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# PROCESSES ACTING UPON OUTER ZONE ELECTRONS

## I. Adiabatic Perturbations

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## ABSTRACT

Five distinct types of processes have been found which cause time variations in the energetic electron fluxes in the outer zone. It is shown how the combined action of these processes can produce the observed time dependences. One process has been definitely identified as being due to a specific physical mechanism, namely, adiabatic betatron acceleration. It is found that changes in both the ring current field and the magnetospheric boundary current field produce predictable changes in the particle fluxes. An example of how trapped particle measurements can be used to compute relatively accurate Dst values is presented. Since the adiabatic effects are predictable, they can be removed to exhibit the non-adiabatic effects more clearly. Using this technique, an occurrence of enhanced loss has been found which may be due to the instability predicted by Kennel and Petschek (1966).

## I. Introduction.

It has been shown in many papers (Forbush, et al, 1962; Hoffman, et al, 1962; McIlwain, 1963; Frank, 1965; Williams, 1965; Williams, 1966; Davis and Williams, 1966) that the outer zone electron fluxes exhibit large temporal variations which are correlated with variations in the earth's magnetic field. In the present paper it is shown that the variations in the electron fluxes can be ascribed to the simultaneous action of at least five distinct processes. One of these processes can be definitely associated with a particular and well understood physical mechanism, namely adiabatic betatron acceleration. It was predicted some years ago that this should be an important mechanism acting upon trapped particles by Dessler and Karplus (1961) but the first experimental verification was only recently made (McIlwain, 1966).

The present paper is primarily concerned with the betatron acceleration process. The other four processes will be treated in more detail in future papers.

## II. Detector.

Most of the data presented here was obtained by a directional scintillation detector which is shielded by at least 2.5 g $cm^{-2}$ in all directions except for a ± 8 degree zone for which the absorber thickness is 0.048 g $cm^{-2}$. For a wide range of electron spectra the efficiency versus energy for the lower electronic threshold (which corresponds to 0.28 Mev energy loss) is well represented by a step function which rises from zero to 0.62 at 0.50 Mev.

The detector points perpendicular to the satellite spin axis. Since the satellite spin period was short compared with the accumulation time, the counting rates obtained correspond to the directional flux averaged over the plane perpendicular to the spin axis. The angular distribution of the outer zone electrons near the magnetic equator is such that only relatively small changes are required to convert the spin average counting rates into rates which correspond to the average over all directions and therefore the omnidirectional intensities. The function used for this conversation is

$$1.0/(1.25 - 0.5\varphi/90) \qquad (1)$$

where $\varphi$ is the angle between the spin axis of the satellite and the computed local $\underline{B}$ vector in degrees. Multiplication of the counting rates by this factor and by $1/\epsilon G = 25{,}000$ yields intensities of electrons with energies greater than 0.5 Mev with absolute errors of less than ± 20% and relative errors which are typically less than 7%.

III. Normalization to $B = B_o$.

Fortunately the action of one of the processes (pitch angle scattering ?) at play in the outer zone is such that the relative variation of the electron intensities along lines of force in the vicinity of the magnetic equator is kept constant in time. The measured variation along lines of force is well represented by

$$J(B) = kB^{-N} \qquad (2)$$

with $N = 0.3$ to $0.4$.

The measurements reported here are confined to the region $B/B_o$ = 1.0 to 3.0 thus normalization to $B = B_o$ involves multiplication by numbers between 1.0 and $3^{0.4} = 1.55$.

Except for short periods immediately following large non-adiabatic perturbations, the B dependence along lines of force (i.e. the latitude dependence) can be ignored thus reducing the important spatial variables to the radial distance (i.e. L) and local time. The orbits of the Explorer 15 and 26 satellites are such that only a narrow range of local time is covered while they are in the outer zone during any particular observation period, thus the local time dependence usually does not need to be considered explicitly in the study of time variations covering a period of only a few months. Most of the data presented here were taken within ± 6 hours of local noon.

IV. The Five Processes.

Figure 1 shows the time variations in the fluxes of electrons with energies greater than 0.5 Mev at L = 4.0 and 5.0 during 1965 as measured with the Explorer 26 satellite. The most obvious features of this data are the rapid increases every month or so and the persistent exponential decay with about a two-week time constant. These features are so easily perceived that little further analysis is required to establish the existence of the first two processes:

Process 1 - Rapid Non-Adiabatic Acceleration

Process 2 - Persistent Decay

Detailed examination of the April 18, 1965 event reveals that Process 1 can cause a large acceleration within only a few hours time period.

There is some indication that the cases in which the acceleration appears to continue over a period of several days actually consist of a series of discrete events each of which last only a few hours. There can be no doubt that Process 1 involves non-adiabatic acceleration, due to the fact that there is no available reservoir with an adequate supply of such energetic electrons. That the acceleration is non-adiabatic is obvious from the fact that the electron fluxes remain high long after the magnetic field perturbations have subsided.

There are many pieces of evidence which indicate that the physical mechanism responsible for Process 2 is pitch angle scattering of the electrons into the loss cone. Some of these are: the persistent precipitation of electrons at low altitudes (O'Brien, 1962; O'Brien, 1964; Paulikas, et al, 1964; Paulikas, et al, 1966), the theoretical prediction of several different mechanisms which cause pitch angle perturbations (Dungey, 1963; Cornwall, 1964; Dungey, 1965; Chang and Pearlstein, 1965; Kennel and Petschek, 1966; Cornwall, 1966; Eviatar, 1966; Pearlstein, et al, 1966; Chang, 1966), the strong tendency to maintain a particular pitch angle distribution, and the apparent increase in the decay time constants with increasing electron energy. Energy loss and scattering due to interaction with the atmosphere is of course important at low altitudes and is almost certain to be an important element in any theory which can properly explain Process 2.

Figure 2 shows the time and L dependence of the electrons with energies greater than 5 Mev following the rapid acceleration which occurred on June 16, 1965. In this figure it can be seen that the lower boundary appears to move inward with time. Considerable theoretical work (Kellogg, 1959; Parker, 1960; Herlofson, 1960; Davis and Chang, 1962; Dungey, 1965; Falthammar, 1965) has been published which predict radial diffusion due to the breakdown of the third adiabatic invariant. It is tempting to follow the suggestion made by Frank (1965) when he published the first evidence that this mechanism is important for trapped electrons and label the third process radial diffusion:

Process 3 - Radial Diffusion

It has been shown that ring current magnetic fields cause an adiabatic acceleration of the inner zone protons (McIlwain, 1966). As predicted by Dessler and Karplus (1961) this process should also act upon the outer zone electrons. That this is in fact the case is shown later in this paper, thus we have:

Process 4 - Adiabatic Acceleration

It has been shown that the trapped proton fluxes sometimes exhibit rapid non-adiabatic decreases (McIlwain, 1964; McIlwain, 1966). Analysis of the data shown in Figures 1 and 2 reveals that the electron fluxes also exhibit rapid non-adiabatic decreases. Examples can be seen on days 187 and 200 in Figures 1 and 2. Since the effect seems to occur at times when the magnetic field is distended by ring current particles, it is tempting to ascribe the decreases to a loss of particles into the magnetospheric tail region (Williams and Ness, 1966). There is no evidence, however, that lines which normally cross the equator as low as 3 earth radii are ever drawn into the tail region, thus the fifth process is given a noncommittal label:

Process 5 - Rapid Loss

where the loss may be a loss in energy or in number of particles.

The characteristic effects of Processes 1, 2, 4 and 5 are illustrated in Figure 3 to demonstrate how the net effect of all four can produce the typical time dependence of outer zone electrons. The effect of Process 3, radial diffusion, is such as to superimpose a gradual increase on the time variation fluxes when there is a large positive gradient with respect to L.

V. The Rapid Non-Adiabatic Processes.

Processes 1 and 5 appear to occur only during times of magnetic storms which in turn often appear to occur when the earth's magnetic field is depressed by the presence of ring current particles. It now seems to be safe to assume that the magnetic field fluctuations are due to plasma instabilities which occur when the magnetic field is loaded with an excessive energy density of trapped particles. Since the average magnetic field depression at the earth, i.e. Dst, can be used as a measure of the average energy density of the trapped particles, it is of interest to examine whether there is any correlation between the maximum Dst values during a magnetic storm, and the maximum magnetic field at which instabilities are manifest. Now Processes 1 and 5 are probably due to the time and longitude dependent electric and magnetic fields created by the instabilities. They can therefore be used to determine how deep into the earth's magnetic field the instabilities penetrated during any given magnetic storm.

A detailed study of the correlation between the maximum Dst values and the innermost lines of force on which Processes 1 and 5 take place will be made in the near future. A preliminary survey however has yielded the following important result:

> There is a high probability that Process 1 will act upon the 0.5 Mev electrons and that Process 5 will act upon the 40 Mev protons on a line of force when the minimum magnetic field along the line of force is less than 10 ± 3 times the average magnetic field depression.

Low latitude aurorae are probably another manifestation of instabilities. A study to determine the relationship between Dst and the minimum latitude of auroral emissions should prove interesting though possibly a little difficult to interpret due to the nondipole shape of the field lines when they are heavily laden with charged particles.

VI. Observations of Adiabatic Accelerations

Figure 4 shows the time dependence of the omnidirectional intensity of electrons with energies greater than 0.5 Mev at the magnetic equator at L = 3.6 and 3.8 earth radii during the operating lifetime of Explorer 15. This is the same data which was published earlier (McIlwain, 1963) except for the application of the improved methods for normalizing the data discussed in Section II. The dependence of the intensities upon L at three different times is shown in Figure 5.

It can be readily seen in Figure 4 that there was a rapid non-adiabatic acceleration (Process 1) on day 352 of 1962, and that there was a general tendency for the fluxes to decrease in time (Process 2).

It can also be seen that there are many other time variations which are far outside the scatter of the data which is typically less than about ± 10%. It is the purpose of the remainder of this paper to show that most of these variations are due to betatron acceleration (Process 4), that is, the acceleration due to the variation of the magnetic flux inside the shells upon which the electrons would stay during their drift motion about the earth if the magnetic field were constant.

If it is assumed that Process 2 is independent of time and is such that it removes a fixed fraction of the electrons per unit time, then multiplication of the data by exp $(\text{time}/\tau)$ should completely remove the effects of this process providing the decay time constant $\tau$ is properly chosen.

The effects of Process 3 are not readily discernible in the 0.5 Mev electron data. If radial diffusion is in fact important for these electrons, then the net effects of this process upon the electron fluxes can apparently be included as part of the exponential time dependence ascribed to Process 2.

It was found that $\tau = 16 \pm 1$ days provided a good fit of the data in Figure 4. The time variations in this data remaining after multiplication by exp $(t/16)$ are shown in Figures 6 and 7. In Figure 7, the normalization was shifted by factors of 25 and 30 for $L = 3.6$ and $3.8$, respectively in order to remove the effects of Process 1 on day 352 of 1962. The continuous line in these figures are the Dst values computed by Sugiura and

Hendricks of the Goddard Space Flight Center using the equation

$$Dst = \frac{1}{n} \sum_{i=1}^{n} (\Delta H_i - S_{qi}) \sec\lambda_i \qquad (3)$$

where $\lambda$ is the magnetic latitude, $\Delta H$ is the deviation of the horizontal magnetic field component from the average quiet time field and Sq is average daily variation at each of the magnetic observatories. For the time period shown here, the hourly mean values from the three stations, Hermaners, San Juan, and Honolulu were used. Note that the Dst values are plotted on linear scales while the electron data are plotted on logarithmic scales thus implying the relationship

$$J_o = k \exp (Dst/\beta) \qquad (4)$$

where $\beta$ = +54 gammas for L = 3.6 and +43 gammas for L = 3.8.

It is easy to find places in Figures 6 and 7 where the correspondence between Dst and the particle data is not particularly good, but overall there can be no doubt but that there is an intimate relationship between the two quantities. It is interesting to note that the early time data at L = 3.8 in Figure 6 is lower than predicted by the Dst trace which is normalized to the later data. The explanation of this is that a Process 1 event occurred on this line of force on day 327 of 1962, a fact which is not readily discernible in Figure 4.

The close correspondence between Dst and the electron fluxes implies that if the Dst effects were removed, the fluxes would exhibit a smooth exponential decay thus indicating that Process 2 is independent of time. One notable deviation from uniform decay can be found in Figure 7 during the period from days 353 to 359 of 1962. Here it can be seen that the Dst values predict increases in the particle fluxes which did not occur. This may well be a manifestation of the instability predicted by Kennel and Petschek (1966) and by Cornwall (1966) which causes a rapid loss of particles when the particle fluxes exceed certain limits. This effect might be labelled as a distinct process, but for now it will be considered as an enhancement of Process 2.

## VII. Theoretical Predictions

In their paper predicting the betatron effect upon trapped particles, Dessler and Karplus (1961) computed the motion and energy change of the trapped particles mirroring at the magnetic equator due to ring current type magnetic field changes. The equations for computing the change in particle intensity (i.e. counting rates) are given in a recent paper (McIlwain, 1966):

$$p^2 = p_1^{\,2} \; B_2/B_1 \tag{5}$$

$$j_2 \; (B_2, E_2) = (p_2/p_1)^2 \; j_1(B_1, E_1) \tag{6}$$

$$B_1 = \left[ (B_2 + K)^{1/3} + 1/2 \; K(B_2 + K)^{-2/3} \right]^3 \tag{7}$$

or for small K

$$B_1 \cong B_2 + 2.5K \tag{8}$$

where it was assumed that the magnetic field change has the same value of -K everywhere, and where p = particle momentum, B = magnetic field at the particle's location, E = particle kinetic energy, and j = directional particle intensity (differential in energy) with the subscripts 1 and 2 corresponding to the values before and after the field change.

Using equations 5 and 8 and the relativistically correct relationship between momentum and energy we find

$$E_1 = \left[ (E_2^{\,2} + 2\,E_r\,E_2)\,(1+2.5K/B_2) + E_r^{\,2} \right]^{\frac{1}{2}} - E_r \qquad (9)$$

where $E_r = m_o\,c^2$ = the particles rest energy.

A useful approximation to equation 8 is

$$E_1 \cong E_2\left(1 + \frac{2.5KA}{B_2}\right) \qquad (10)$$

where

$$A = 1\text{-}0.5E_2/(E_2+E_r) \qquad (11)$$

Now if the original spatial and energy dependence can be represented by

$$j_i\,(B,E) = g\,(B)\,\exp\,(-E/E_o) \qquad (12)$$

then the integral intensity measured before the field change by a detector sensitive to particles with energies greater than $E_d$ is

$$J_i = g\,(B_i) \int_{E_d}^{\infty} \exp\,(-E/E_o)\,dE$$

$$= g\,(B_i)\,E_o \exp\,(-E_d/E_o) \tag{13}$$

Now if the detector remains at the same location in space, then after the field change the B value at that location will be $B_i$ - K, (Note: It is still assumed that the field change is the same everywhere in space) thus by equation 8, it will measure the particles that were at $B_i$ + 1.5 K. Taking

$$B_1 = B_i + 1.5\,K \tag{14}$$

$$B_2 = B_i - K \tag{15}$$

equation 7 gives the differential flux after the change to be

$$j_f\,(E_2) = g\,(B_1)\,\frac{B_2}{B_1}\,\exp\,(-E_1/E_o) \tag{16}$$

Now if $E_o$ is not large compared to $E_d$, then the variation of the factor A (see equation 10) with energy can be neglected and the integral flux after the change will be

$$J_f = \int_{E_d}^{\infty} j_f (E_2) \, dE_2$$

$$\cong g (B_1) \frac{B_2 E_o}{B_1} \exp \left[ - E_d \left(1 + \frac{2.5 K A}{B_2}\right)/E_o \right] \tag{17}$$

where A might be evaluated at $E_d + E_o/2$.

Dividing equation 17 by equation 13 gives the counting rate of a detector sensitive to particles with energies greater than $E_d$ at a fixed location in space to be

$$r = J_i/J_f = \frac{B_2}{B_1} \frac{g (B_1)}{g (B_i)} \exp \left[ - 2.5 K A E_d/B_2 E_o \right]$$

$$= \frac{B_i - K}{B_i + 1.5K} \frac{g(B_i + 1.5K)}{g(B_i)} \exp \left[-2.5 K A E_d/E_o(B_i - K)\right] \tag{18}$$

after a field decrease of K relative to the initial counting rate at the initial field value of $B_i$.

If we let the initial B dependence be represented by

$$g (B) = k \exp (a B + b B^2) \tag{19}$$

then

$$r = \frac{B_i - K}{B_i + 1.5K} \exp \left[1.5 aK + 3bB_i K + 2.25bK^2 - 2.5AE_d/E_o(B_i - K)\right] \tag{20}$$

This equation gives the change in the directional flux of particles which mirror at the magnetic equator. It is felt however, that no serious error will be made if it is used to compute the changes in omnidirectional fluxes in the near vicinity of the equator providing the B values used correspond to the equatorial field on the lines of force.

VIII. Comparison with Observations

First let us see whether equation 20 gives the kind of relationship implied by Figures 6 and 7, i.e. that given by equation 4. If for simplicity we let b = 0, then the spatial dependence over the three month time period gives values for 1/a ranging from about -90 to -370 gammas at L = 3.6, while the energy dependence varies little from $E_o$ = 0.4 Mev. Thus with $E_d$ = 0.5 Mev giving A = 0.71 and with L = 3.6 giving $B_i = M/L^3$ = 668 gammas we have

$$r = \frac{668-K}{668+1.5K} \exp\left(- \frac{1.5K}{90} - \frac{2.2K}{668-K}\right) \qquad (21)$$

to

$$r = \frac{668-K}{668+1.5K} \exp\left(- \frac{1.5K}{370} - \frac{2.2K}{668-K}\right) \qquad (22)$$

which for small K can be approximated respectively by

$$r = \exp\ (- K/40) \qquad (23)$$

and

$$r = \exp\ (- K/90) \qquad (24)$$

Now if we let K = -Dst it can be seen that the predicted dependence of the counting rates is not only of the same form as implied in Figures 6 and 7, but also that the predicted sensitivity to Dst is also similar: $\beta$ (predicted) = 40 to 90 gammas compared with $\beta$ (implied by the figures) = 54 gammas.

It is of interest to see whether the change in the spatial dependence is the same as predicted. As can be seen in Figure 6, there was a substantial change in Dst during day 319 of 1962. In Figure 8 the fluxes measured before and after this change are plotted versus $B_o \equiv M/L^3$ which is the predicted equatorial field with no contributions from external current systems. As before it is assumed that the true value of the magnetic field is $B_o - K$. Also shown in this figure is the $B_o$ dependence predicted by equation 16 if K is taken to be zero initially and 50 gammas after the change in Dst. It can be seen that the predictions lie within about $\pm$ 10% of the measured values which are up to a factor of 2 lower than the initial fluxes. The difference in the Dst values between the times of these two sets of data was only -28 gammas but it will be shown later that the particle measurements probably provide a more accurate determination of the spatial average of the field change than the Dst values computed from the field measured at only three ground stations.

Two other examples of changes in the $B_o$ dependences are shown in Figures 9 and 10 where it can be seen that again, values for $\Delta B = -K$ can be chosen such as to provide good fits to the observations. The departure of the predictions from the observed values in Figure 9 in the region where $B_o$ is less than 450 gammas may be due to the fact that the satellite was at a magnetic latitude of about 30 degrees at this time and that the actual equatorial magnetic field on these lines may be considerably less than the assumed values of $M/L^3 - K$ since the field lines may be stretched into a non-dipolar shape when K is not zero.

That the magnetospheric boundary current as well as the ring current can cause predictable particle acceleration can be seen by the large increase during day 338 of 1962 (see Figure 7) following a sudden commencement.

## IX. Other Outer Zone Observations

Many sets of data have been published, which demonstrate clear correlations with magnetic disturbances. One early attempt to determine the relationship of the electron fluxes with Dst (Forbush, et al, 1962) yielded rather mixed results due to the action of the other four processes which caused large effects that could not be readily identified and removed as has been done in the present paper. Presumably it will be possible to interpret many of the previous outer zone electron observations in terms of the five processes.

It has been shown that the 40 Mev trapped protons respond predictably to the Dst variations (McIlwain, 1966) and Fillius (1966) has shown that the 1 Mev trapped protons also respond to the Dst variations. The data published by Davis and Williamson (1966) on 140 kev protons (see Davis and Williamson's Figure 10) show a very clear dependence upon Dst which can be represented by equation 4 with $\beta$ equal to about +120 gammas. The 20 to 100 kev electron time variations at L = 3.75 presented in this paper (see Davis and Williamson's Figure 9) show a clear anti-correlation with Dst which is represented with fair accuracy by equation 4 with $\beta$ equal to about -25 gammas. An equally good fit is obtained by use of the equation

$$I = 0.06\,(10 - Dst) \qquad (25)$$

where I is the measured energy flux in ergs $cm^{-2}$ $sr^{-1}$ $sec^{-1}$ and Dst is in gammas. The chief deviations of the data from this equation are at times of rapid decreases in Dst and at times Dst is low. The discrepancies at the times of rapid decreases in Dst may well be due to the local time asymmetries in the ring current particles which have been demonstrated to exist at early times during magnetic storms (Cahill, 1966; Akasofu, 1966). The deviations at times Dst is small may be due to the fact that Dst also includes the magnetic effects of the time dependent magnetospheric boundary currents. Equation 25 would indicate that these 20 to 100 kev electrons are actually a constituent of the long sought ring current particles. If it is assumed that similar fluxes extend over a reasonably large volume, such as $4 \times 10^{28}$ $cm^3$ then they would in fact produce about 1/2% of the total magnetic field depression.

It has been shown by Frank (1966) that electrons of still lower energies actually do comprise an important part of the ring current particle energy density. Historically, one reason for making the assumption that the ring current particles are protons is the fact that the loss of low energy protons due to charge exchange gives about the observed decay time constant of $2 \pm 1$ days. It is now clear however, that the mechanisms responsible for Process 2 are capable of causing a loss of low energy electrons in comparatively short times, thus there remains little reason for the prior prejudice in favor of protons.

X. Dst Based Upon Particle Flux Variations

The fact that many fluctuations of the trapped particle intensities are clearly caused by global changes in the earth's magnetic field suggests the possibility of using the trapped particle measurements themselves to measure Dst. Since the particles respond to the changes in magnetic flux inside the magnetic shell upon which they are trapped, they are quite insensitive to the effects of ionospheric currents which plague ground based observations. The particle fluxes are of course also perturbed by the action of the other four processes, thus it is unlikely that they can be used to measure the variations in Dst over any extended period of time.

That the energetic electrons in the outer zone can be used to obtain Dst values for a time period of at least one week can be seen in Figure 11 where all of the Explorer 15 0.5 Mev electron data taken at L values greater than 3.4 during the week beginning November 11, 1962 have been converted into Dst values by the procedure outlined below.

First, equation 19 was used to fit the B dependence of the data taken early on day 318 of 1962. Noting that the Dst values from the ground observatories were -2 gammas at this time, this data was assumed to correspond to Dst = -2. A value for r in equation 20 was then obtained for each reading telemetered by the satellite using the equation

$$r = J \exp\left[(t - t_o)/16\right]/g(B) \qquad (26)$$

where J is the measured flux, g (B) is the fit to the data on day 318, and where the exponential factor is employed to remove the decay due to Process 2. Equation 20 was then solved for K for each r value. The Dst values were then assumed to be equal to -K and were plotted versus time as shown in Figure 11.

It is readily seen that for a large fraction of the time during this one week interval, the Dst values obtained from the ground observatories and from the satellite agree to within 10 gammas. Some of the discrepancies are undoubtedly due to errors in the normalization of the data from the spin averages obtained at points off the equator to omnidirectional intensities on the equator while other discrepancies may well be due to the action of other processes. It is quite probable however, that many of the discrepancies are in fact due to errors in the ground based values. One indication of this is that the data from the different ground stations often differ from each other by more than 10 gammas in a fashion which suggests contamination due to ionospheric currents. Another is the fact that there is almost a 12-hour gap between Hermanus and Honolulu so that any asymmetry in the ring current field may result in a large error in the longitudinal average. Specifically, the magnetographs for day 319 of 1962 show the presence of a local time asymmetry of the type found by Akasofu (1966) and Cahill (1966). Furthermore, the magnetographs indicate that at 1600 hours UT the maximum decrease in the field was located in the gap between Hermanus and Honolulu. The discrepancy at this time which can be seen in Figure 11b and which was mentioned before in connection with Figure 8 is almost certainly due to poor longitudinal averaging in the ground data and not to errors in the satellite measurements.

The particle data used here are by no means the best which can be obtained for determining Dst. First, a major improvement would result if the satellite orbit were circular and had zero inclination so that data could be obtained continuously and could be predicted more accurately since motion in B-L space would be much smaller. Second, the proton fluxes would probably provide a better measure since they do not seem to be as radically perturbed by the other processes, or at least the effects of the other processes tend to cancel each other. Third, the primary error made in the satellite measurements of Dst is in assuming that the field at the satellite is B + Dst, where B is value computed with a spherical harmonic representation of the earth's field. If a magnetometer on the satellite were to measure the field at the satellite to an accuracy of ± 1 gamma, it appears quite possible that the true spatial averages of the field changes inside the particles' orbits could also be obtained with an accuracy of about ± 1 gammas.

## XI. Radial Diffusion

When the magnetic field perturbations are longitude dependent and occur within times comparable or short compared with the drift period of the particles, a radial diffusion will occur. It can be shown that the effects of this diffusion for any given perturbation will invariably be of second order compared with the adiabatic effects. To directly measure the non-adiabatic effects therefore requires that the adiabatic effects be removed with a high accuracy. This in return requires very accurate values for Dst. It is important therefore, that further efforts be made in improving the determinations of Dst.

Another mechanism which can cause radial diffusion of electrons even in the absence of fast field fluctuations has been suggested by Roderer (1965). When the field lines are distorted into nondipolar shapes in a longitude dependent fashion such as by an asymmetric ring current or by magnetospheric boundary and tail current systems, then the electrons which are on the same line of force at one longitude but which have different pitch angles will drift to different lines of force. Thus, if the rapid pitch angle diffusion implied by Process 2 is taking place, the drift paths of the electrons will be continuously changing as their pitch angles are changed. The net result is diffusion across lines of force.

## XII. Conclusion

It has been shown that the slowly changing global magnetic fields, as determined by Dst values, causes large and predictable changes in the outer zone particle fluxes. The Dst values can be used therefore to remove the effects of these adiabatic changes and thus make it possible to study the non-adiabatic effects of the other processes with far greater accuracy.

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## FIGURE CAPTIONS

Figure 1 Time variations in the omnidirectional intensities of electrons with energies greater than 0.5 Mev at L = 4.0 and 5.0 measured during 1965 by the Explorer 26 satellite. The rapid increases at times of magnetic disturbances and the tendency to decay with about a two-week time constant are easily seen.

Figure 2 Isointensity contours of high energy electrons following the rapid acceleration on June 16, 1965. The inward motion apparently due to radial diffusion and the rapid loss on days 187 and 200 are of particular interest.

Figure 3 Characteristic effects of Processes 1, 2, 4, and 5 and their combined effect upon the energetic electrons in the outer zone.

Figure 4 Time dependence of the 0.5 Mev electron fluxes at L = 3.6 and L = 3.8 during the operating lifetime of Explorer 15. In addition to the large increase on day 352 of 1962 and the general tendency to decay, many nonstatistical fluctuations can be seen to occur.

Figure 5 Radial dependence of the 0.5 Mev electron fluxes at three different times as measured by Explorer 15.

Figure 6 The first half of the data shown in Figure 4 after multiplication by exp (t/16) to remove the effects of Process 2. The close correspondence with Dst which is given by the continuous lines is readily discerned. Note that at L = 3.8 a Process 1 event occurred on day 327.

Figure 7 A continuation of Figure 6 with the data renormalized to remove the effects of the Process 1 event on day 352 of 1962. Note that the intensities following this event did not increase as predicted by Dst thus implying an enhanced loss rate.

Figure 8 The dependences upon $B_o$ before and after the decrease in Dst on day 319 of 1962 compared with the predicted dependence computed from the upper curve assuming a field change of -50 gammas.

Figure 9 A second example of the change in the $B_o$ dependence due to Process 4. See the text for a possible explanation of the discrepancies at low $B_o$ values.

Figure 10 A third example of the change in the $B_o$ dependence due to process No. 4.

Figure 11a Dst values derived from ground observations and from the fluxes of 0.5 Mev electrons measured by the Explorer 15 satellite at L values greater than 3.4. The motion of the satellite in B-L space is shown in the upper part of the figure.

Figure 11b Continuation of Figure 11a. Note that the fluctuations during a satellite pass tends to be larger at the time $K_p$ is high. The large discrepancy (about 20 gammas) at 1600 hours UT on day 319 of 1962 can be shown to be due to poor longitudinal averaging in the ground based data.

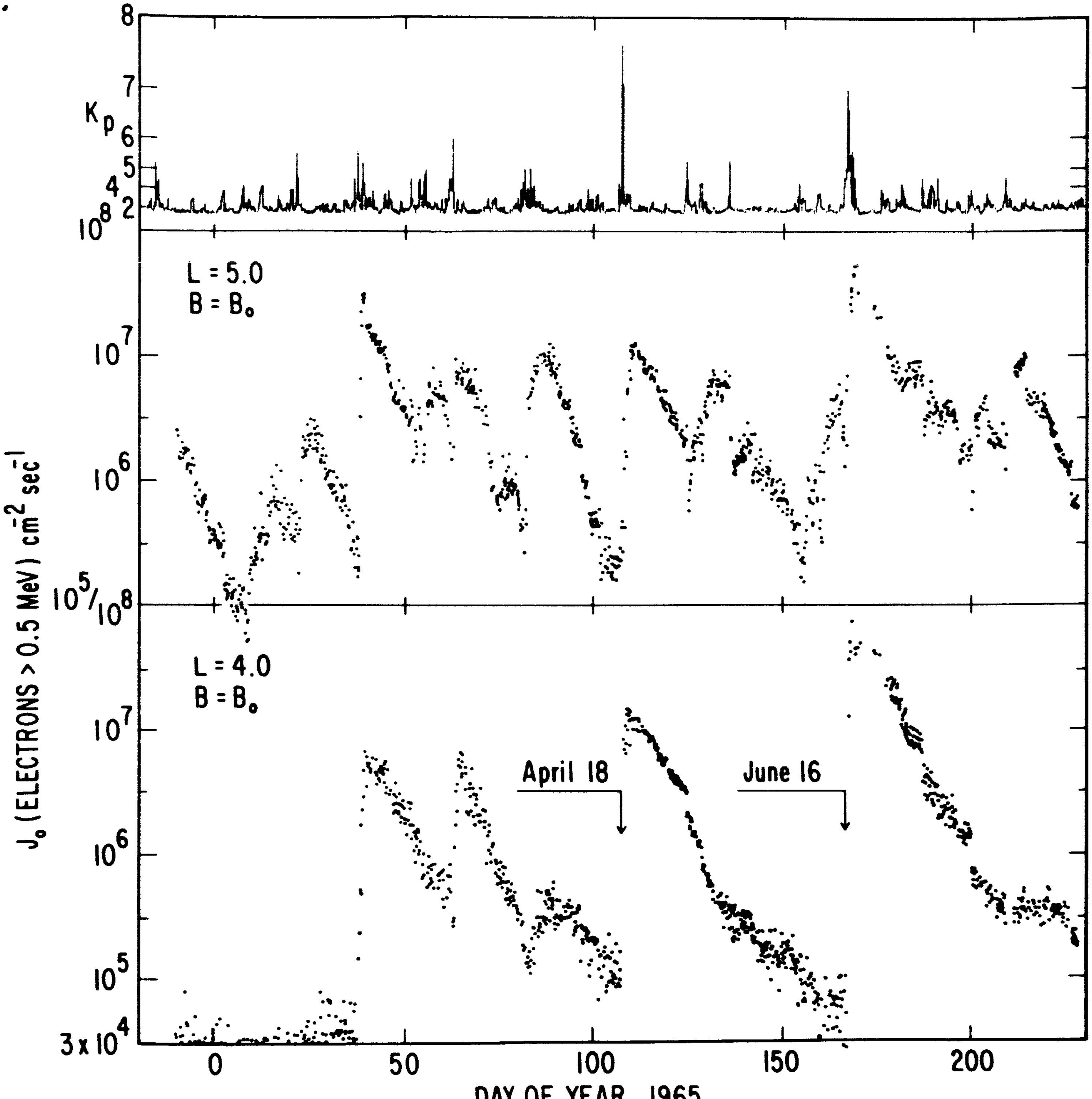

Kp
8
7
6
5
4
2
L = 5.0
B = B₀
$10^8$
$10^7$
$10^6$
$10^5/10^8$
L = 4.0
B = B₀
$10^5$
$3 \times 10^4$
April 18
June 16
$J_0$ (ELECTRONS > 0.5 MeV) $cm^{-2}$ $sec^{-1}$
0
50
100
150
200
DAY OF YEAR, 1965

FIGURE 1

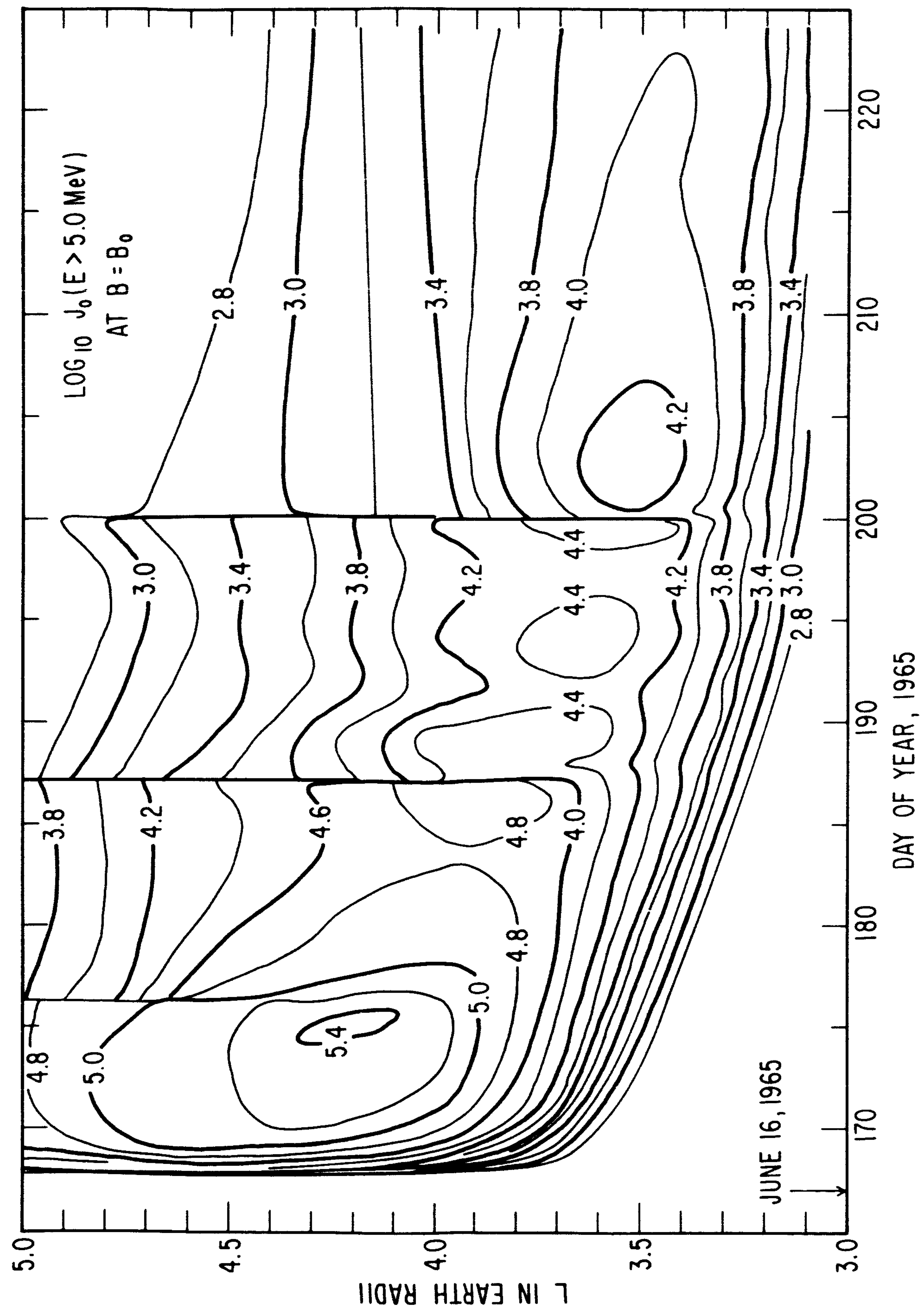

LOG10 J0(E > 5.0 MeV)
AT B = B0
L IN EARTH RADII
DAY OF YEAR, 1965
JUNE 16, 1965
5.0
4.5
4.0
3.5
3.0
170
180
190
200
210
220
2.8
3.0
3.4
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.4

FIGURE 2

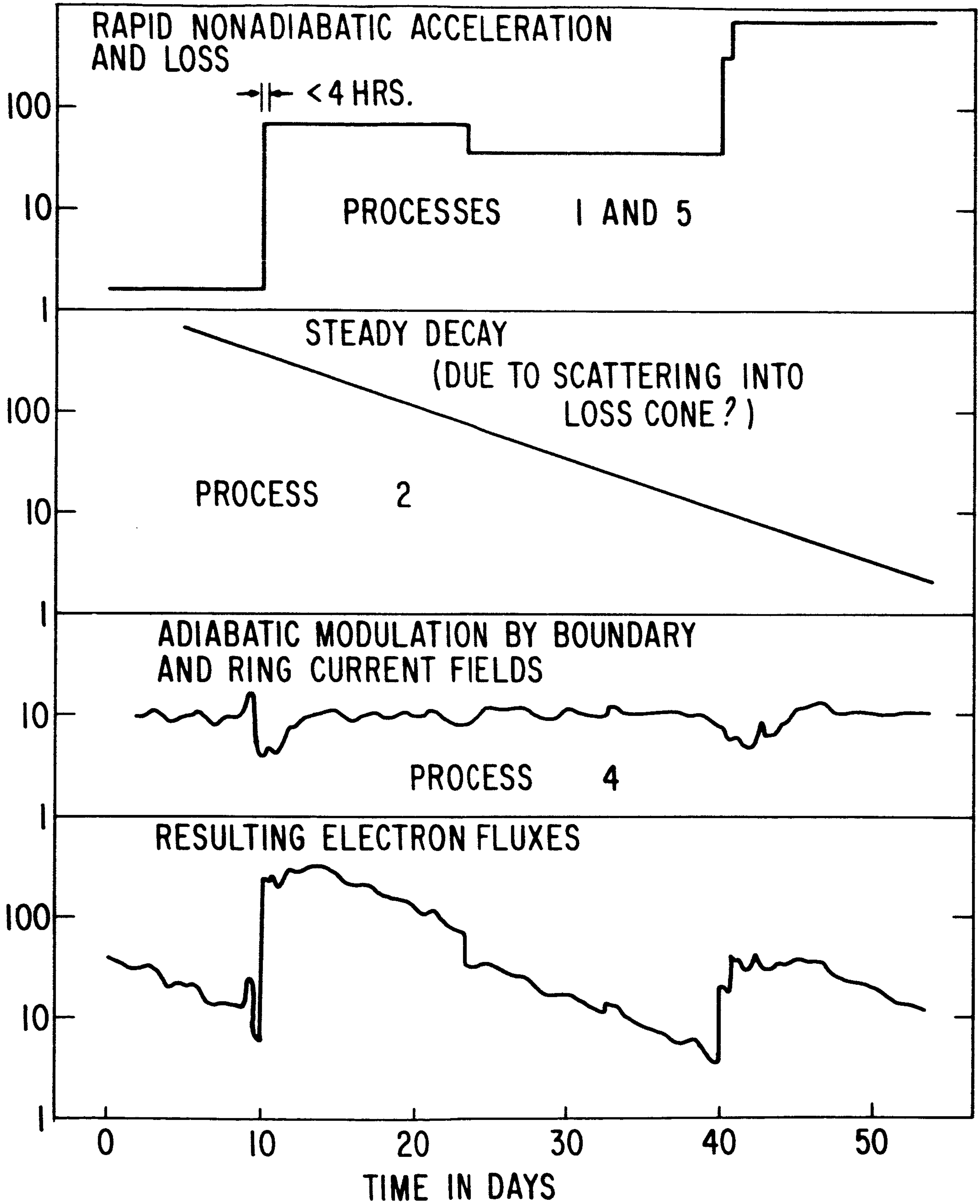

RAPID NONADIABATIC ACCELERATION AND LOSS
<4 HRS.
PROCESSES 1 AND 5
STEADY DECAY
(DUE TO SCATTERING INTO LOSS CONE?)
PROCESS 2
ADIABATIC MODULATION BY BOUNDARY AND RING CURRENT FIELDS
PROCESS 4
RESULTING ELECTRON FLUXES
100
10
1
0
10
20
30
40
50
TIME IN DAYS

FIGURE 3

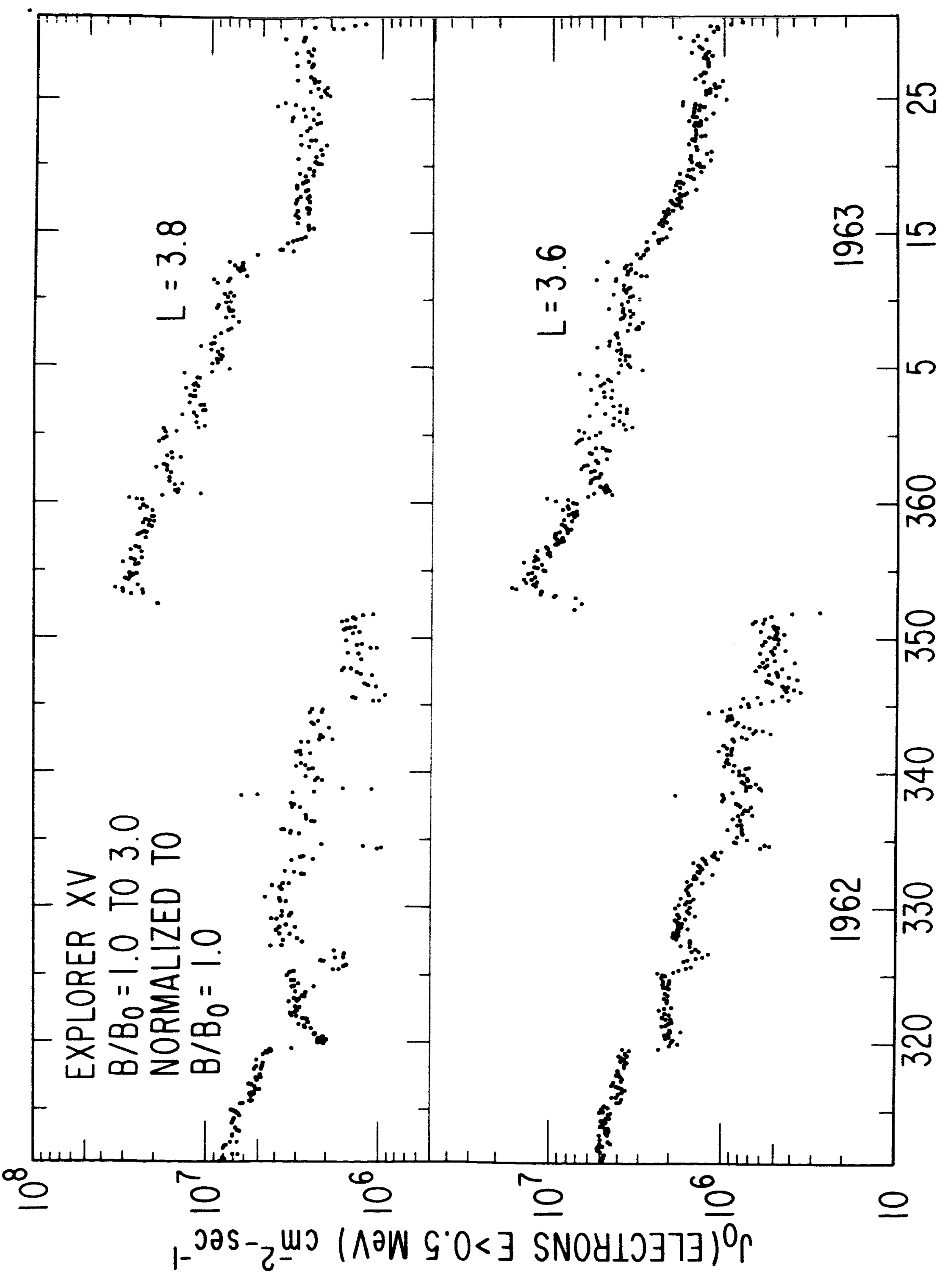
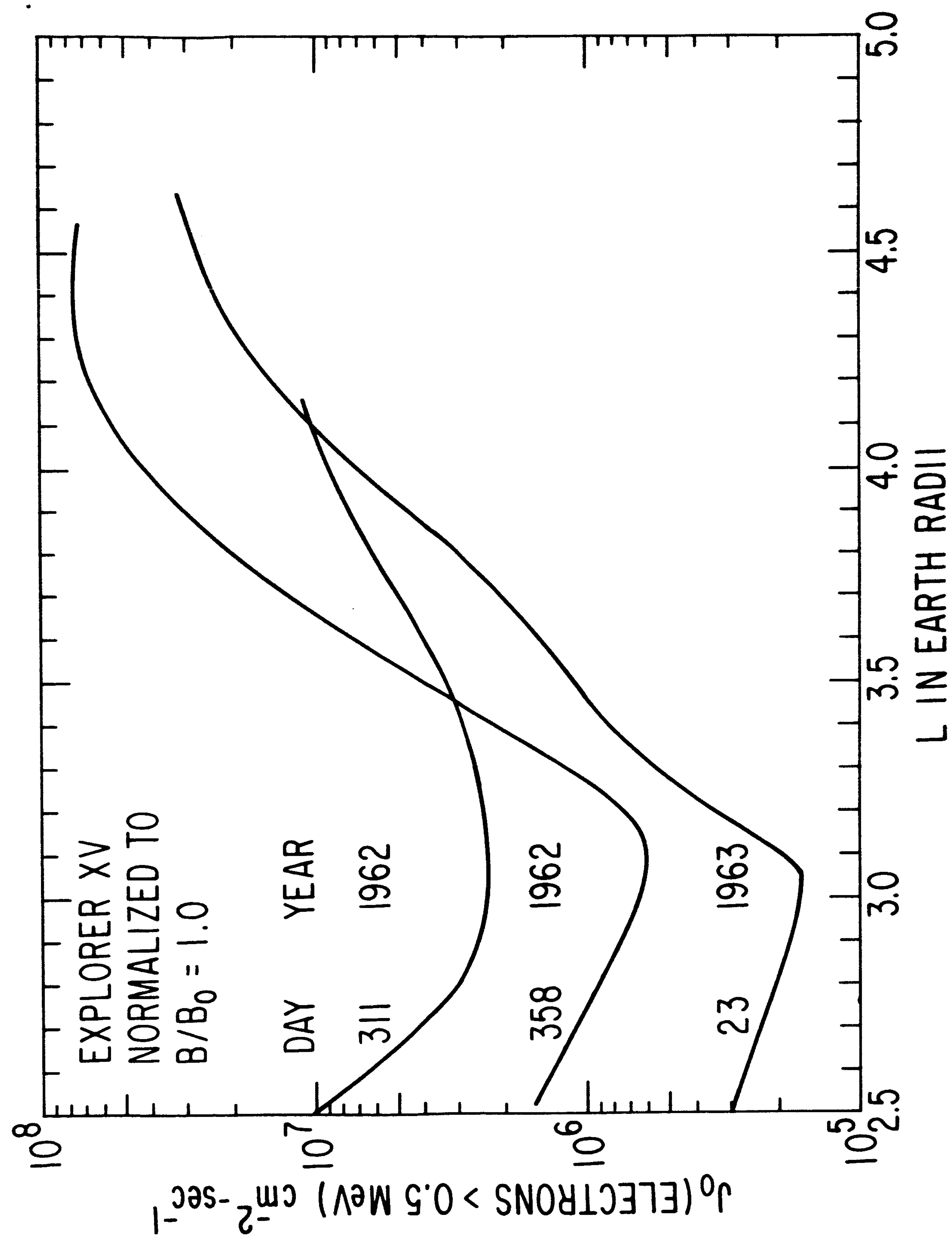
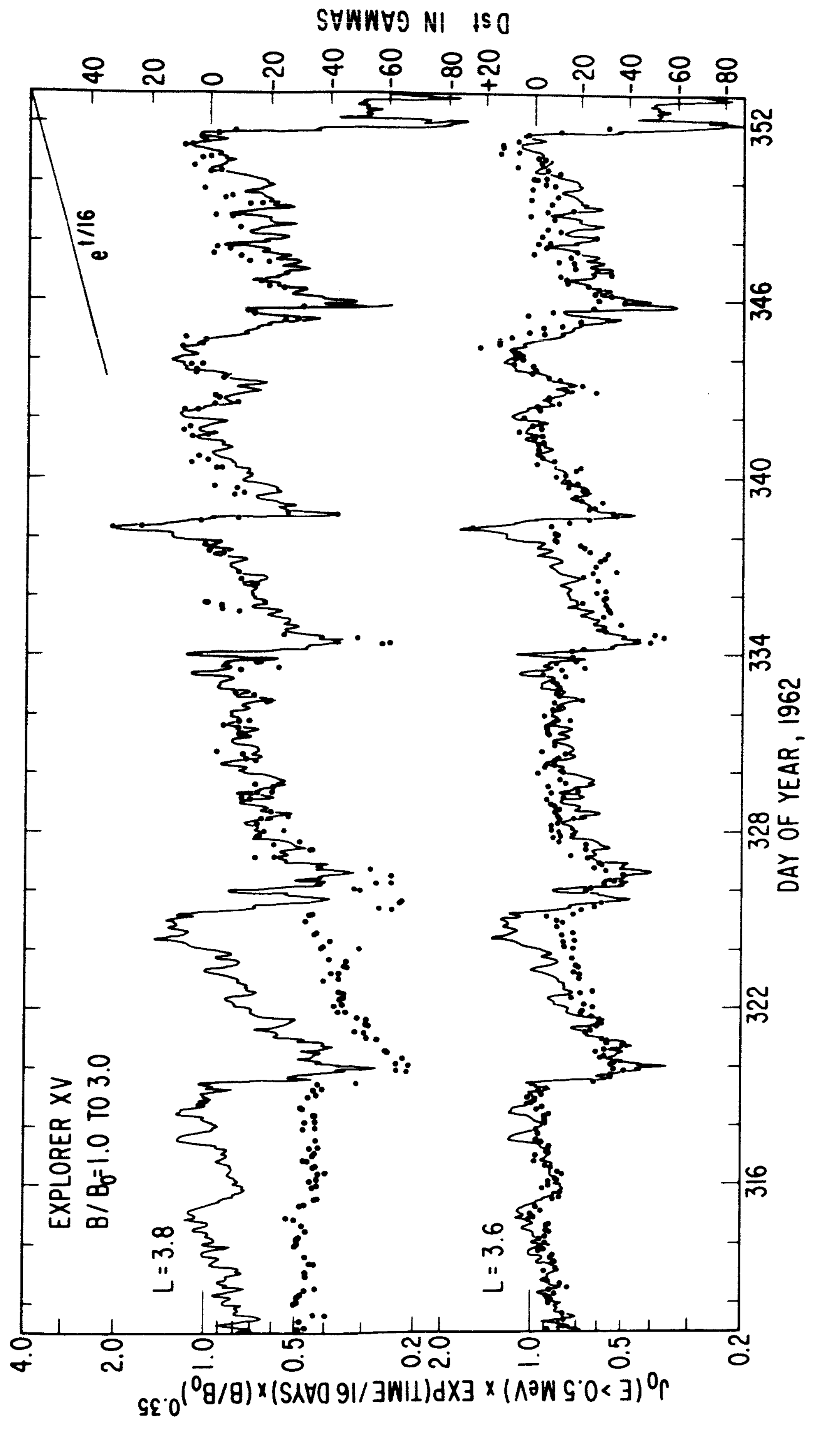

EXPLORER XV
B/B0 = 1.0 TO 3.0
NORMALIZED TO
B/B0 = 1.0
L = 3.8
L = 3.6
1962
1963
DAY OF YEAR
320
330
340
350
360
5
15
25
J0(ELECTRONS E>0.5 MeV) cm-2-sec-1
10^8
10^7
10^6
10^7
10^6
10

FIGURE 4



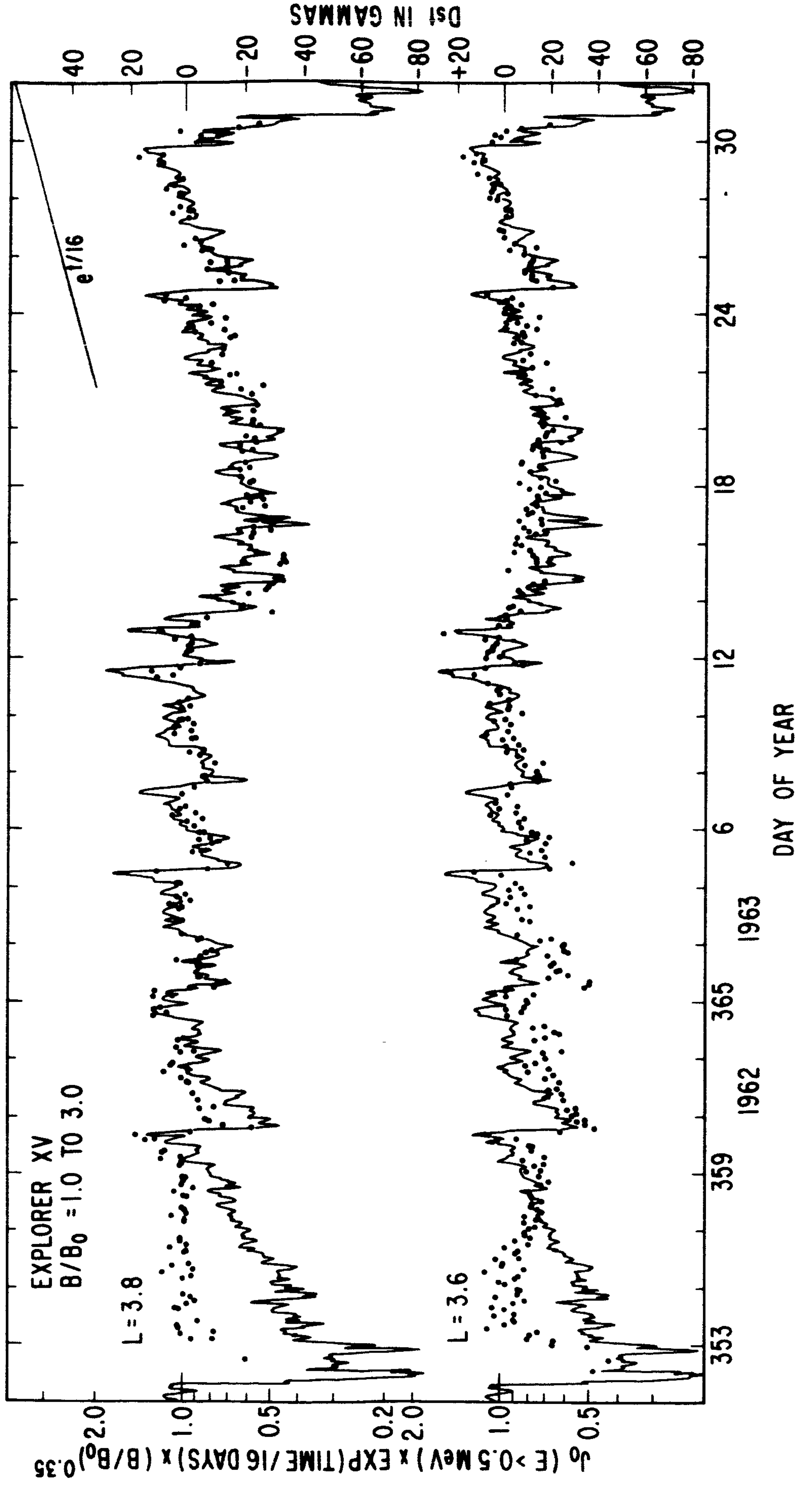
EXPLORER XV
NORMALIZED TO
$B/B_0 = 1.0$
DAY YEAR
311 1962
358 1962
23 1963
$J_0$ (ELECTRONS > 0.5 MeV) $cm^{-2}$-$sec^{-1}$
$10^8$
$10^7$
$10^6$
$10^5$
2.5
3.0
3.5
4.0
4.5
5.0
L IN EARTH RADII


FIGURE 5



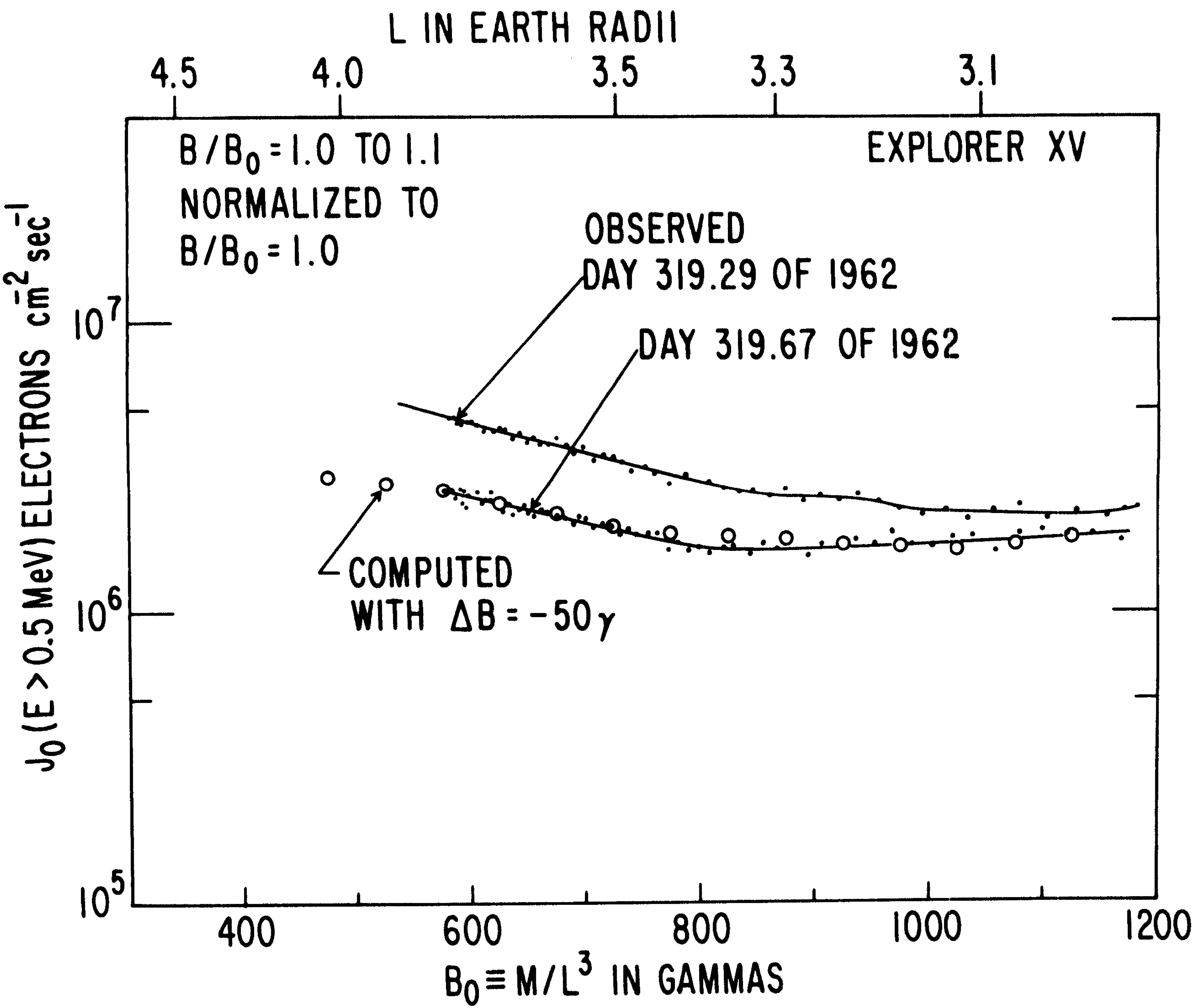
EXPLORER XV
B/B0=1.0 TO 3.0
L = 3.8
L = 3.6
e t/16
DAY OF YEAR, 1962
Dst IN GAMMAS
J0(E > 0.5 MeV) x EXP(TIME/16 DAYS) x (B/B0)0.35


FIGURE 6



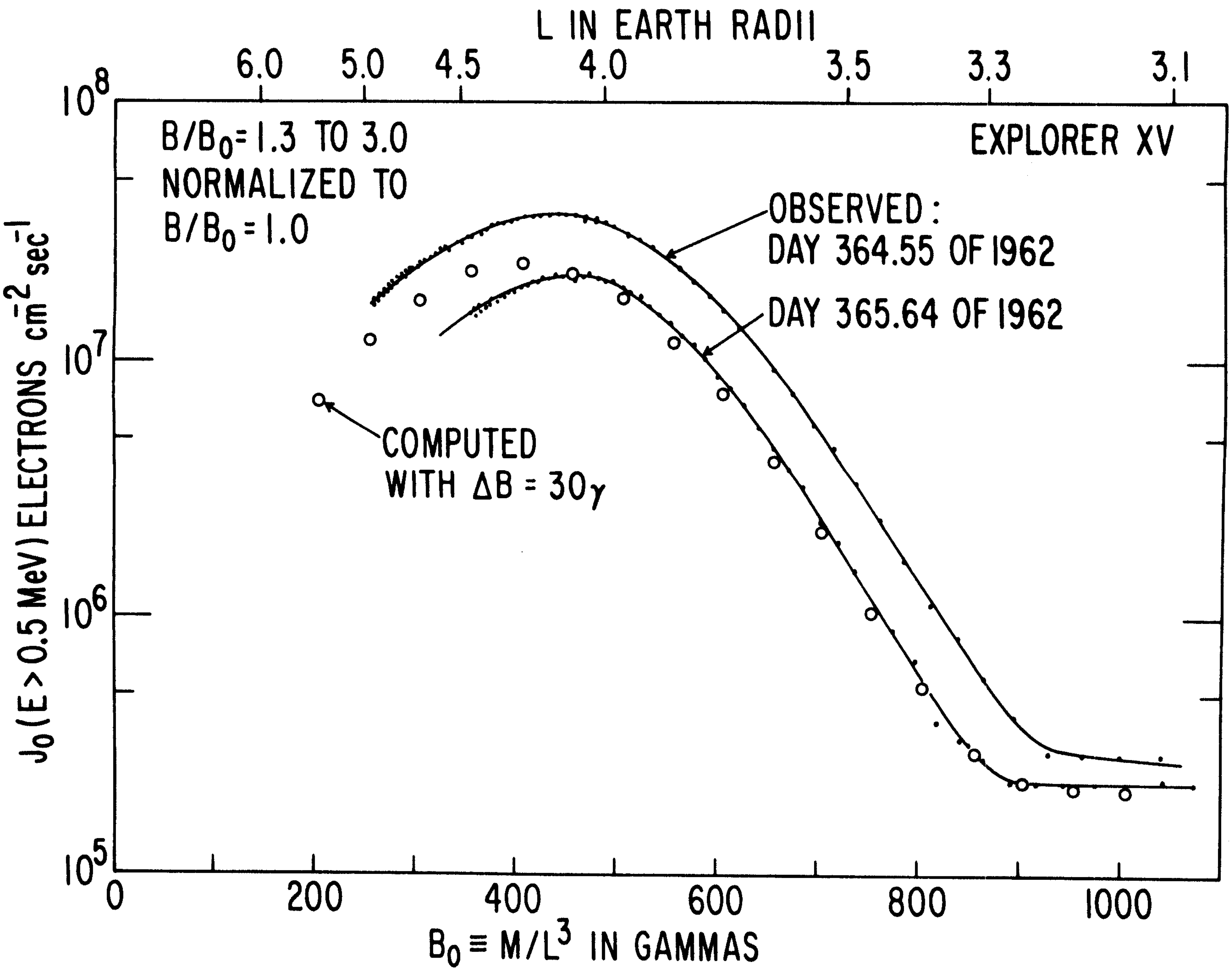
EXPLORER XV
B/B0 =1.0 TO 3.0
L = 3.8
L = 3.6
e^{t/16}
DAY OF YEAR
1962
1963
Dst IN GAMMAS
J0 (E > 0.5 MeV) x EXP(TIME/16 DAYS) x (B/B0)^0.35


FIGURE 7



L IN EARTH RADII
4.5
4.0
3.5
3.3
3.1
B/B$_0$ = 1.0 TO 1.1
NORMALIZED TO
B/B$_0$ = 1.0
EXPLORER XV
OBSERVED
DAY 319.29 OF 1962
DAY 319.67 OF 1962
COMPUTED
WITH ΔB = −50γ
$10^7$
$10^6$
$10^5$
$J_0$ (E > 0.5 MeV) ELECTRONS cm$^{-2}$ sec$^{-1}$
400
600
800
1000
1200
B$_0$ ≡ M/L$^3$ IN GAMMAS


FIGURE 8



L IN EARTH RADII
6.0
5.0
4.5
4.0
3.5
3.3
3.1
EXPLORER XV
$B/B_0$ = 1.3 TO 3.0
NORMALIZED TO
$B/B_0$ = 1.0
OBSERVED:
DAY 364.55 OF 1962
DAY 365.64 OF 1962
COMPUTED
WITH ΔB = 30γ
$J_0$(E > 0.5 MeV) ELECTRONS $cm^{-2}sec^{-1}$
$10^8$
$10^7$
$10^6$
$10^5$
0
200
400
600
800
1000
$B_0 \equiv M/L^3$ IN GAMMAS


FIGURE 9

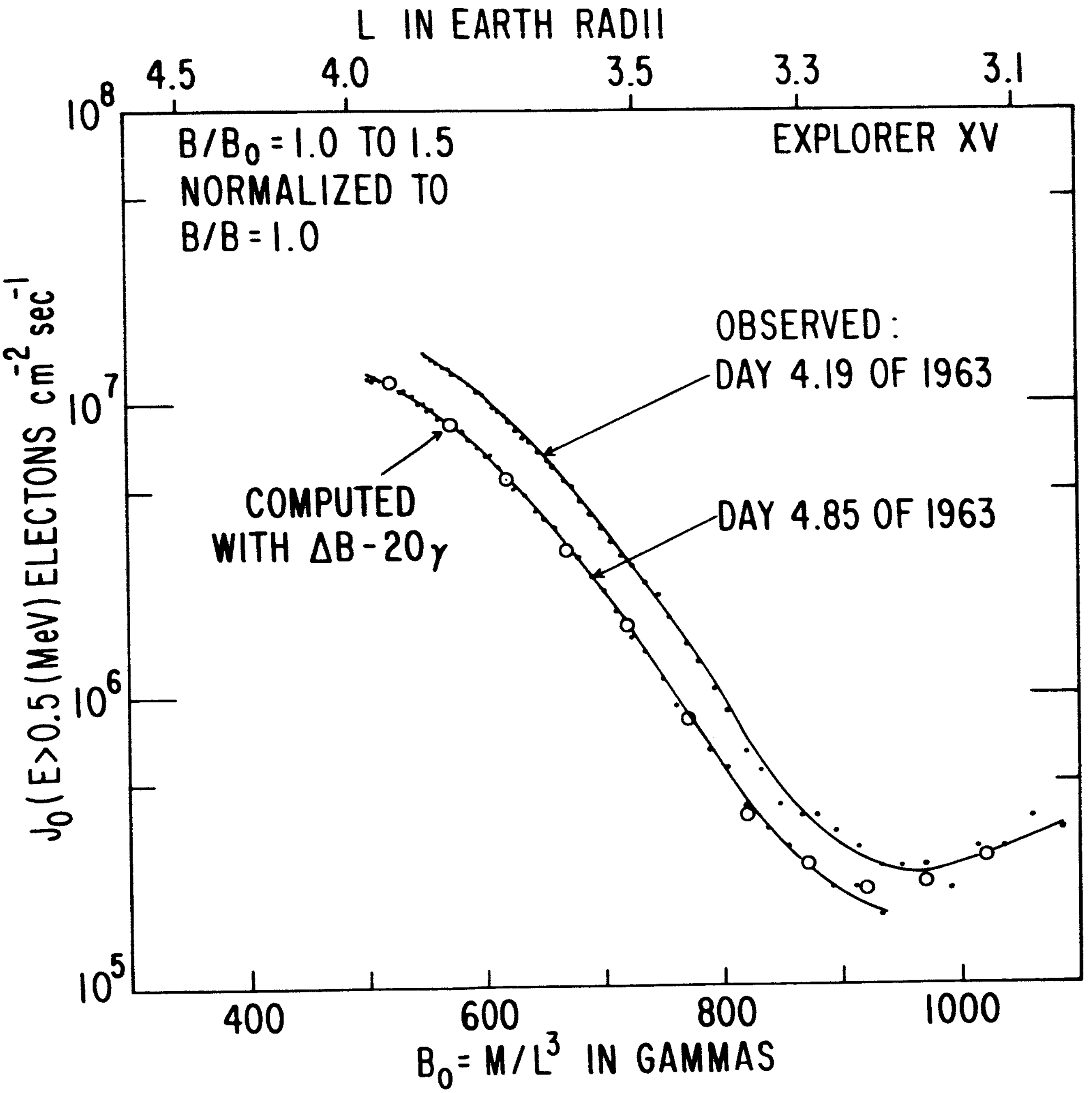
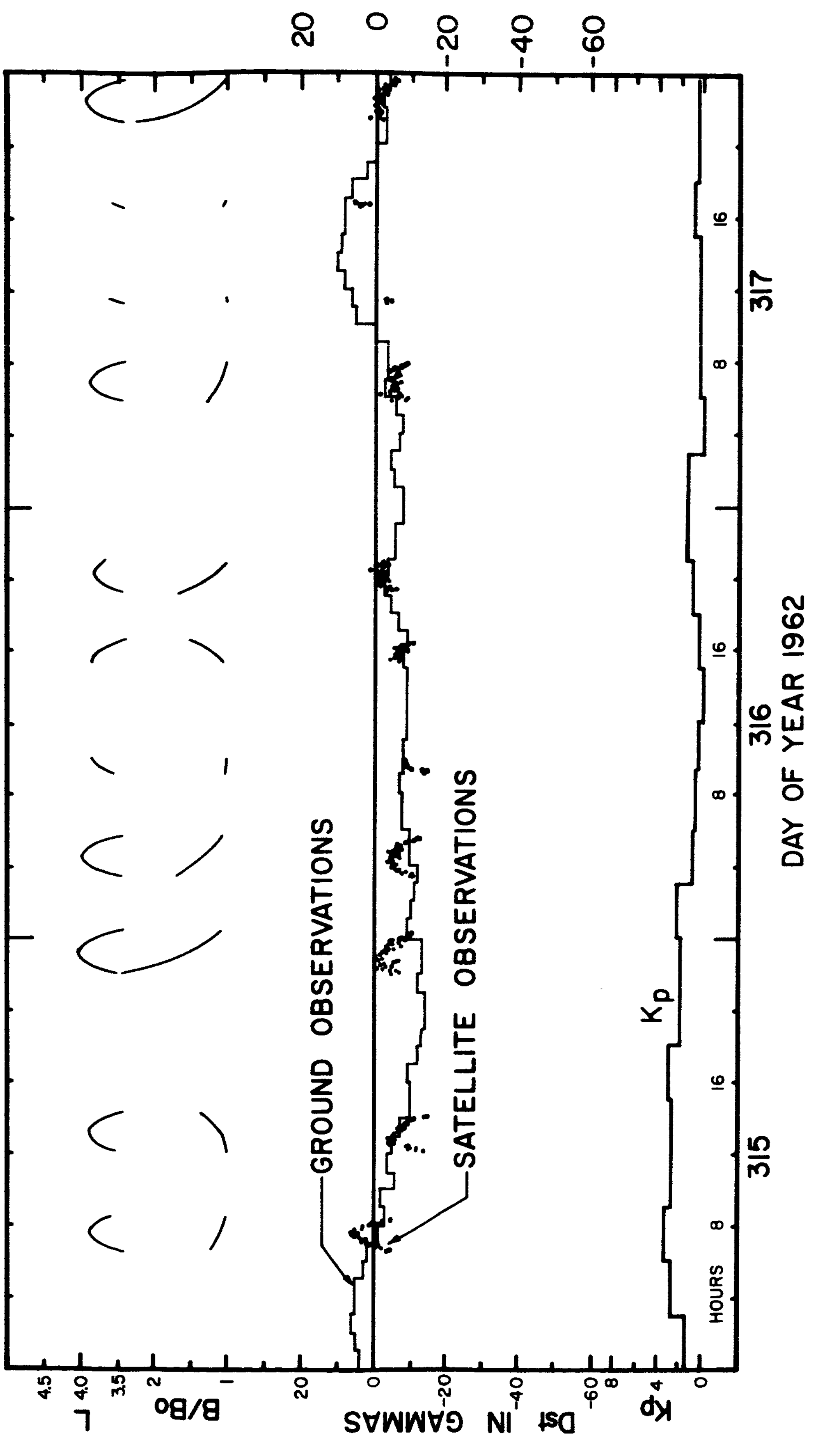
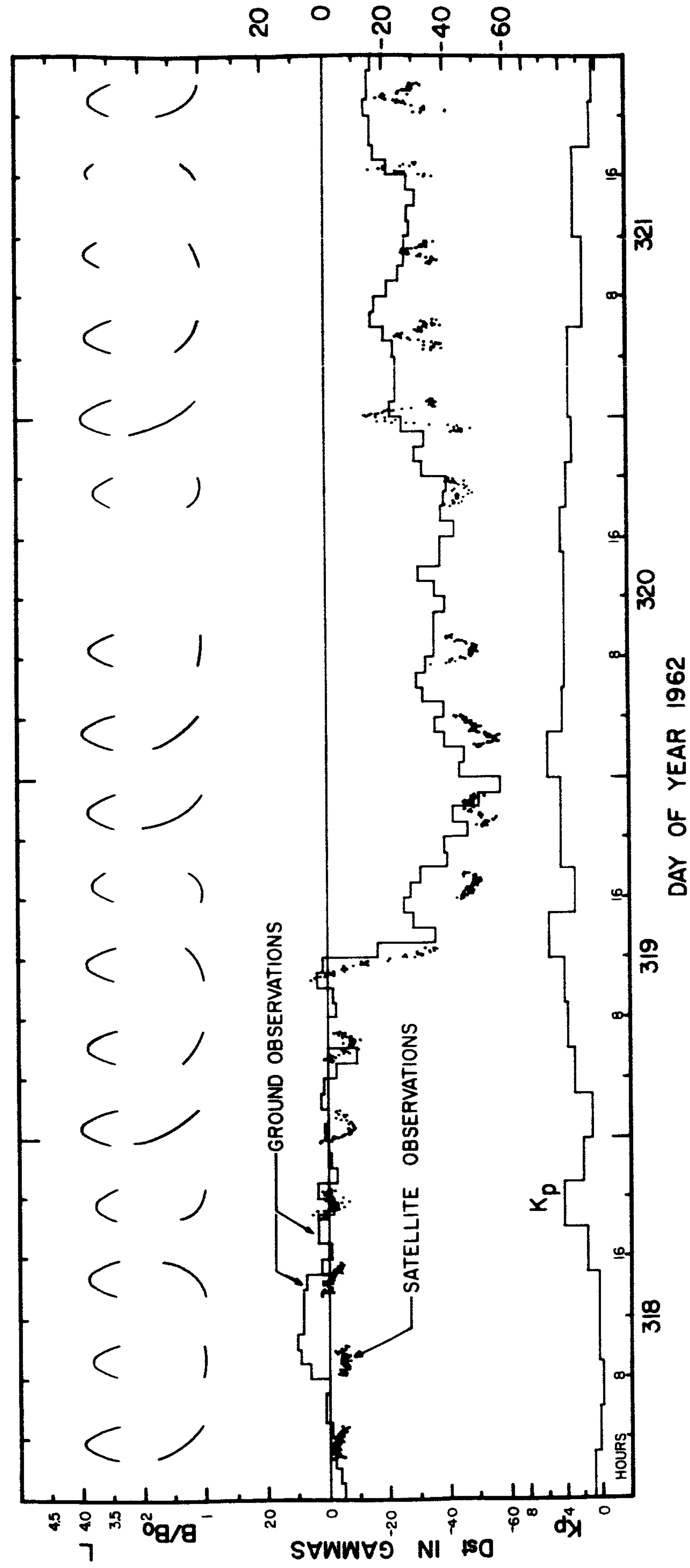

L IN EARTH RADII
4.5
4.0
3.5
3.3
3.1
B/B0 = 1.0 TO 1.5
NORMALIZED TO
B/B = 1.0
EXPLORER XV
OBSERVED:
DAY 4.19 OF 1963
DAY 4.85 OF 1963
COMPUTED
WITH ΔB - 20γ
J0 (E>0.5 (MeV) ELECTONS cm-2 sec-1
10^8
10^7
10^6
10^5
400
600
800
1000
B0 = M/L3 IN GAMMAS

FIGURE 10



L
B/Bo
Dst IN GAMMAS
Kp
4.5
4.0
3.5
2
1
20
0
-20
-40
-60
8
4
0
GROUND OBSERVATIONS
SATELLITE OBSERVATIONS
Kp
HOURS
8
16
315
316
317
DAY OF YEAR 1962


FIGURE 11 a



L
B/Bo
Dst IN GAMMAS
Kp
GROUND OBSERVATIONS
SATELLITE OBSERVATIONS
HOURS
DAY OF YEAR 1962
318
319
320
321


FIGURE 11 b

PROCESSES ACTING UPON OUTER ZONE ELECTRONS - I. Adiabatic Perturbations (UCSD-SP-66-5)

## ERRATA SHEET

Page 1 - Last Line - Insert between first and second words the following: "Andronov and Trakhtengerts (1964) and by".

References (pages 23-26)

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Corrected References


Chang, D. B., Some plasma instabilities of the magnetosphere, Radiation Trapped in the Earth's Magnetic Field, Proceedings of Advanced Study Institute, 491-503, 1966.

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