Department of Physics and Astronomy

THE UNIVERSITY OF IOWA

Iowa City, Iowa

U. of Iowa 65-13

Inward Radial Diffusion of Electrons E > 1.6 MeV in the Outer Radiation Zone*

by

L. A. Frank

April 1965

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

*Research supported in part by the National Aeronautics and Space Administration under Grant NsG-233-62 and by the Office of Naval Research under Contract Nonr-1509(06).

ABSTRACT

24303

Observations of the temporal variations of electron ($E > 1.6$ MeV) intensities near the geomagnetic equator in the outer radiation zone with Explorer XIV (2 October 1962 to 8 August 1963) strongly suggest that replenishment of energetic electrons in the outer radiation zone during the several weeks following a period of geomagnetic activity proceeds by an inward radial motion of energetic electrons from $L > 5$. The apparent, inward radial velocity of the "wave" of electrons ($E > 1.6$ MeV) is ~ 0.4 earth radius $(\text{day})^{-1}$ at $L = 4.7$ and ~ 0.03 earth radius $(\text{day})^{-1}$ at $L = 3.4$ and varies as $\sim L^8$ between these L-shells. These inward radial velocities for the several replenishment cycles of outer zone electrons ($E > 1.6$ MeV) observed with Explorer XIV at a given L-shell are equal to within experimental errors. These measurements provide evidence for a continually active mechanism for diffusing energetic electrons across L-shells in the outer radiation zone.

Author

I. INTRODUCTION

The existence of a belt of energetic electrons ($E \sim 1$ MeV) encircling the earth and centered at $\sim$ 25,000 km geocentric radial distance in the geomagnetic equatorial plane (i.e., the outer radiation zone) was demonstrated by *in situ* measurements with some of the earliest earth satellites and space probes [cf. Van Allen, Ludwig, Ray, and McIlwain, 1958; Van Allen and Frank, 1959 a, b]. Since measurements of energetic electrons in the interplanetary medium beyond the earth's magnetosphere and of energetic electrons precipitated into the earth's upper atmosphere reveal that the interplanetary intensities are insufficient for maintaining the outer zone intensities, a "local" (i.e., within or in the immediate vicinity of the earth's magnetosphere) acceleration mechanism driven with the energy of the solar wind is generally invoked in order to account for the energetic electrons of the outer radiation zone. The morphology of outer zone electron intensities has been studied by means of a variety of Geiger-Mueller tubes and scintillators on several earth satellites [cf. Forbush et al., 1962; McIlwain, 1963; Frank et al., 1964; Freeman, 1964]. Briefly, the temporal variations of these electron intensities during and following a period of geomagnetic activity are characterized by (a) an immediate enhancement of ~ 40 keV electron intensities beyond $L \simeq 3.5$ and (b) a severe decrease of ~ 1 MeV electron intensities at the onset of the geomagnetic activity, (c) subsequent decay of electron $E \sim 40$ keV intensities after the initial increase of intensities, (d) an increase of electron $E \sim 1$ MeV intensities within a few days after the onset of the geomagnetic activity at $L \simeq 5$ and an increasing time delay (~ three weeks at $L \simeq 3.5$) for the enhancement of intensities with decreasing L-value, and (e) an orderly decay of electron ($E \sim 1$ MeV) intensities after the enhancement of intensities at a given L-shell. Detailed inspection of Explorer XIV data [Frank et al., 1964] revealed that the temporal variations of the radial profile of electron ($E > 1.6$ MeV) intensities near the geomagnetic equatorial plane were characterized by an inward radial motion of the inner boundary of the intensity peak persisting for periods of at least several weeks and an apparent radial velocity ~ 0.02 earth radius $(\text{day})^{-1}$ following a magnetic storm. This apparent radial motion strongly indicates that inward diffusion of energetic electrons across L-shells from $L > 5$ is a source of energetic outer zone electrons. The following investigation extends the above preliminary analysis of the apparent radial diffusion of energetic electrons ($E > 1.6$ MeV) observed by Explorer XIV.

II. DESCRIPTION OF THE EXPERIMENTAL APPARATUS

The S.U.I. detector array in Explorer XIV (launch, 2 October 1962; apogee altitude, 98,533 km; perigee altitude, 281 km; orbital inclination, 33°) included three collimated Anton type 213 thin-windowed Geiger-Mueller tubes with differing particle energy thresholds and an omnidirectional, shielded Anton type 302 Geiger-Mueller tube. (For a detailed description of these detectors, see Frank, Van Allen, and Hills [1964].) Of particular interest in the present investigation is the response of the familiar 302 G.M. tube (shielding of 265 mg $(cm)^{-2}$ magnesium and 400 mg $(cm)^{-2}$ stainless steel) to penetrating energetic electrons ($E > 1.6$ MeV) in the outer radiation zone from $L \simeq 3$ to $L \simeq 5$. The response of the shielded 302 G.M. tube has been shown to be that due to penetrating electrons ($E > 1.6$ MeV) over this L-shell range by demonstrating that the response due to penetrating protons $E > 23$ MeV [McIlwain, 1963] and due to nonpenetrating electron bremsstrahlung [Frank, 1962; Frank et al., 1964] is negligible in comparison to the penetrating electron response. The omnidirectional geometric factor (ϵG) of the 302 G.M. tube for counting electrons ($E > 1.6$ MeV) is 0.1 ($\pm$ 0.05) cm^2 for typical outer radiation zone spectrums; the present study is concerned with the comparison of the L-shell profiles of the relative responses of this detector for sequences of consecutive passes of the satellite through the outer radiation zone. The response of the 302 G.M. tube is sampled for 10.24 seconds every 76.8 seconds and the corresponding sample density is ~ 1 sample per 300 km geocentric radial distance along the portions of the Explorer XIV trajectory of interest in the present investigation.

III. OBSERVATIONS

An example of apparent, radially inward motion of energetic electrons ($E > 1.6$ MeV) as observed by Explorer XIV has been given by Frank, Van Allen, and Hills [1964] and is presently reviewed in Figures 1 and 2. Figure 1 displays the omnidirectional intensity profiles of electrons ($E > 1.6$ MeV) as a function of L for three similar passes (in magnetic latitude) through the outer radiation zone preceding a period of geomagnetic activity beginning on 17 December 1962. An orderly decline of intensities over the entire L-shell range displayed here is evident and the absence of the "slot" or minimum of intensities at $L \sim 3$ is due to artificially injected electrons from the Soviet high-altitude nuclear explosions in late October and early November 1962. Continuing these L-shell intensity profiles after the period of geomagnetic activity, Figure 2 clearly shows the systematic movement of the inner edge of the intensity profile from $L \simeq 3.8$ to $L \simeq 3.3$ and a slow decay of peak intensities over a period of ~ 20 days, and a return of the intensities observed at $L > 4.7$ to pre-storm values by 8 January 1963. It is essential to the above observation of this slow radial movement of energetic electrons that the period of geomagnetic activity be followed by a period of several weeks characterized by relative magnetic quiescence insofar as compounded cycles cannot be easily separated in an observational sense. For example, the Kp daily sums Σ Kp for the period discussed above were ≥ 30 for 17-20 December and ≤ 15 over the period 23 December 1962 to 8 January 1963 with the exceptions of Σ Kp = 23 and 18 on 26 and 31 December respectively (see Frank et al. [1964]). The apparent inward radial velocity of the inner edge of the outer radiation zone in the example given above is $\sim 3 \times 10^{-2}$ earth radius $(\text{day})^{-1}$ at $L \simeq 3.4$.

The long operational lifetime of Explorer XIV provided several observations of the chain of events discussed above. Another example of the replenishment of energetic electron ($E > 1.6$ MeV) intensities is shown in Figure 3 for the period 9-24 March 1963 when the satellite passed through the outer radiation zone along a trajectory of similar B and L every three days. The intensity profiles of Figure 3 are displayed as a function of radial distance from the center of earth and the variations of magnetic latitude for this series of profiles are indicated by a sample geomagnetic latitude given at 30,000 km for each profile. The salient features of the temporal variations of the profiles displayed in Figure 3 are the characteristic sparsity of electrons during the storm period on 9 March 1963, the subsequent increase of electron ($E > 1.6$ MeV) intensities in the outer radiation zone until ~ 15 March with a peak intensity at a radial distance of $\sim 25{,}000$ km during a period of geomagnetic activity, and subsequent decay of intensities beyond $\sim 25{,}000$ km with an apparent motion of the peak of intensities inward to $\sim 20{,}000$ km by 24 March. This set of chronological intensity profiles suggests that the electron ($E > 1.6$ MeV) intensities are rapidly enhanced during the several days following the initial decrease in intensities at the onset of geomagnetic activity for $L > 5$ and proceed to lower L-shells by radial diffusion. Since the rate of radial diffusion is a strong function of L, increasing rapidly with increasing L, the initial enhancement for $L > 5$ shown in Figure 3 can occur by diffusion of electrons from the vicinity of the magnetopause but is beyond the temporal resolution of the Explorer XIV orbit. Further, since the instrument is sensitive to only electrons ($E > 1.6$ MeV) and, if the first adiabatic invariant μ is conserved in this diffusion process, then the electrons which radially drift into the outer radiation zone to $L \sim 4$ with $E \sim 1.6$ MeV (detector threshold for penetrating electrons) have energies $\lesssim 150$ keV at $L = 10$ and hence are well below the

302 G.M. tube penetrating-electron energy threshold. The above two factors limit the L-shell range over which we can determine the rates of inward radial diffusion of these electrons.

The third and final example of replenishment of electrons ($E > 1.6$ MeV) in the outer radiation zone is shown in Figure 4; the relative intensity contours preceding the period of geomagnetic activity beginning 30 April displayed an orderly decline over the L-shells 3.2 to 4.6 with a more rapid decay with increasing L. During the storm period a typical rapid decrease was detected on the 1 April Explorer XIV pass through the outer zone on all L-shells presented here with somewhat smaller decreases on the lower L-shells. Following the decrease the intensities of electrons ($E > 1.6$ MeV) were enhanced with increasing time delay and decreasing amplitude for decreasing values of L. The observation of no significant increase of intensities at $L = 3.2$ may be a manifestation of the inability of the present experimental apparatus to discern a small increase of intensities on this L-shell above the intensities of artificially injected electrons from the Soviet high-altitude explosions (see Figure 2) although the absolute intensities at $L = 3.2$ and 3.4 do not differ by more than 30% and the intensities at $L = 3.4$ increased by a factor of ~ 5. The time history of the decay of artificially injected electrons in the "slot" at $L \sim 3$ (Figures 1, 2, and 4) indicates that loss mechanisms in this region are not more effective than in the outer radiation zone [cf. Van Allen, 1964] and indicates that perhaps the presence of the "slot" is not primarily a manifestation of a loss mechanism which is more effective along these L-shells but may be attributed to a weaker source. The temporal intensity profiles of Figures 2 and 4 allow a rough determination of the velocities of inward radial diffusion as a function of L in the outer radiation zone. These velocities have been estimated by calculating the apparent inward radial velocity of the logarithmic half-maximum of the inner side of the "wave" of energetic electrons. The results of this calculation for the two electron ($E > 1.6$ MeV) replenishment cycles of December 1962--January 1963 and April-May 1963 are shown in Figure 5. At $L = 4.7$ the apparent rate of inward diffusion of electrons ($E > 1.6$ MeV) is ~ 0.4 earth radius $(\text{day})^{-1}$ and at $L = 3.4$ is ~ 0.03 earth radius $(\text{day})^{-1}$ and the dependence of this rate of diffusion upon L is $\sim L^8$. The inward radial velocities for the two replenishment cycles are equal at a given L-shell within the experimental errors of the present experiment. The anomalously low point at $L = 3.2$ may be a manifestation of the instrument's inability to detect a change in intensity on this L-shell over the background of artificially injected electrons. A coarse upper limit of ~ 0.003 earth radius $(\text{day})^{-1}$ at L = 2.1 has been obtained from Explorer IV measurements [Van Allen, McIlwain, and Ludwig, 1959; McIlwain, 1961] of artificially injected electrons produced by the Argus tests during 1958. It is of interest to note that if the present result is extrapolated to higher L-shells and assuming that this apparent inward radial velocity is not a strong function of electron energy, diffusion of electrons from L ~ 10 (near the magnetopause) to L $\simeq$ 5 would take place in a period of ~ 1 day, a result which is completely satisfactory with regard to the temporal resolution of the Explorer XIV orbit for successive outer radiation zone passes (orbital period of satellite: 36.4 hours).

IV. DISCUSSION

The present study of the temporal variations of electron ($E > 1.6$ MeV) intensities in the outer radiation zone during several replenishment cycles following periods of geomagnetic activity strongly implies that inward radial diffusion of electrons from the vicinity of the magnetospheric boundary is the primary source of the energetic electrons in the outer radiation zone $L \gtrsim 3.0$. The inward radial velocity of the "wave" of electrons ($E > 1.6$ MeV) is ~ 0.4 earth radius $(\mathrm{day})^{-1}$ at $L = 4.7$ and ~ 0.03 earth radius $(\mathrm{day})^{-1}$ at $L = 3.4$ and varies as $\sim L^8$ between these L-shells. The onset of period of geomagnetic activity (roughly, $\sum Kp \gtrsim 30$) is followed within approximately 1 or 2 days by the appearance of large increases in the intensities of electrons ($E > 1.6$ MeV) in the outer radiation zone beyond $L \sim 5$ and the subsequent inward motion of this "wave" of electrons over a period of weeks following the geomagnetic storm period. The mechanism responsible for this diffusion of energetic electrons across L-shells is active during periods of relative magnetic quiescence and the radial diffusion velocities (see Figure 5) are equal to within experimental uncertainties for each replenishment cycle of the outer radiation zone during this period of observations. From extrapolation of the present result and assuming that the rate of diffusion is not a strong function of electron energy, it is estimated that approximately 1 or 2 days are required for an electron to diffuse inward from the vicinity of the magnetospheric boundary to $L \sim 5$ in agreement with the observations of the temporal variations of electron ($E > 1.6$ MeV) intensities reported here. Hence it appears that the increases of electrons ($E > 1.6$ MeV) intensities in the outer radiation zone reflect, with the appropriate time delay, increases of energetic electron intensities in the vicinity of the magnetopause during periods of geomagnetic activity as indicated by ΣKp and hence are positively correlated with the solar wind velocity [Snyder, Neugebauer, and Rao, 1963]. If the first adiabatic invariant μ is conserved as an electron moves by radial diffusion from $L \sim 10$ to $L \sim 4$, then a 150 keV electron at the magnetopause will acquire $\gtrsim 1.5$ MeV upon arrival at $L \simeq 4$. Hence from the above interpretation in order to account for the increases of electron ($E > 1.6$ MeV) intensities in the outer radiation zone an increase of electron ($E \sim 150$ keV) intensities in the transition region or just within the magnetopause must be positively correlated with an increased solar wind velocity. The existence of large intensities ($\sim 10^6$ to 10^8 cm^2 $(sec)^{-1}$) of electrons $E \gtrsim 40$ keV inside the magnetopause is well known [cf. Freeman, 1964; Frank, 1965]; and recent measurements [Fan et al., 1964; Frank and Van Allen, 1964; Anderson and Harris, 1965] have shown that 'spikes' of intensities of electrons in this energy range are frequent in the transition region and are positively correlated with 3-hour Kp values [cf. Frank and Van Allen, 1964]. Parker [1960] and Herlofson [1960] have suggested that diffusion is an important source of energetic electrons in the outer radiation zone; and recent calculations by Hess et al. [1964], Mead and Nakada [1964], and Nakada et al. [1964] assuming that charged particle trans-L diffusion proceeds with conservation of the first two adiabatic invariants of motion show that the diffusion times (i.e., the time required for a charged particle to move from $L = 6$, for example, to a lower L-shell) would vary as L^{-8} in agreement with the present coarse experimental result. McIlwain [1965] has recently reported an inward radial movement of a secondary peak of proton ($40 < E < 110$ MeV) intensities at $L \simeq 2.2$ by 0.15 R_E over a period of two years or $\sim 2 \times 10^{-4}$ earth radius $(\text{day})^{-1}$ which is only a factor of ~ 5 less than that given by extrapolation of the present result for electrons ($E > 1.6$ MeV) to $L = 2.2$. This comparison of results may indicate that the mechanism responsible for radial diffusion of charged particles is not strongly dependent upon particle mass. It will be of interest to compare the present results obtained near solar minimum with observations during a different portion of the solar cycle by Explorers VI and VII which were also equipped with shielded 302 G.M. tubes. Further experiments with increased sensitivity over a larger energy range, and for longer periods of observation are necessary in order to further investigate diffusion mechanisms as sources of energetic electrons in the outer radiation zone.

ACKNOWLEDGEMENTS

I am indebted to Dr. J. A. Van Allen for several stimulating discussions concerning the present investigation. This research was supported in part by the National Aeronautics and Space Administration under grant NsG-233-62 and by the Office of Naval Research under contract Nonr-1509(06).

REFERENCES

Anderson, K. A., H. K. Harris, and R. J. Paoli, Energetic electron fluxes in and beyond the earth's outer magnetosphere, J. Geophys. Res., 70, 1039-1050, 1965.

Fan, C. Y., G. Gloeckler, and J. A. Simpson, Evidence for > 30 keV electrons accelerated in the shock transition region beyond the earth's magnetospheric boundary, Phys. Rev. Letters, 13, 149-153, 1964.

Forbush, S. E., G. Pizzella, and D. Venkatesan, The morphology and temporal variations of the Van Allen radiation belt, October 1959 to December 1960, J. Geophys. Res., 67, 3651-3668, 1962.

Frank, L. A., Efficiency of a Geiger-Mueller tube for non-penetrating electrons, J. Franklin Institute, 273, 91-106, 1962.

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

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

Frank, L. A., J. A. Van Allen, and H. K. Hills, A study of charged particles in the earth's outer radiation zone with Explorer 14, J. Geophys. Res., 69, 2171-2191, 1964.

Freeman, J. W., The morphology of the electron distribution in the outer radiation zone and near the magnetospheric boundary as observed by Explorer XII, J. Geophys. Res., 69, 1691-1723, 1964.

Herlofson, N., Diffusion of particles in the earth's radiation belts, Phys. Rev. Letters, 5, 414-416, 1960.

Hess, W. N., J. W. Dungey, and M. P. Nakada, On fluxes of outer belt protons, Trans. Am. Geophysical Union, 45, 85, 1964 (abstract).

McIlwain, C. E., Coordinates for mapping the distribution of magnetically trapped particles, J. Geophys. Res., 66, 3681-3692, 1961.

McIlwain, C. E., The radiation belts, natural and artificial, Science, 142, 355-361, 1963.

McIlwain, C. E., Long-term changes in the distribution of the 40- to 110-MeV trapped protons, Trans. Am. Geophysical Union, 46, 141, 1965 (abstract).

Mead, G. D., and M. P. Nakada, The Parker mechanism and protons in the outer radiation belt, Trans. Am. Geophysical Union, 45, 85, 1964 (abstract).

Nakada, M. P., J. W. Dungey, and W. N. Hess, Theoretical studies of protons in the outer radiation belt, Goddard Space Flight Center Res. Rep. X-640-64-110, 1964.

Parker, E. N., Geomagnetic fluctuations and the form of the outer zone of the Van Allen radiation belt, J. Geophys. Res., 65, 3117-3130, 1960.

Snyder, C. W., M. Neugebauer, and U. R. Rao., The solar wind velocity and its correlation with cosmic-ray variations and with solar and geomagnetic activity, J. Geophys. Res., 68, 6361-6370, 1963.

Van Allen, J. A., Lifetimes of geomagnetically trapped electrons of several MeV energy, Nature, 203, 1006-1007, 1964.

Van Allen, J. A., and L. A. Frank, Radiation around the earth to a radial distance of 107,400 kilometers, Nature (London), 183, 430-434, 1959a.

Van Allen, J. A., and L. A. Frank, Radiation measurements to 658,300 km with Pioneer IV, Nature (London), 184, 219-224, 1959b.

Van Allen, J. A., G. H. Ludwig, E. C. Ray, and C. E. McIlwain, Observation of high intensity radiation by satellites 1958 alpha and gamma, Jet Propulsion, 28, 588-592, 1958.

Van Allen, J. A., C. E. McIlwain, and G. H. Ludwig, Satellite observations of electrons artificially injected into the geomagnetic field, J. Geophys. Res., 64, 877-891, 1959.

FIGURE CAPTIONS

Figure 1. Measurements of electron ($E > 1.6$ MeV) intensities in the outer radiation zone ($\lambda_m \lesssim 30°$) as a function of L for several passes of Explorer XIV preceding and during the onset of geomagnetic activity on 17 December 1962 (after Frank, Van Allen, and Hills, 1964).

Figure 2. A continuation of Figure 1 during the geomagnetically quiescent period after 22 December which displays the systematic inward motion of the inner side of the peak of electron ($E > 1.6$ MeV) intensities (after Frank, Van Allen, and Hills, 1964).

Figure 3. A selected set of radial profiles of the omnidirectional intensities of electrons ($E > 1.6$ MeV) for several similar Explorer XIV passes through the outer radiation zone.

Figure 4. Relative omnidirectional intensity contours of electrons ($E > 1.6$ MeV) as a function of time for various L-shells preceding and after the onset of geomagnetic activity on 30 April 1963 which display the initial sudden decrease followed by an orderly replenishment of electron intensities.

Figure 5. Velocity of inward radial motion of the inner edge of the outer radiation zone peak of electron ($E > 1.6$ MeV) intensities as a function of L. A straight line has been drawn through the data points. If these data are fitted with a power law kL^n then $n = 8$ ($\pm$ 1) (see text).

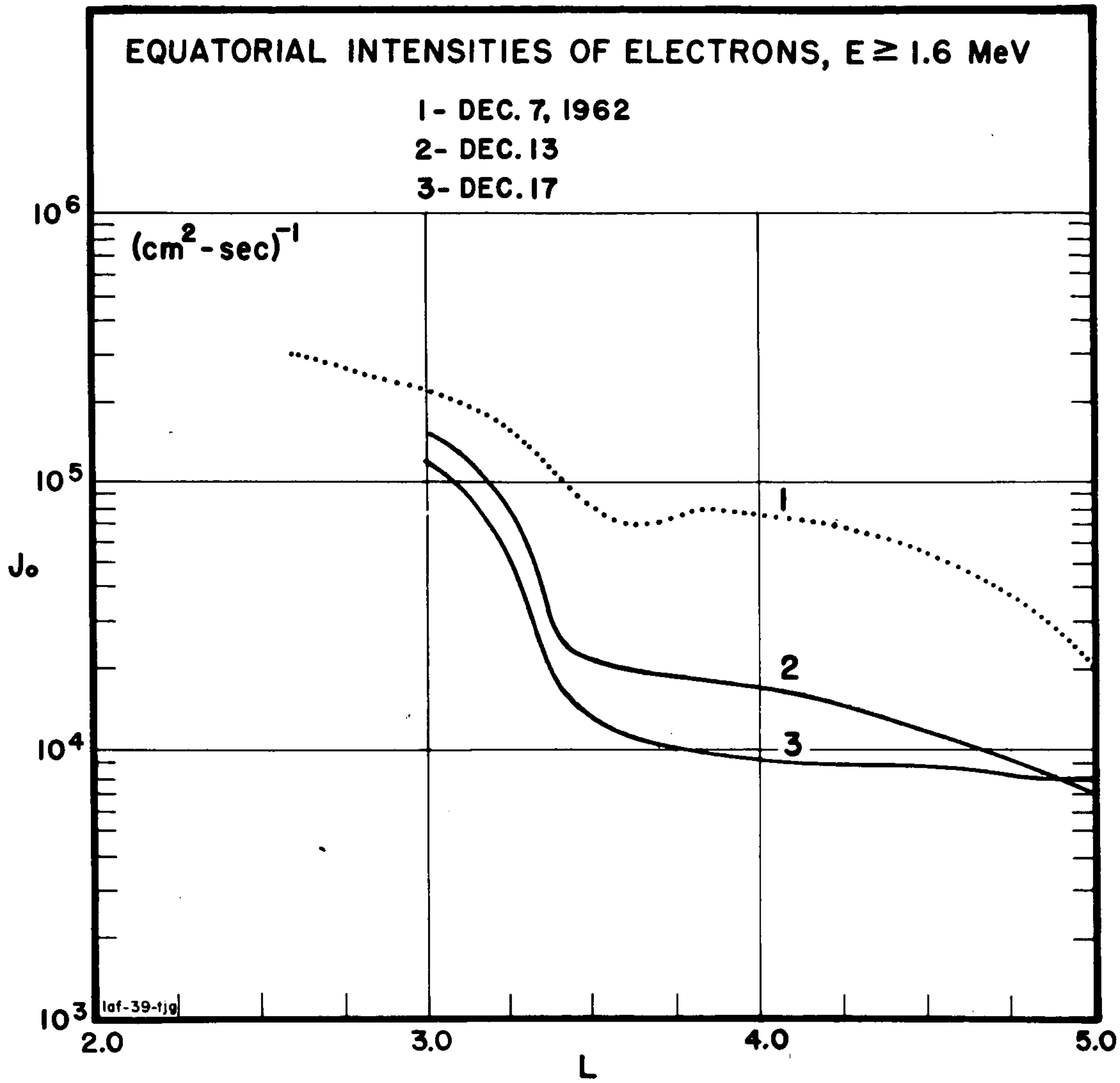
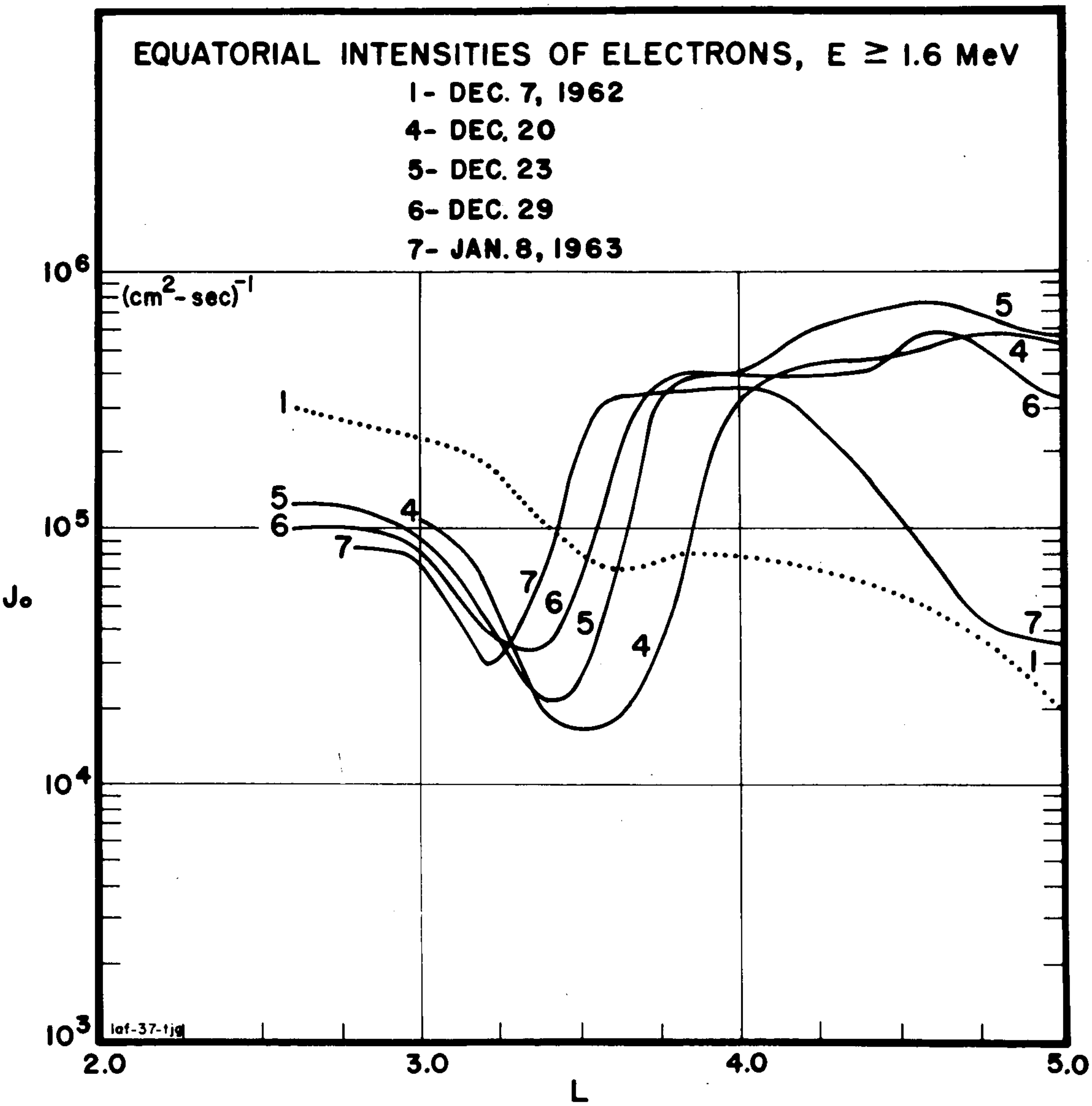
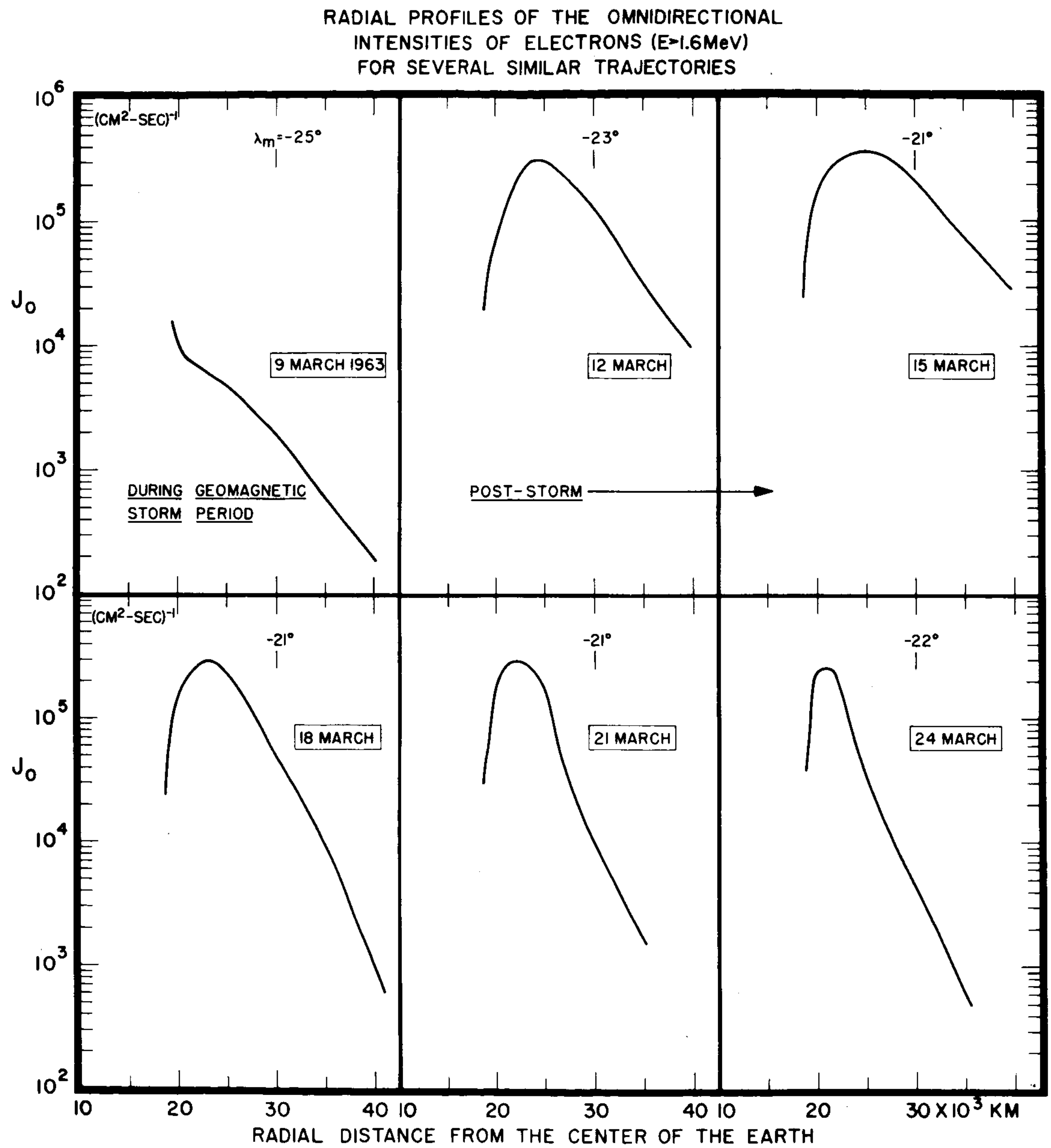

EQUATORIAL INTENSITIES OF ELECTRONS, E ≥ 1.6 MeV
1 - DEC. 7, 1962
2 - DEC. 13
3 - DEC. 17
10^6
$(cm^2\text{-}sec)^{-1}$
10^5
J_o
10^4
10^3
laf-39-fjg
1
2
3
2.0
3.0
4.0
5.0
L

FIGURE 1



EQUATORIAL INTENSITIES OF ELECTRONS, E ≥ 1.6 MeV
1- DEC. 7, 1962
4- DEC. 20
5- DEC. 23
6- DEC. 29
7- JAN. 8, 1963
(cm²-sec)⁻¹
Jo
10⁶
10⁵
10⁴
10³
2.0
3.0
4.0
5.0
L
1
4
5
6
7
laf-37-tjg

FIGURE 2



RADIAL PROFILES OF THE OMNIDIRECTIONAL
INTENSITIES OF ELECTRONS (E>1.6MeV)
FOR SEVERAL SIMILAR TRAJECTORIES
(CM2-SEC)-1
λ_m=-25°
-23°
-21°
9 MARCH 1963
12 MARCH
15 MARCH
DURING GEOMAGNETIC STORM PERIOD
POST-STORM
-21°
-21°
-22°
18 MARCH
21 MARCH
24 MARCH
J_0
10^6
10^5
10^4
10^3
10^2
10
20
30
40
30 X 10³ KM
RADIAL DISTANCE FROM THE CENTER OF THE EARTH

FIGURE 3

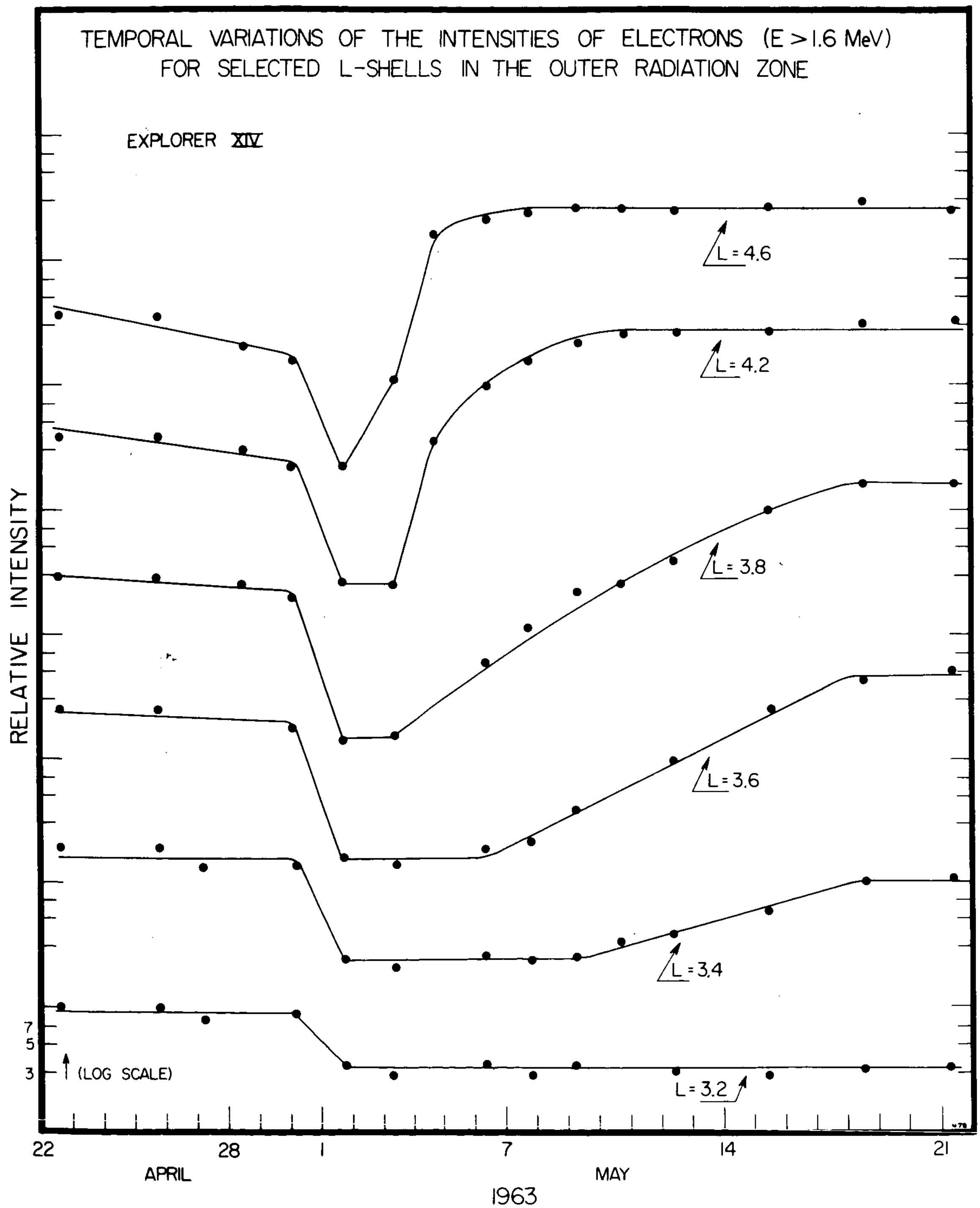
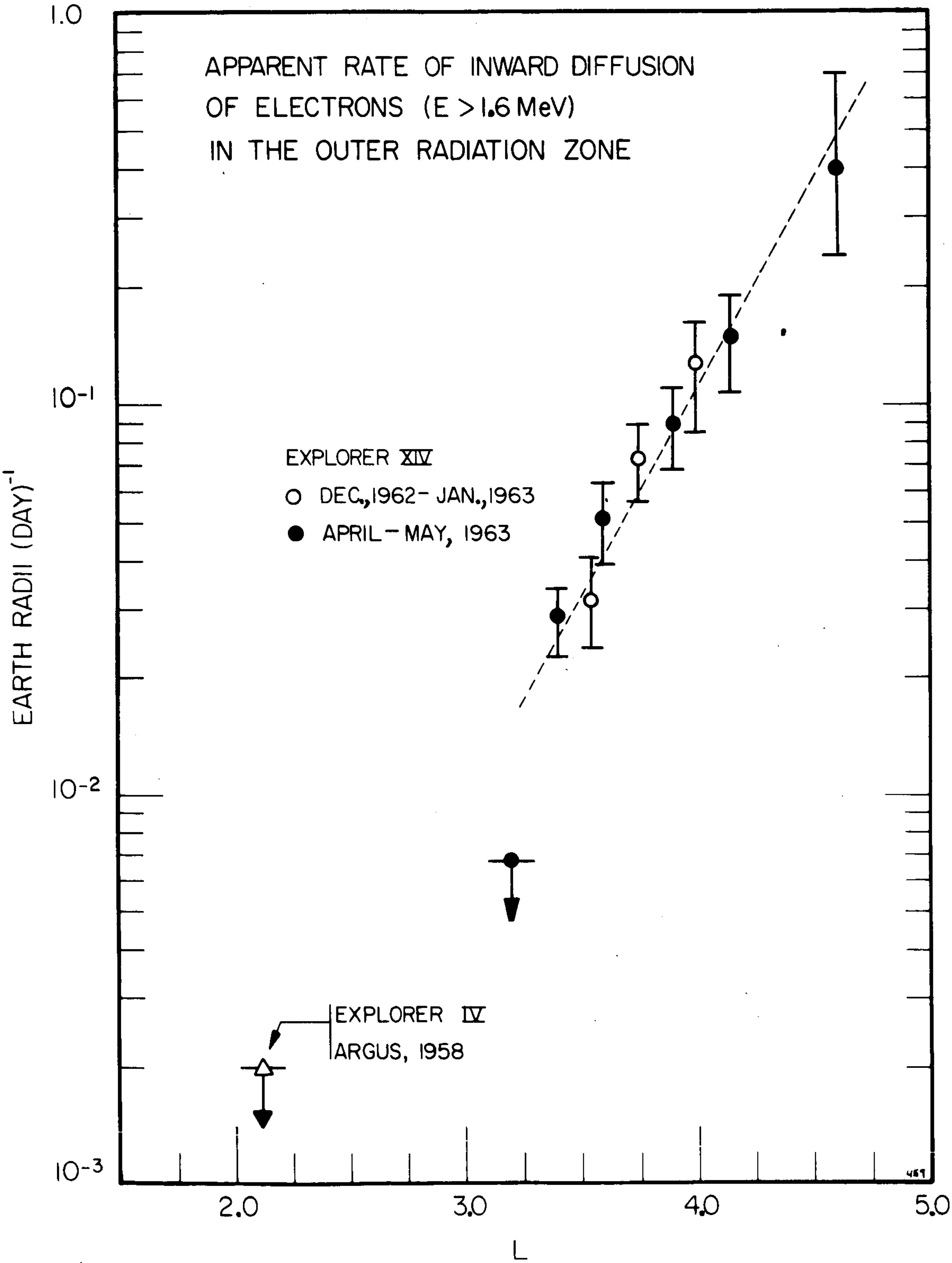

TEMPORAL VARIATIONS OF THE INTENSITIES OF ELECTRONS (E > 1.6 MeV)
FOR SELECTED L-SHELLS IN THE OUTER RADIATION ZONE
EXPLORER XIV
RELATIVE INTENSITY
L = 4.6
L = 4.2
L = 3.8
L = 3.6
L = 3.4
L = 3.2
7
5
3
(LOG SCALE)
22
28
1
7
14
21
APRIL
MAY
1963

FIGURE 4



APPARENT RATE OF INWARD DIFFUSION
OF ELECTRONS (E > 1.6 MeV)
IN THE OUTER RADIATION ZONE
EXPLORER XIV
DEC., 1962 - JAN., 1963
APRIL - MAY, 1963
EXPLORER IV
ARGUS, 1958
EARTH RADII (DAY)$^{-1}$
1.0
10^{-1}
10^{-2}
10^{-3}
2.0
3.0
4.0
5.0
L

FIGURE 5