identical passes through the outer zone between March 31 and April 12, 1963, which illustrates the spatial and temporal changes which occur in the intensities of electrons (E > 40 keV, > 230 keV, > 1.6 MeV) during a typical geomagnetic disturbance. The inward motion of the maximum response of the 302 is an indication of trans-L diffusion.

Figure 12. A set of consecutive outer zone profiles which demonstrates the inward motions of several secondary maxima of the intensities of electrons (E > 1.6 MeV) during May 18 and 19, 1963.

Figure 13. The velocities of inward motion of outer zone *relative maxima* of the intensities of electrons (E > 1.6 MeV) as observed at low altitudes with Injun 3 as a function of L. The velocity of inward radial motion of the *leading edge* of the outer zone of electron (E > 1.6 MeV) intensities as observed near the equatorial plane [Frank, 1965] is included for comparison.

Figure 14. A continuation of Figure 11, for the period from April 28 to May 4, 1963. The catastrophic depletion of the intensities of these electrons was observed during the same hour in which the horizontal component of the geomagnetic field increased by ~ 200 γ at College, Alaska ($L \sim 5.5$).

Figure 15. A comparison of the time histories of the intensities of low altitude outer zone electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) at $L = 4.0 \pm 0.1$ during several geomagnetically disturbed periods with those of the horizontal component of the geomagnetic field at College, Alaska ($L = 5.5$) and the 3-hour values of K_p for the corresponding periods.

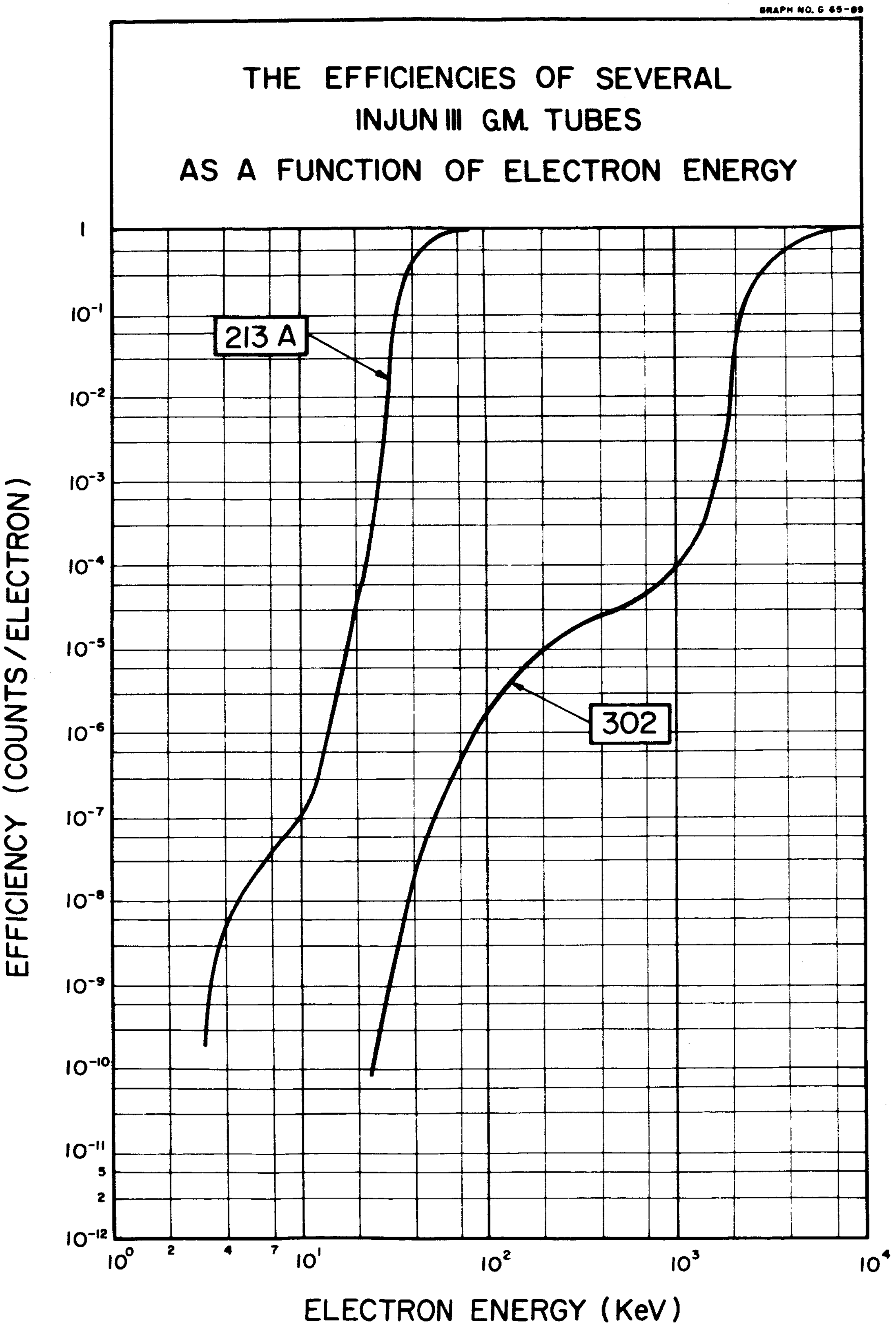

GRAPH NO. G 65-89
THE EFFICIENCIES OF SEVERAL INJUN III G.M. TUBES AS A FUNCTION OF ELECTRON ENERGY
213 A
302
EFFICIENCY (COUNTS/ELECTRON)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
5
2
10^{-12}
10^{0}
2
4
7
10^{1}
10^{2}
10^{3}
10^{4}
ELECTRON ENERGY (KeV)

Figure 1

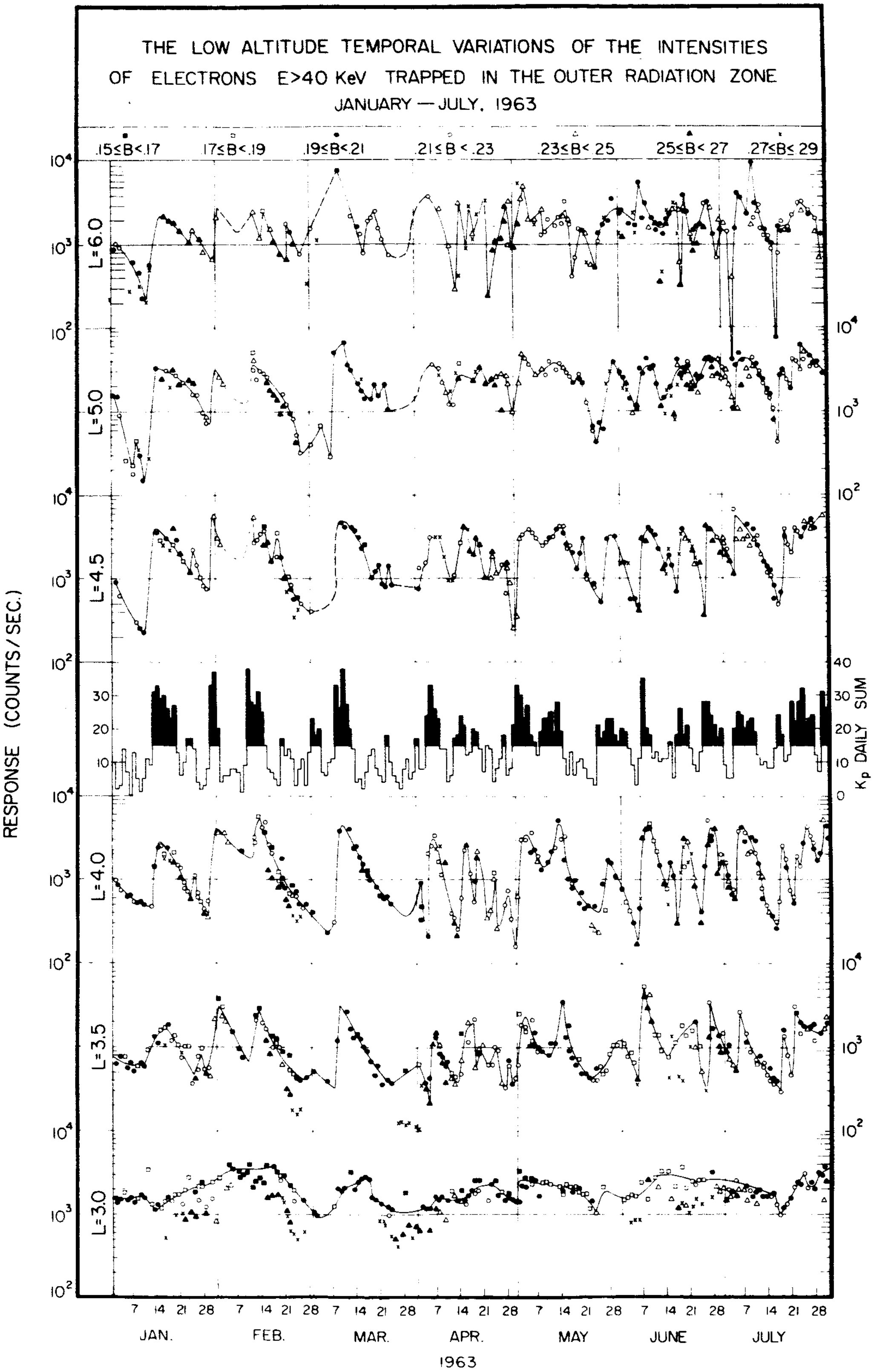

THE LOW ALTITUDE TEMPORAL VARIATIONS OF THE INTENSITIES
OF ELECTRONS E>40 KeV TRAPPED IN THE OUTER RADIATION ZONE
JANUARY — JULY, 1963
.15≤B<.17
.17≤B<.19
.19≤B<.21
.21≤B<.23
.23≤B<.25
.25≤B<.27
.27≤B≤.29
L=6.0
L=5.0
L=4.5
L=4.0
L=3.5
L=3.0
RESPONSE (COUNTS/SEC.)
10^4
10^3
10^2
Kp DAILY SUM
0
10
20
30
40
7
14
21
28
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
1963

Figure 2

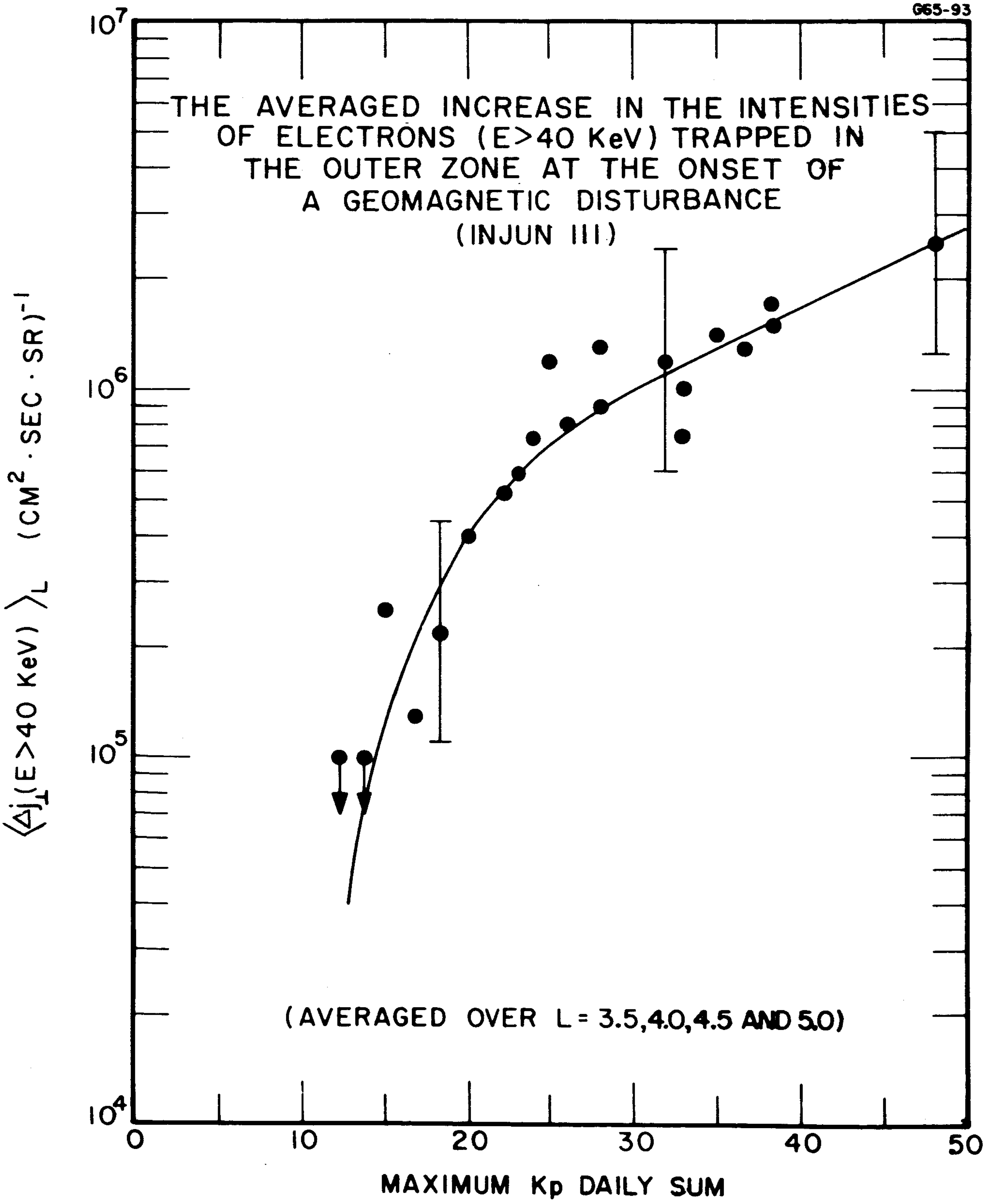

G65-93
THE AVERAGED INCREASE IN THE INTENSITIES OF ELECTRONS (E>40 KeV) TRAPPED IN THE OUTER ZONE AT THE ONSET OF A GEOMAGNETIC DISTURBANCE
(INJUN III)
(AVERAGED OVER L = 3.5, 4.0, 4.5 AND 5.0)
$\langle \Delta j_\perp (E>40 \text{ KeV}) \rangle_L \quad (\text{CM}^2 \cdot \text{SEC} \cdot \text{SR})^{-1}$
10^7
10^6
10^5
10^4
0
10
20
30
40
50
MAXIMUM Kp DAILY SUM

Figure 3

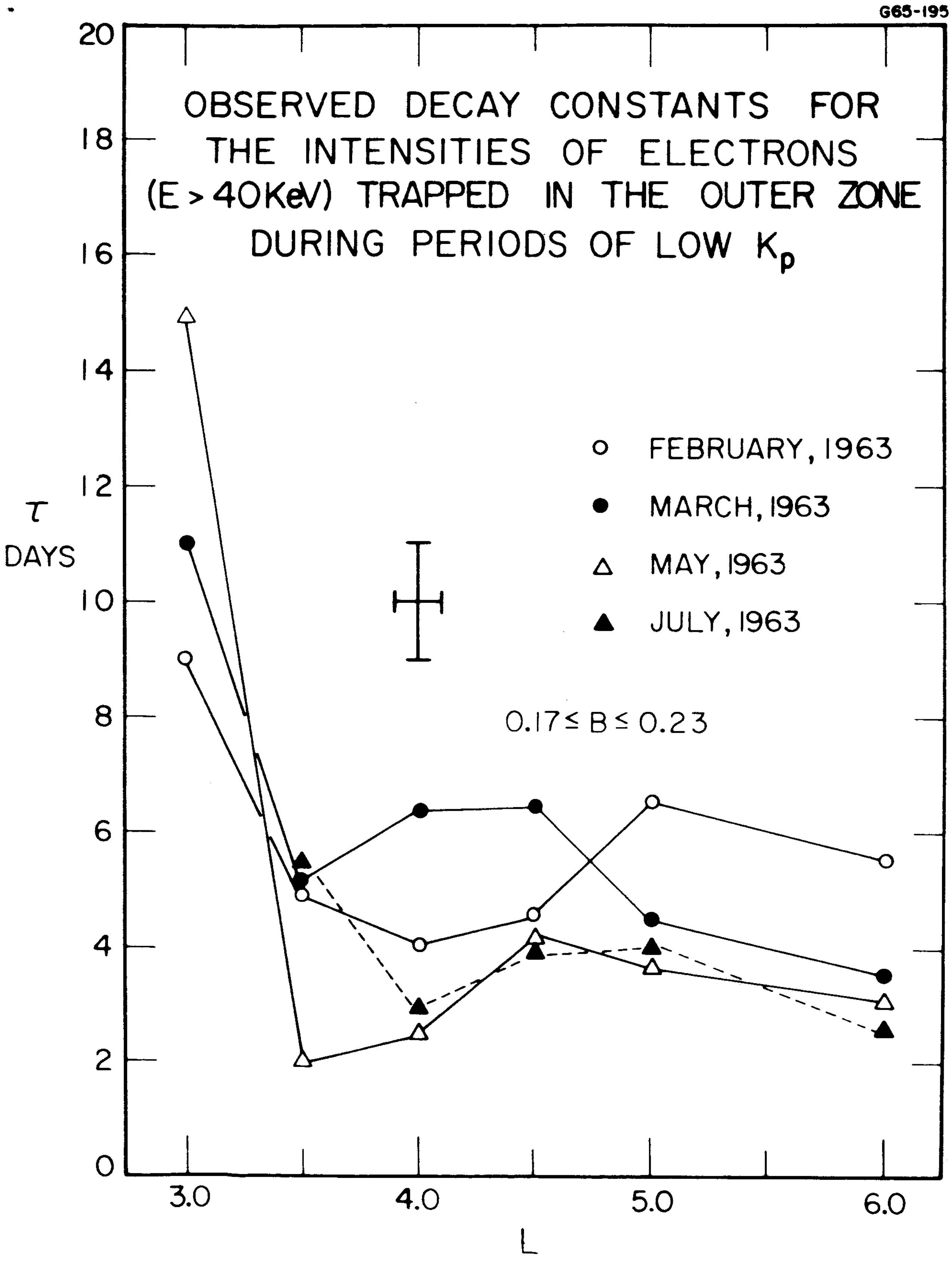

G65-195
OBSERVED DECAY CONSTANTS FOR THE INTENSITIES OF ELECTRONS (E > 40KeV) TRAPPED IN THE OUTER ZONE DURING PERIODS OF LOW K_p
○ FEBRUARY, 1963
● MARCH, 1963
△ MAY, 1963
▲ JULY, 1963
$0.17 \leq B \leq 0.23$
τ DAYS
0
2
4
6
8
10
12
14
16
18
20
3.0
4.0
5.0
6.0
L

Figure 4

G 65-196

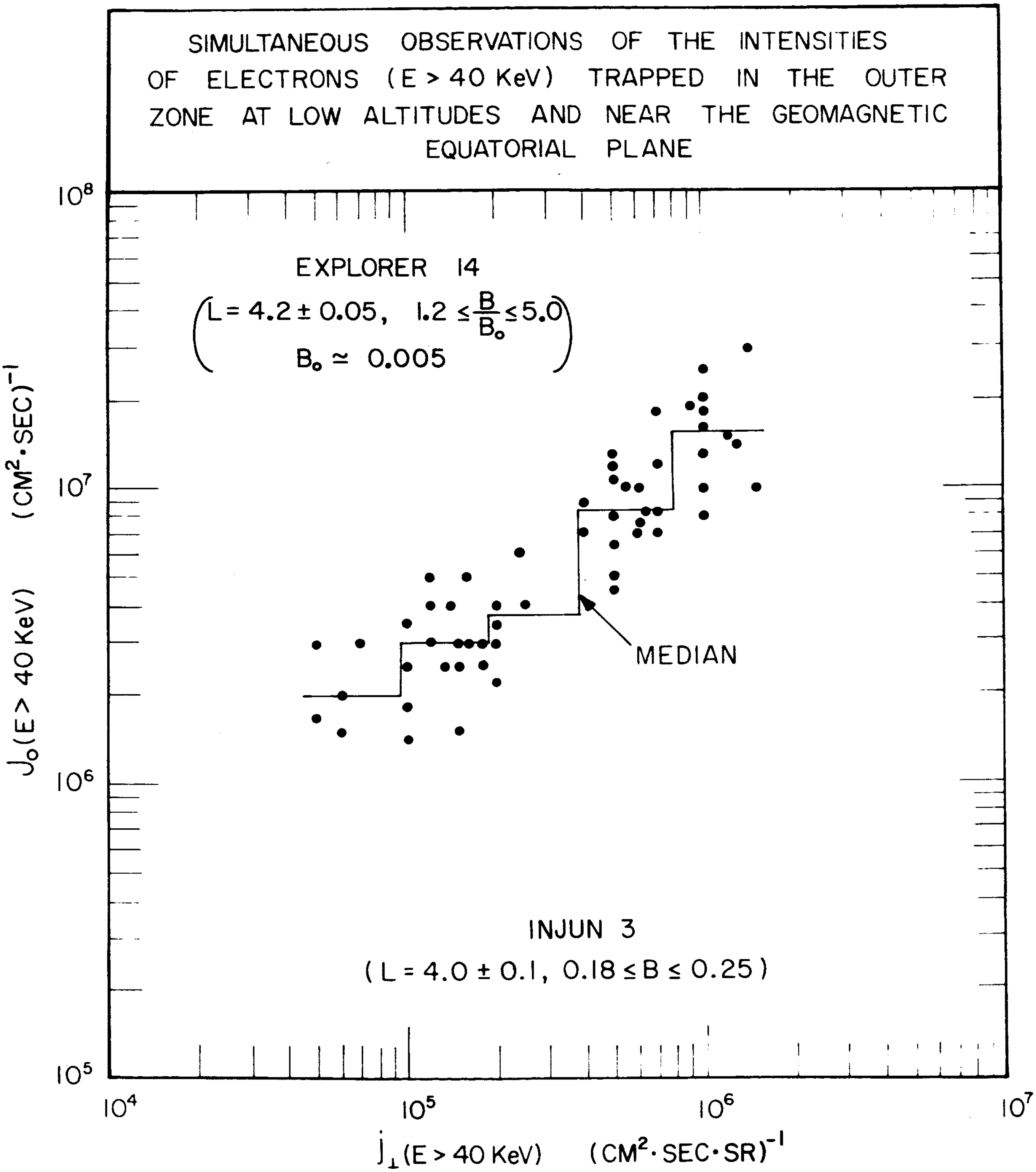
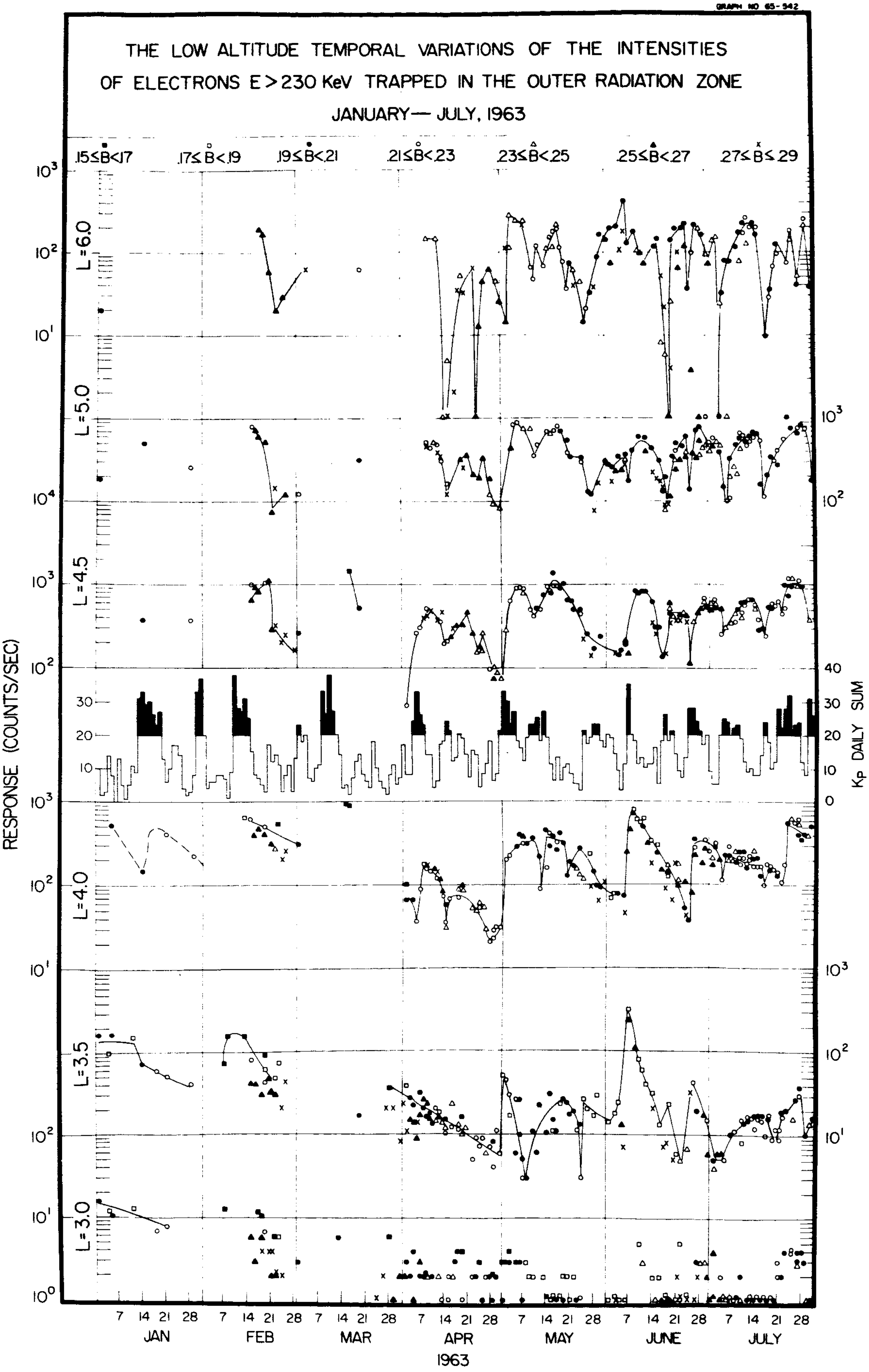


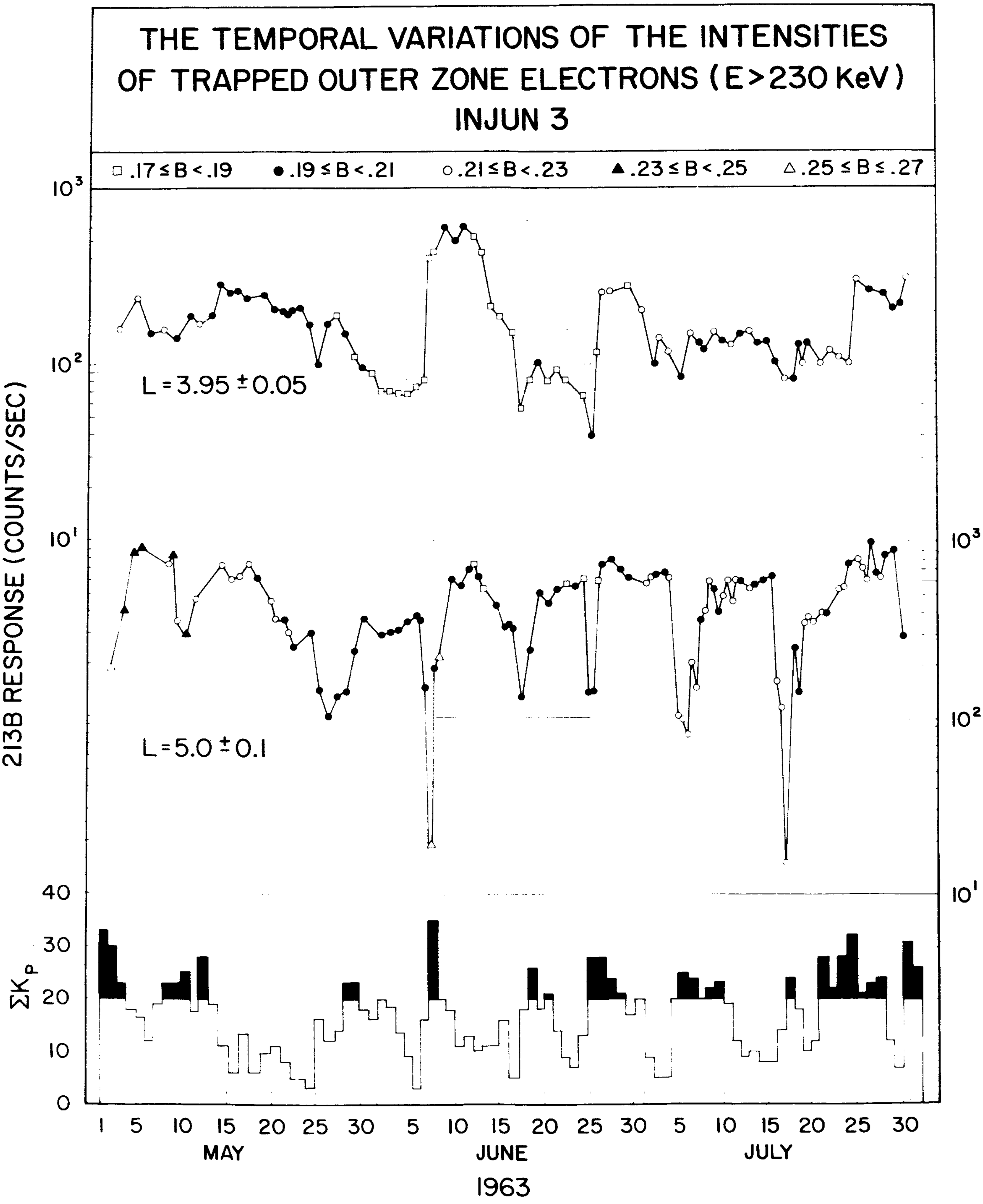
Figure 5



GRAPH NO 65-542
THE LOW ALTITUDE TEMPORAL VARIATIONS OF THE INTENSITIES
OF ELECTRONS E > 230 KeV TRAPPED IN THE OUTER RADIATION ZONE
JANUARY— JULY, 1963
.15≤B<.17
.17≤B<.19
.19≤B<.21
.21≤B<.23
.23≤B<.25
.25≤B<.27
.27≤B≤.29
L=6.0
L=5.0
L=4.5
L=4.0
L=3.5
L=3.0
10^3
10^2
10^1
10^4
10^3
10^2
10^3
10^2
10^1
10^2
10^1
10^0
30
20
10
40
30
20
10
0
10^3
10^2
10^3
10^2
10^1
RESPONSE (COUNTS/SEC)
Kp DAILY SUM
7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28
JAN
FEB
MAR
APR
MAY
JUNE
JULY
1963

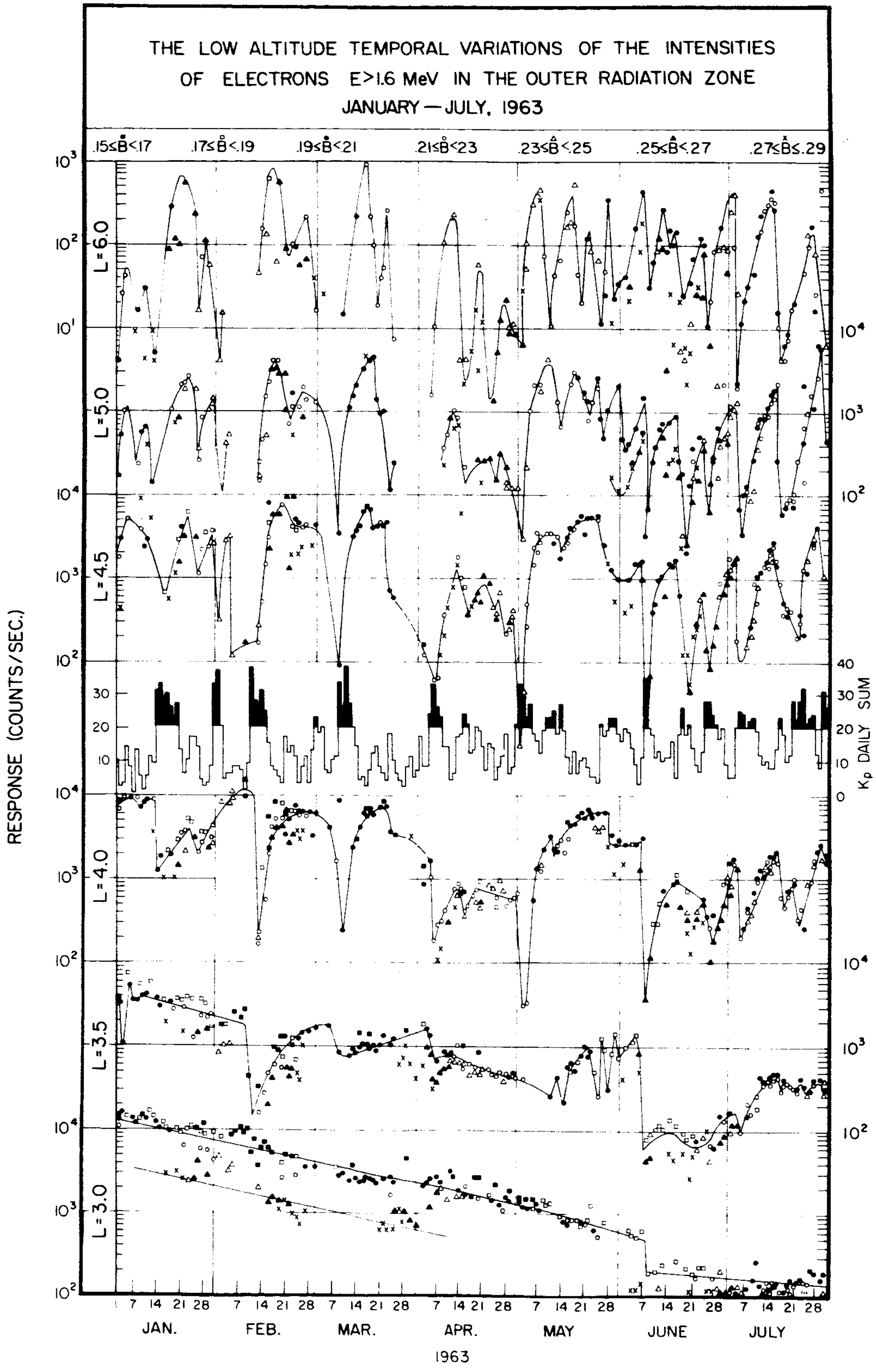
Figure 6

G 66-217



THE TEMPORAL VARIATIONS OF THE INTENSITIES OF TRAPPED OUTER ZONE ELECTRONS (E>230 KeV) INJUN 3

Figure 7



THE LOW ALTITUDE TEMPORAL VARIATIONS OF THE INTENSITIES OF ELECTRONS E>1.6 MeV IN THE OUTER RADIATION ZONE JANUARY — JULY, 1963

Figure 8

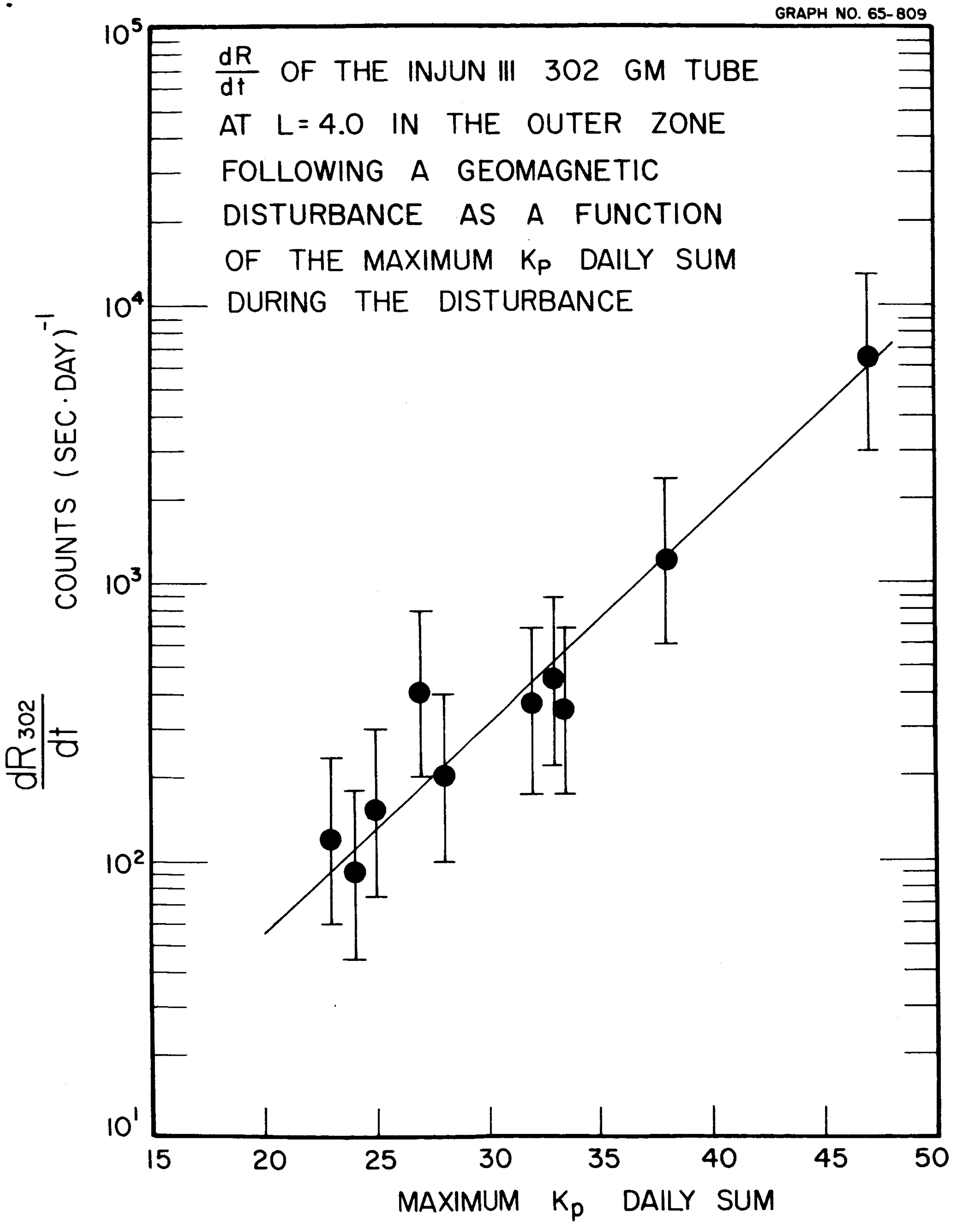

GRAPH NO. 65-809
$\frac{dR}{dt}$ OF THE INJUN III 302 GM TUBE
AT L = 4.0 IN THE OUTER ZONE
FOLLOWING A GEOMAGNETIC
DISTURBANCE AS A FUNCTION
OF THE MAXIMUM K_p DAILY SUM
DURING THE DISTURBANCE
$\frac{dR_{302}}{dt}$ COUNTS $(\text{SEC} \cdot \text{DAY})^{-1}$
10^5
10^4
10^3
10^2
10^1
15
20
25
30
35
40
45
50
MAXIMUM K_p DAILY SUM

Figure 9

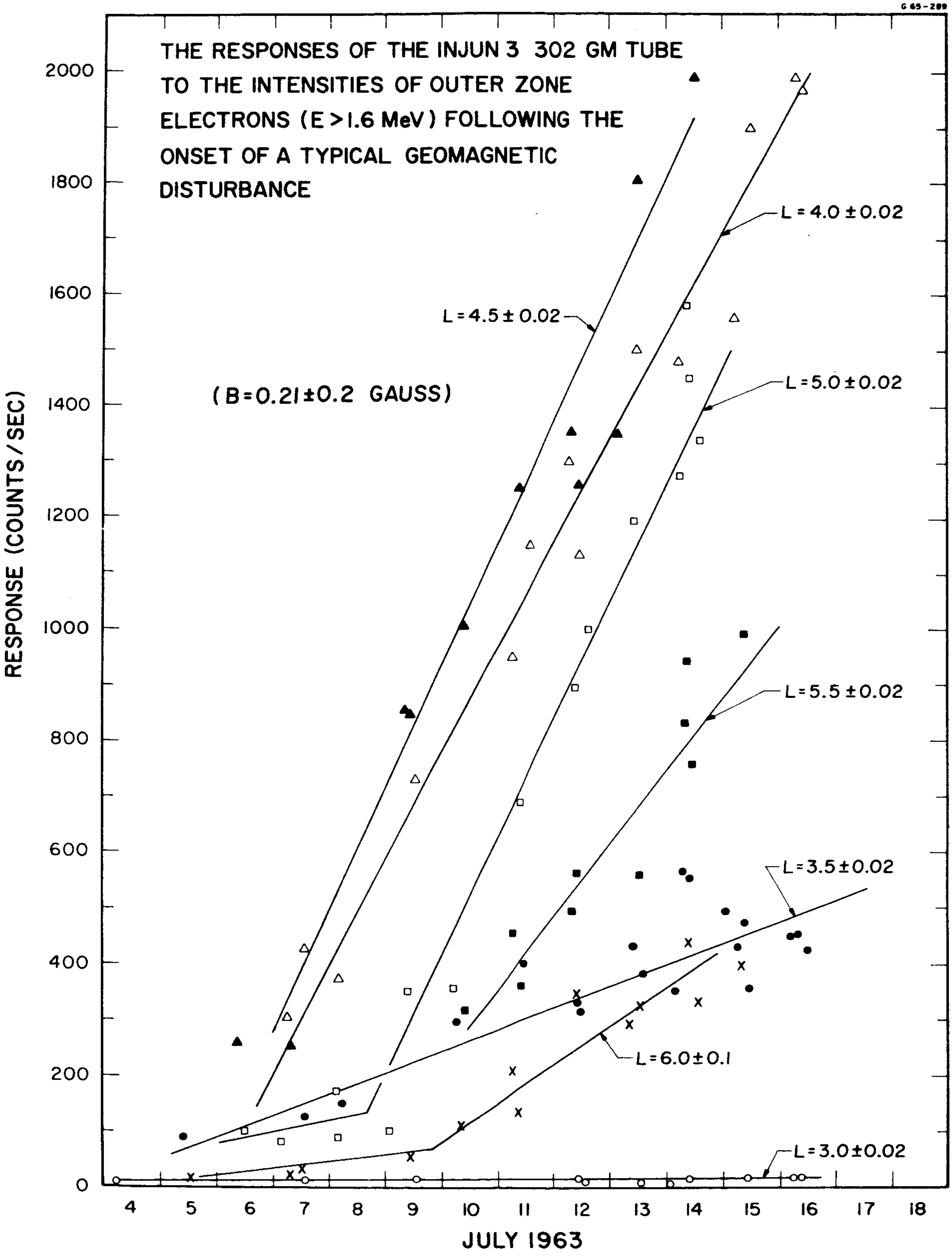
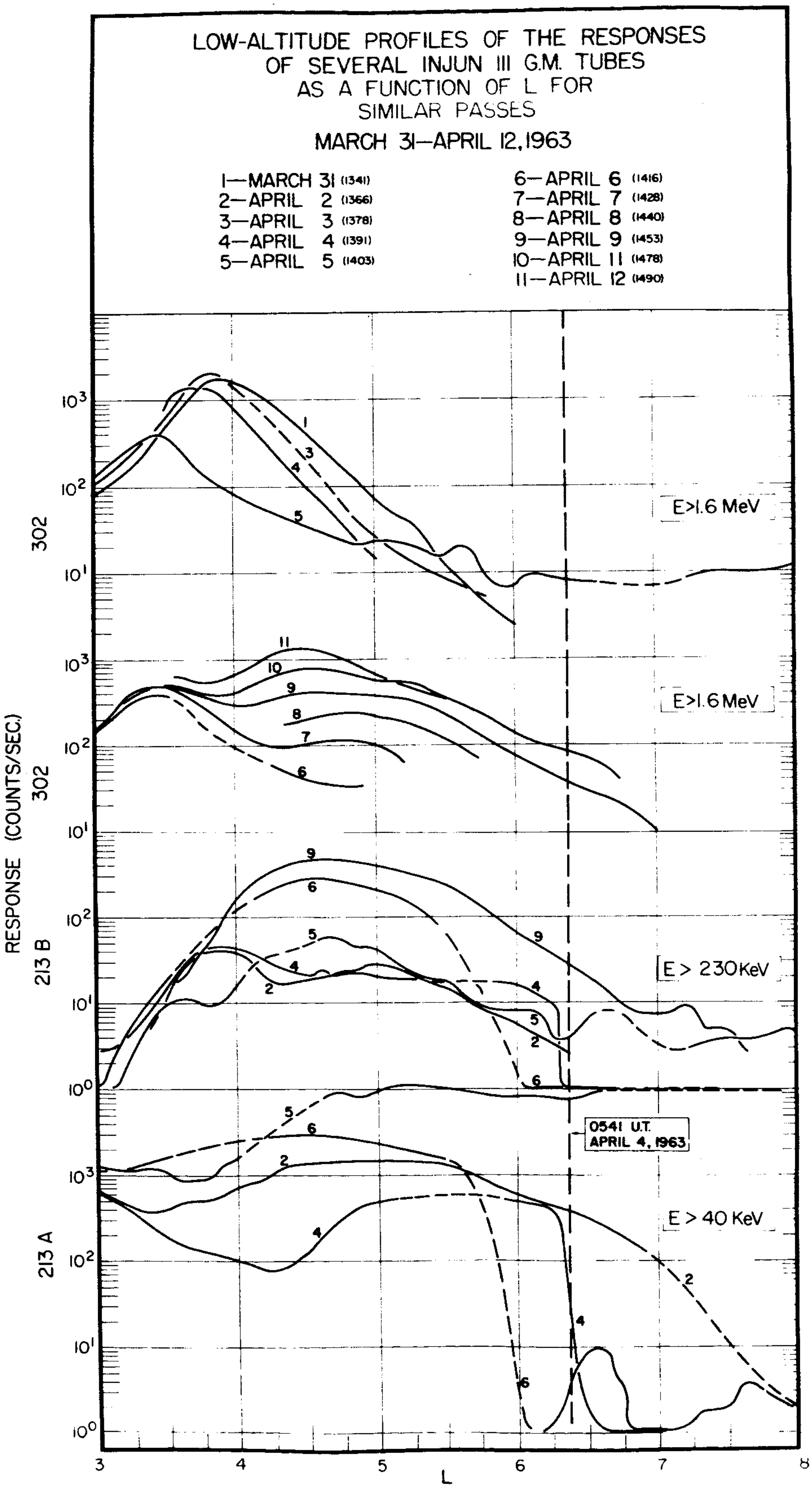

G 65-289
THE RESPONSES OF THE INJUN 3 302 GM TUBE TO THE INTENSITIES OF OUTER ZONE ELECTRONS (E > 1.6 MeV) FOLLOWING THE ONSET OF A TYPICAL GEOMAGNETIC DISTURBANCE
(B = 0.21 ± 0.2 GAUSS)
L = 4.0 ± 0.02
L = 4.5 ± 0.02
L = 5.0 ± 0.02
L = 5.5 ± 0.02
L = 3.5 ± 0.02
L = 6.0 ± 0.1
L = 3.0 ± 0.02
RESPONSE (COUNTS/SEC)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
JULY 1963

Figure 10



LOW-ALTITUDE PROFILES OF THE RESPONSES OF SEVERAL INJUN III G.M. TUBES AS A FUNCTION OF L FOR SIMILAR PASSES

MARCH 31—APRIL 12, 1963

Figure 11

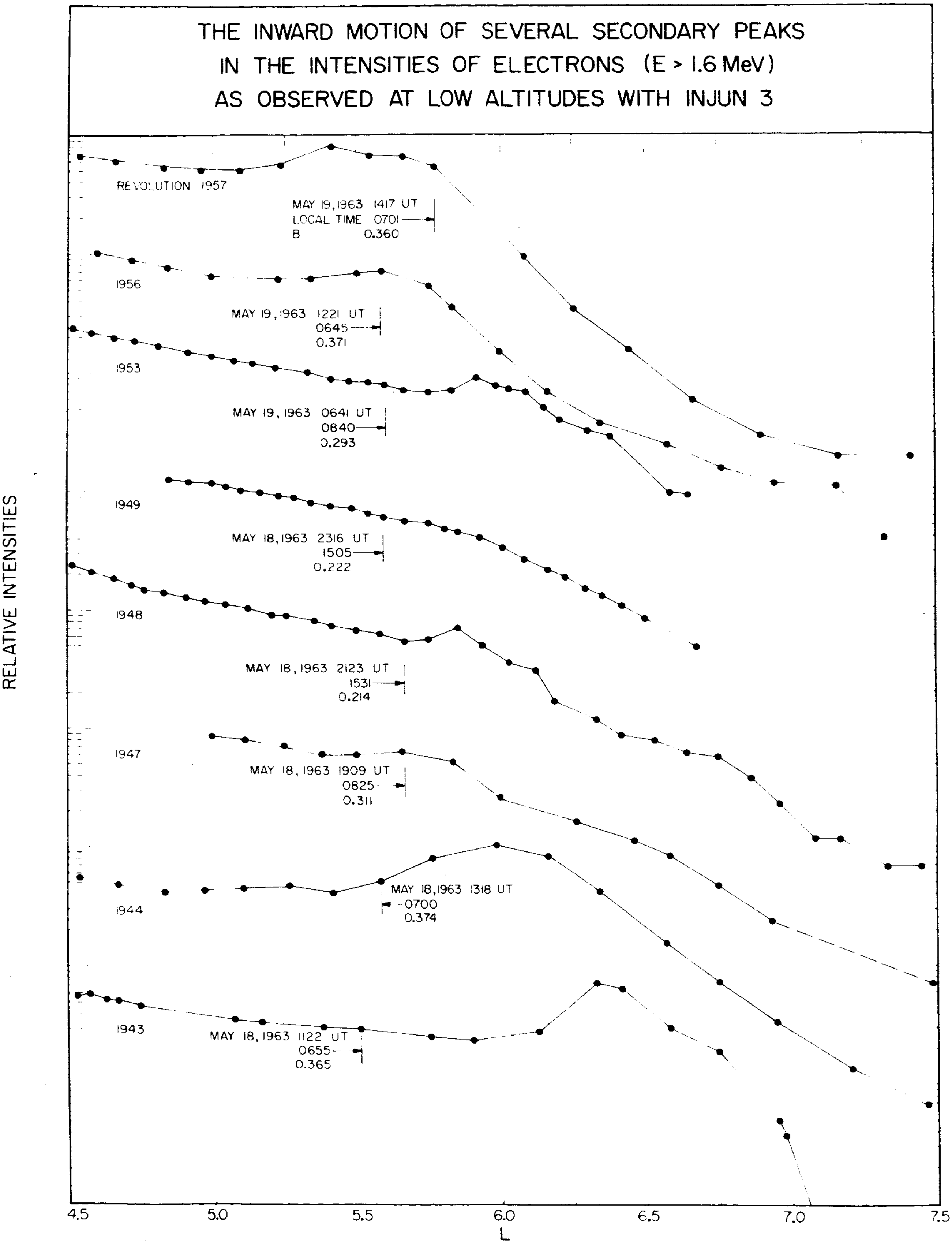

THE INWARD MOTION OF SEVERAL SECONDARY PEAKS
IN THE INTENSITIES OF ELECTRONS (E > 1.6 MeV)
AS OBSERVED AT LOW ALTITUDES WITH INJUN 3
REVOLUTION 1957
MAY 19, 1963 1417 UT
LOCAL TIME 0701
B 0.360
1956
MAY 19, 1963 1221 UT
0645
0.371
1953
MAY 19, 1963 0641 UT
0840
0.293
1949
MAY 18, 1963 2316 UT
1505
0.222
1948
MAY 18, 1963 2123 UT
1531
0.214
1947
MAY 18, 1963 1909 UT
0825
0.311
1944
MAY 18, 1963 1318 UT
0700
0.374
1943
MAY 18, 1963 1122 UT
0655
0.365
RELATIVE INTENSITIES
4.5
5.0
5.5
6.0
6.5
7.0
7.5
L

Figure 12

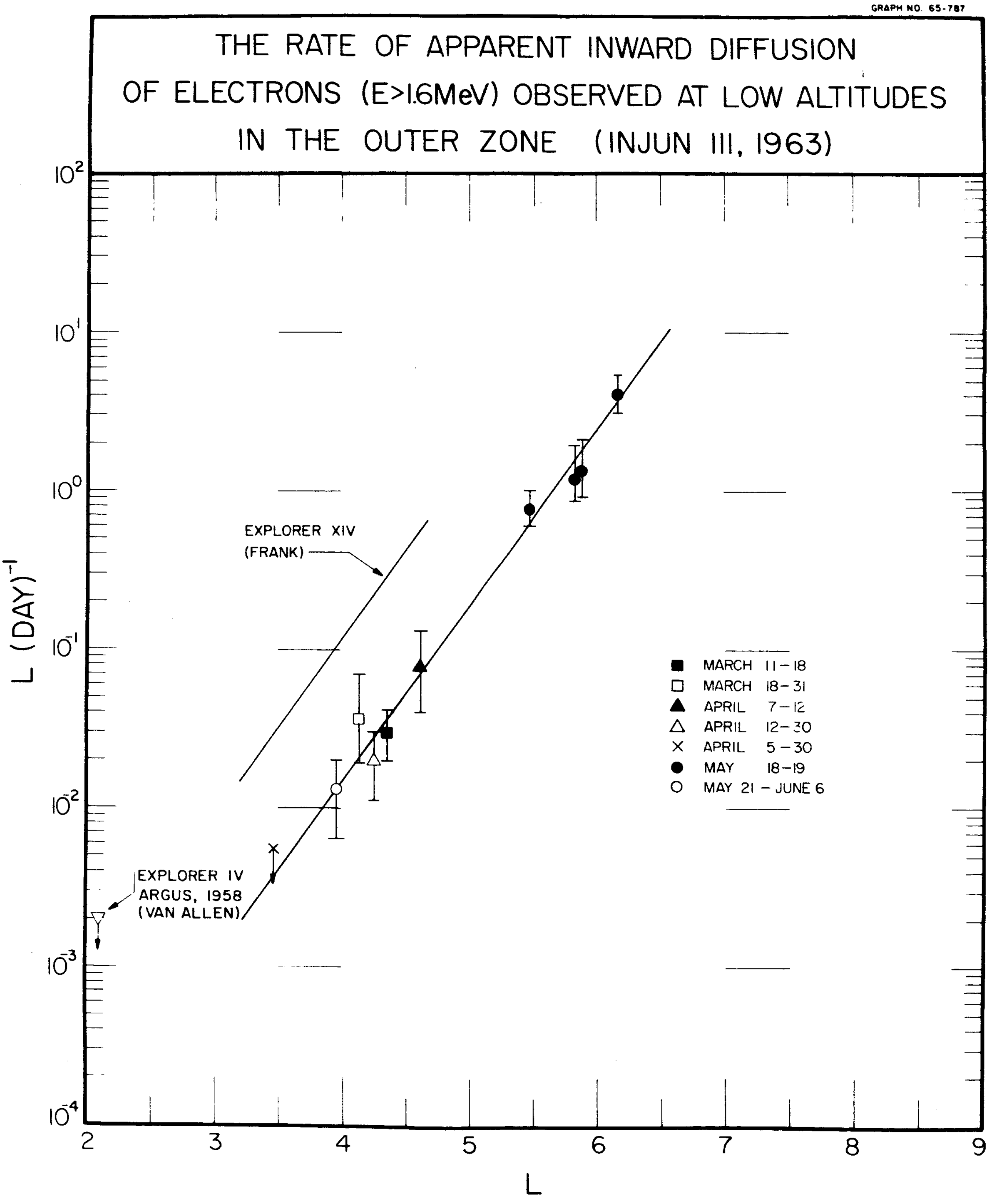

GRAPH NO. 65-787
THE RATE OF APPARENT INWARD DIFFUSION
OF ELECTRONS (E>1.6MeV) OBSERVED AT LOW ALTITUDES
IN THE OUTER ZONE (INJUN III, 1963)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
L (DAY)$^{-1}$
EXPLORER XIV
(FRANK)
EXPLORER IV
ARGUS, 1958
(VAN ALLEN)
■ MARCH 11 – 18
□ MARCH 18 – 31
▲ APRIL 7 – 12
△ APRIL 12 – 30
× APRIL 5 – 30
● MAY 18 – 19
○ MAY 21 – JUNE 6
2
3
4
5
6
7
8
9
L

Figure 13

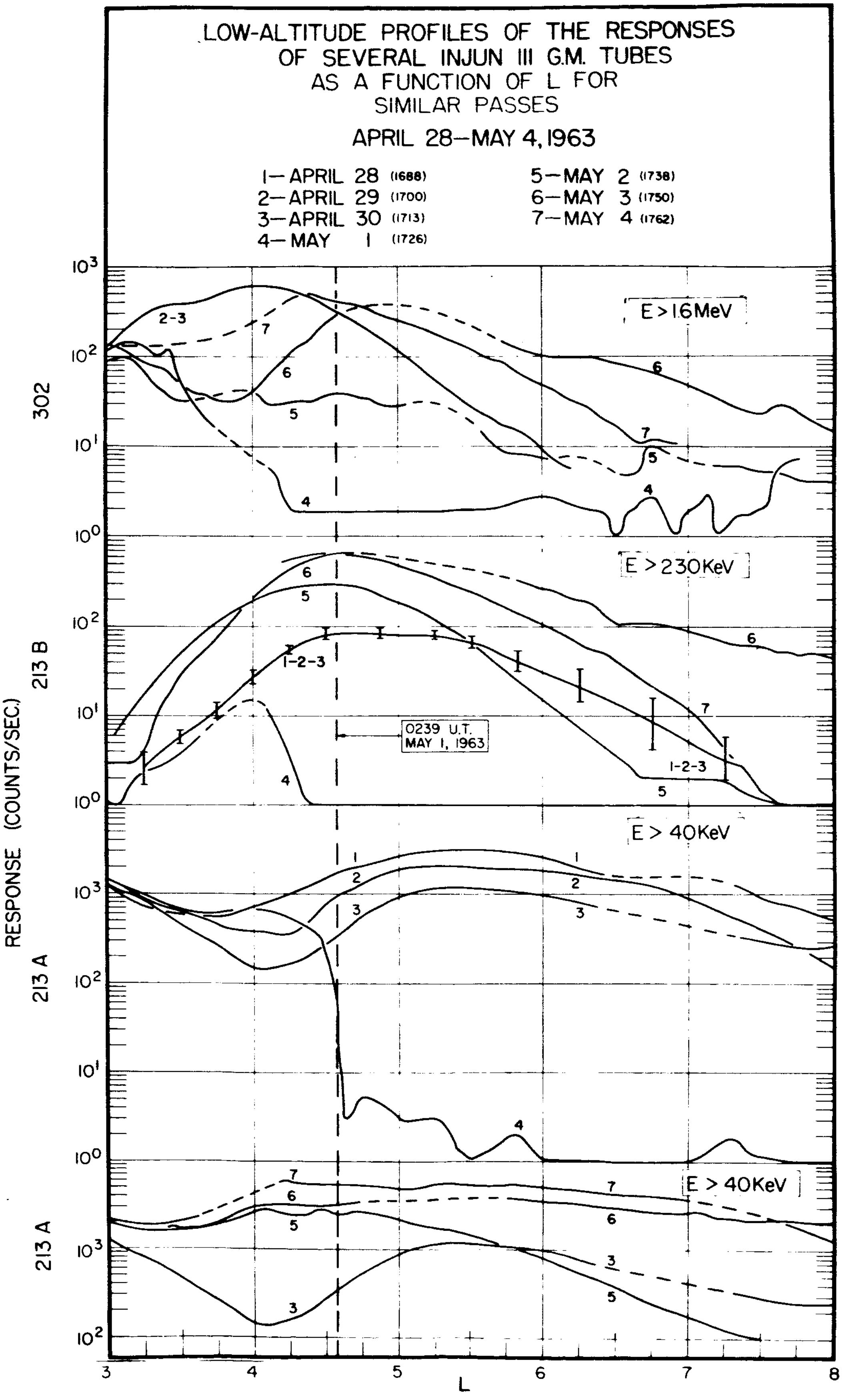
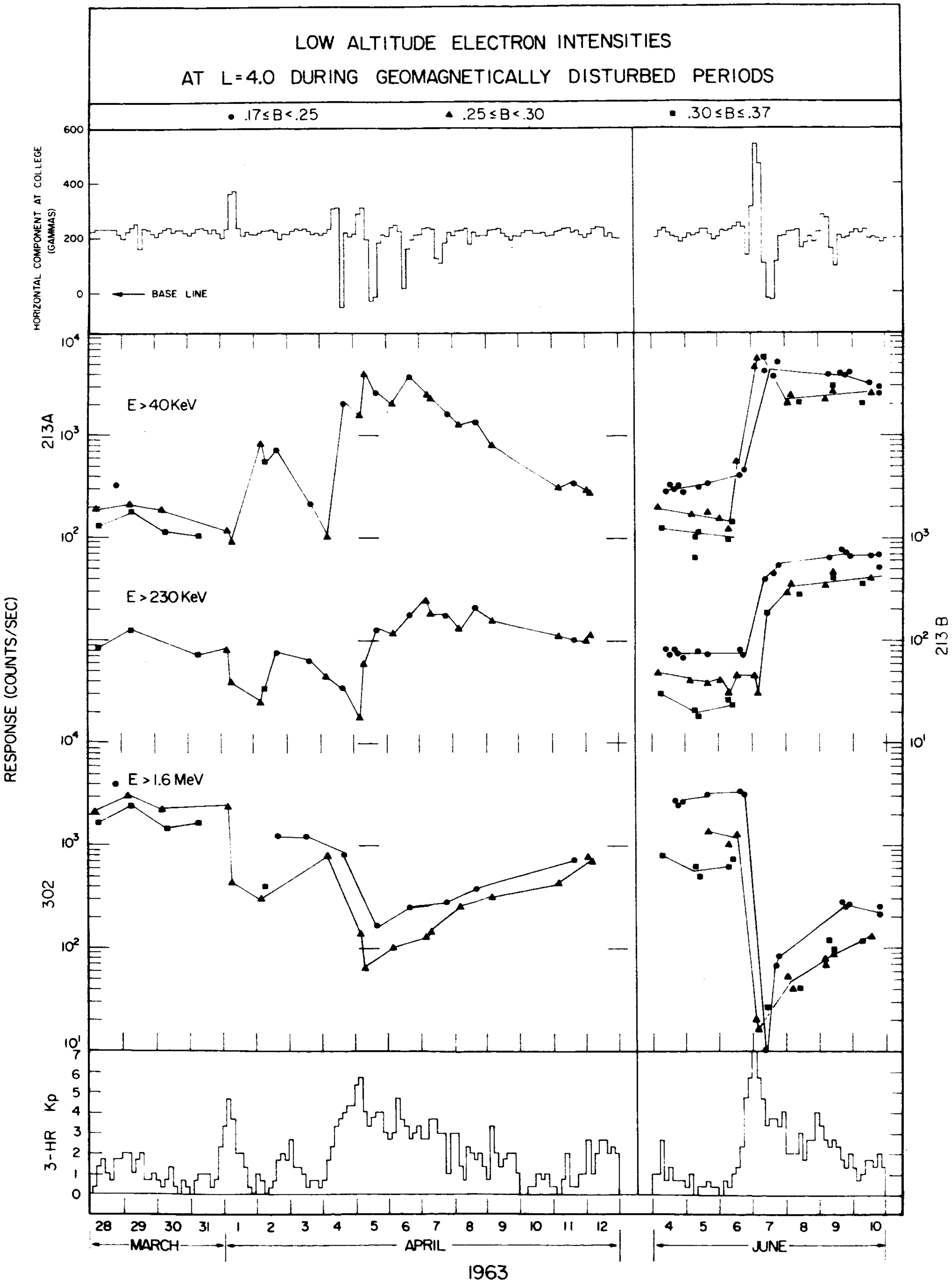

LOW-ALTITUDE PROFILES OF THE RESPONSES
OF SEVERAL INJUN III G.M. TUBES
AS A FUNCTION OF L FOR
SIMILAR PASSES
APRIL 28–MAY 4, 1963
1–APRIL 28 (1688)
2–APRIL 29 (1700)
3–APRIL 30 (1713)
4–MAY 1 (1726)
5–MAY 2 (1738)
6–MAY 3 (1750)
7–MAY 4 (1762)
RESPONSE (COUNTS/SEC.)
302
E > 1.6MeV
213 B
E > 230KeV
0239 U.T.
MAY 1, 1963
213 A
E > 40KeV
213 A
E > 40KeV
10^3
10^2
10^1
10^0
2-3
1-2-3
3
4
5
6
7
8
L

Figure 14



LOW ALTITUDE ELECTRON INTENSITIES AT L=4.0 DURING GEOMAGNETICALLY DISTURBED PERIODS

Figure 15

Unclassified

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DOCUMENT CONTROL DATA - R&D

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1. ORIGINATING ACTIVITY (Corporate author)
University of Iowa
Department of Physics and Astronomy

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
The Temporal Variations of Electron Intensities at Low Altitudes in the Outer Radiation Zone as Observed with Satellite Injun 3

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Progress

5. AUTHOR(S) (Last name, first name, initial)
Craven, John D.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1966	72	42

8a. CONTRACT OR GRANT NO.
Nonr-1509(06)

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
U. of Iowa 66-12

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12. SPONSORING MILITARY ACTIVITY
Office of Naval Research

13. ABSTRACT

Temporal variations of the intensities of electrons ($E > 40$ keV, > 230 keV, > 1.6 MeV) trapped in the outer radiation zone in the region $3.0 \leq L \leq 6.0$ and mirroring at altitudes of ~ 1500 km have been studied during a seven-month period from January 1 to July 31, 1963, by means of three Geiger-Mueller tubes on-board the U. of Iowa/Office of Naval Research research satellite Injun 3. From observations during some twenty geomagnetically disturbed periods, it is shown that the largest intensity variations occur at the onset of such disturbances and that subsequent behavior is dependent on the magnitudes of the disturbances as measured by the maximum daily sums of the planetary magnetic disturbance parameter K_p. The time histories of these intensity variations are compared with those of 3-hour averages of the horizontal component of the geomagnetic field at College, Alaska ($L = 5.5$), for several disturbed periods.

(Continued on attached sheet)

Unclassified

Security Classification

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Outer Radiation Zone, Geomagnetically Trapped Radiation						

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ABSTRACT (Cont'd)

Nearly simultaneous measurements of the directional intensities of electrons ($E > 40$ keV), which mirror at low altitudes, with Injun 3, and omnidirectional intensities of these electrons near the geomagnetic equatorial plane, with Explorer 14, indicate similar temporal behavior at $L \sim 4$. The highest observed intensities of trapped electrons ($E > 40$ keV) in the outer zone at low altitudes appear to occur under a condition of approximate isotropy and equal omnidirectional intensities $\lesssim 10^8$ $(\text{cm}^2\text{-sec})^{-1}$ along a magnetic field line at all altitudes above several hundreds of kilometers.

During four periods of post-disturbance geomagnetic calm, the intensities of electrons ($E > 40$ keV) were observed by Injun 3 to decrease exponentially in time with decay constants $\tau = 12 \pm 3$ days at $L = 3.0$, and $\tau = 4 \pm 2$ days in the region $3.5 \leq L \leq 6.0$. Simultaneously measured values of the decay constants for these electron intensities near the geomagnetic equatorial plane at $L \sim 4$ agree, within observational error. Long-term exponential decays in the intensities of artifically injected electrons ($E > 1.6$ MeV) were observed by Injun 3 to be characterized by $\tau = 40 \pm 5$ and 45 ± 5 days at $L = 3.0$ and 3.5, respectively.

Further evidence for the diffusion of electrons ($E > 1.6$ MeV) is presented.