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On the Local-Time Dependence of Outer Radiation Zone Electron ($E > 1.6$ MeV) Intensities Near the Magnetic Equator*

by

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ABSTRACT

A study of approximately 10 months of Explorer 14 observations of energetic electrons ($E > 1.6$ MeV) in the outer radiation zone near the geomagnetic equator $|\lambda_m| < 25°$ shows that if the omnidirectional intensity measurements are organized in a B-L system based upon surface measurements of the geomagnetic field, a large local-time dependence of intensities on a given L-shell is observed beyond $L \simeq 6$. The 'average' isoflux contour $J_o = 10^2$ $(cm^2\text{-sec})^{-1}$ in a L-local time coordinate system is at $L \simeq 10$ (maximum L) and at $L \simeq 8$ (minimum L) near the local noon and midnight meridians, respectively. For the contours of higher intensities (and hence smaller radial distances) this local-time variation weakens; for $J_o = 10^4$ $(cm^2\text{-sec})^{-1}$, maximum $L \simeq 7$ near local noon, minimum $L \simeq 6$ near local midnight. A geostationary satellite at 6.6 R_E (earth radii) should observe an average diurnal variation in electron ($E > 1.6$ MeV) intensity by a factor ~ 50. At higher magnetic latitudes, $|\lambda_m| > 25°$, near local noon, the electron ($E > 1.6$ MeV) intensity profiles were often not monotonically decreasing with increasing radial distance beyond ~ 5 R_E as were the profiles at lower magnetic latitudes but displayed frequent secondary peaks of intensity

from 5 to 12 R_E which may be indicative of an acceleration mechanism for energetic electrons $E \gtrsim 1$ MeV in the local day portion of the magnetosphere. The diurnal variations of electron ($E > 1.6$ MeV) intensities observed near the geomagnetic equatorial plane are consistent with the expected distortion of the geomagnetic field in these regions by the solar wind.

I. INTRODUCTION

The distortion of the geomagnetic field by the flow of plasma, or solar wind, past the earth has been actively investigated by Chapman and Ferraro [1931, 1933], Dungey [1958], Beard [1960, 1962], Midgley and Davis [1963], Mead [1964], and others. Recent direct measurements of the distant geomagnetic field have shown that the geomagnetic field is terminated at ~ 10 R_E (earth radii) geocentric radial distance along the earth-sun direction [Cahill and Amazeen, 1963; Ness et al., 1964], that the radial distance to this boundary, or magnetopause, increases to ~ 15 R_E for measurements obtained near the local morning meridian, and that the geomagnetic field on the night side of the earth is drawn out in the anti-solar direction to beyond 30 R_E and is characterized by a neutral sheet near the solar-magnetospheric equatorial plane [Ness, 1964]. Such large distortions of the geomagnetic field must in turn be reflected in the spatial distributions of charged particles in the magnetosphere [Malville, 1960; Hones, 1963; Fairfield, 1964]; the convenient B and L coordinates [McIlwain, 1961] as derived from a surface expansion of the geomagnetic field lose much of their effectiveness beyond L ~ 6. Since low-altitude (~ 1,000 km) observations of trapped and of precipitated charged particles are related to phenomena occurring in the distant magnetosphere via the geomagnetic lines of force diurnal variations in the intensities of these particles are to be expected and have been observed [O'Brien, 1963; Frank et al., 1964; McDiarmid and Burrows, 1964; Williams and Palmer, 1965]. In situ measurements of local-time asymmetries in the spatial distribution of charged particles in the distant magnetosphere have been obtained by Frank et al. [1963], Frank [1965], Anderson et al. [1965], and others. The present investigation discusses the local-time dependence of the radial extent of energetic electron ($E > 1.6$ MeV) intensities in the outer radiation zone near the geomagnetic equator observed with Explorer 14.

II. EXPERIMENT DESCRIPTION

The longevity of Explorer 14 (effectively continuous transmission of data from 2 October 1962 to 8 August 1963) and its highly eccentric orbit (apogee altitude 98,533 km and perigee altitude 283 km at launch) allowed a unique survey of the outer radiation zone with respect to a nearly complete local-time survey of outer zone phenomena over a large range of geocentric radial distances and near the geomagnetic equatorial plane utilizing the same instrumentation. The SUI detector complement of Geiger-Mueller tubes included a shielded 302 G.M. tube ($\epsilon G = 0.1$ ($\pm$ 0.05) cm^2 for counting electrons $E > 1.6$ MeV for typical outer zone electron spectrums) and adequate simultaneous measurements of the intensities of lower energy ($E > 40$ keV) electrons to ascertain that this detector was not responding to electron bremsstrahlung (see Frank, Van Allen, and Hills [1964] for a detailed description of this instrumentation).

III. OBSERVATIONS

Observations of magnetospheric phenomena with Explorer 14 include approximately 300 passes with reasonably continuous telemetry coverage through the outer radiation zone. Of present interest are representative sets of contours of the shielded 302 G.M. tube response to penetrating, outer zone electrons ($E > 1.6$ MeV) as a function of geocentric radial distance for selected ranges of magnetic latitude and of local time of satellite apogee position. Figure 1 displays a set of five contours obtained over the period 21-28 February 1963 when the direction from the center of the earth to satellite apogee position (local time ~ 22:00) was near the anti-solar direction. The relative response of the 302 G.M. tube is shown in Figure 1 (and the following Figures 2 and 3), but the true counting rate of the detector may be determined by noting that the cosmic ray background rate (dashed line) corresponds to 1.6 counts $(sec)^{-1}$. Both inbound and outbound passes have been included in Figure 1 (solar-ecliptic latitudes of ~ -10° and -40°, respectively, at 75,000 km geocentric radial distance) and passes with various low magnetic latitudes have been included in order to provide an abridged catalog of typical profiles near the magnetic equatorial plane. The radial extent of measurable response of the 302 G.M. tube over background counting rates in Figure 1 on the night side of the earth near the magnetic equatorial plane is typically $\sim$ 50,000-60,000 km for the range of magnetic latitudes sampled, or if a B-L coordinate system as derived from magnetic field measurements at the surface of the earth [McIlwain, 1961] is adopted the corresponding $L \sim 8$. Use of the convenient B-L coordinates in the present investigation is to provide a charged particle coordinate system based upon surface measurements of the earth's magnetic field which, assuming negligible electric drift terms, rapid diffusion (on a time scale $\lesssim$ one longitudinal drift period), etc., in turn yields an indirect test of the distortion of the geomagnetic field by requiring a degeneracy in the observed omnidirectional intensities of charged particles on a given L-shell with respect to local time and also to $\lambda_m = -\lambda_m$ (i.e., symmetry with respect to the geomagnetic equator). Asymmetry of the isoflux contours of electrons ($E > 1.6$ MeV) with respect to the geomagnetic equator beyond $\sim 6\ R_E$ at low latitudes has already been observed [Frank, 1965]; the present investigation is concerned with the isoflux contours near the magnetic equatorial plane as a function of local time. The small secondary peak of intensities at 45,000 to 60,000 km for the contour of 21-22 February 1963 of Figure 1 is typical of several contours obtained by Explorer 14 on the night of the earth but are much more commonly observed for high latitude passes near the local noon meridian (cf. Figure 3). The radial extent of measurable electron ($E > 1.6$ MeV) intensities near the magnetic equator near the local noon meridian observed during the period 30 May--15 June 1963 as shown in Figure 2 is typically 70,000 to 80,000 km ($L \simeq 12$). Further comparison with Figure 1 which displays typical profiles near the midnight meridian at similar magnetic latitudes shows that the midnight profiles rise significantly more rapidly as a function of radial distance than the profiles near local noon of Figure 2. The profiles at a given local time and range of magnetic latitude show a high degree of consistency in their gross characteristics. Hence it is of interest to summarize the large body of Explorer 14 measurements as exemplified above in terms of isoflux contours near the geomagnetic equatorial plane in a geocentric radial distance (or L)--local time coordinate system.

Although the present investigation stresses measurements of the intensities of electrons ($E > 1.6$ MeV) near the geomagnetic equatorial plane, a few samples of typical profiles at the higher magnetic latitudes reached by Explorer 14 near the local noon meridian are displayed in Figure 3. The time period over which this data is taken is 29 May--19 June, or the same general period as the lower latitude data of Figure 2. Comparison of the profiles of Figures 2 and 3 shows that the radial extent of observable intensities is ~ 70,000 to 80,000 km in both cases but that the frequently irregular contours at higher latitudes of Figure 3 are contrasted with the smooth profiles at the lower latitudes of Figure 2. The 302 G.M. tube counting rate profile obtained with Pioneer 4 [Van Allen and Frank, 1959] which carried a similarly shielded 302 G.M. tube through the day side of the magnetosphere is reminiscent of the profiles of 29 May, 4 and 10 June (Figure 3) with Explorer 14. The irregular and variable structure of the profiles of electrons ($E > 1.6$ MeV) at the higher latitudes from ~ 30,000 km to ~ 80,000 km may be indicative of a strong acceleration mechanism for energetic electrons in the local day portion of the magnetosphere.

The local-time dependence of the intensities of electrons ($E > 1.6$ MeV) near the geomagnetic equatorial plane is investigated here by inspecting each of the counting rate profiles such as those displayed in Figures 1 and 2 and determining the maximum L-value at which a given omnidirectional intensity is observed. If the B-L coordinate system based upon surface measurements of the geomagnetic field is valid for organizing the observed spatial distributions of electrons the median L-value at which a given intensity is observed should be independent of the local time of the satellite position. Figure 4 shows the maximum L-values for which omnidirectional intensities of electrons ($E > 1.6$ MeV) $J_o = 10^2\ (cm^2 - sec)^{-1}$ were observed for all passes $|\lambda_m| < 25°$ and for which continuous data were available through the outer radiation zone, as a function of local time of the measurement; each of the 155 data points represents an individual pass of Explorer 14 through the outer radiation zone. Although there is a large scatter of the data, the two-hour median L-value shows a continuous and discernible dependence upon local time. The median L-value for $J_o = 10^2\ (cm^2 - sec)^{-1}$ at local noon is $L \simeq 10$ and the corresponding median L-value near the local midnight meridian is $L \simeq 8$ in the vicinity of the geomagnetic equator, and the temporal variations are from $L \simeq 8$ to 11 and from $L \simeq 5$ to 10, respectively. Since the time period covered by the observations of Figure 4 is ~ 10 months and the satellite apogee position as a function of local time sweeps slowly from ~ 8:00 at launch through local midnight (late January 1963) to ~ 10:00 in early August, it is of interest to determine whether a variation in relative magnetic activity is adequate to account for the local-time dependence of the median L-value ($J_o = 10^2\ (cm^2 - sec)^{-1}$). In Figure 5 are plotted the data points of Figure 4, one graph showing the maximum L value at which $J_o = 10^2\ (cm^2 - sec)^{-1}$ was observed versus the corresponding Kp daily sum, $\sum$ Kp, and the right-hand graph showing $\sum$ Kp as a function of local time for each observation. These graphs display a scatter of data points (corresponding medians are given in Figure 5) which indicates that the observed difference in the median L-value of the intensities of electrons ($E > 1.6$ MeV), $\Delta L \simeq 2$, in the solar and antisolar directions is not a manifestation of a correlation of geomagnetic activity with local time of the observation. Roughly the dependence of the L-value for which $J_o = 10^2\ (cm^2 - sec)^{-1}$ upon $\sum$ Kp is ~ 0.05 L (unit $\sum$ Kp$)^{-1}$.

A polar summary of the median L-values near the magnetic equatorial plane as a function of local time is shown in Figure 6 for omnidirectional electron ($E > 1.6$ MeV) intensities $J_o = 10^2$, 3×10^2, 10^3 and 10^4 $(cm^2 - sec)^{-1}$. The largest local-time effect is at the higher L-values for $J_o = 10^2$ $(cm^2 - sec)^{-1}$ with a noon-midnight median L-value difference $\Delta L \simeq 2$. For higher intensities, and hence at lower L-values, this effect diminishes with a local-time variation $\Delta L \lesssim 1$ (local noon $L \simeq 7$, local midnight $L \simeq 6$) for an omnidirectional intensity $J_o = 10^4$ $(cm^2 - sec)^{-1}$. The systematic variation of the median L-value upon local time is evident for each of the isoflux contours of Figure 6 with larger L-values near local noon with respect to observations near the midnight meridian.

IV. DISCUSSION

The present analysis of 155 Explorer 14 passes through the outer radiation zone near the geomagnetic equator ($|\lambda_m| < 25°$) obtained over a period of ~ 10 months shows that, if a B-L coordinate system based upon surface measurements of the geomagnetic field is used to organize the data, a local-time dependence of the intensities of electrons ($E > 1.6$ MeV) is observed on L-shells with $L \gtrsim 6$. If this local-time dependence is found by determining the median of all maximum L-values for which $J_o = 10^2$ $(cm^2 - sec)^{-1}$, for example, and for a given two-hour local-time sector then the maximum $L \simeq 10$ occurs near local noon and the minimum $L \simeq 8$ is near the local midnight meridian. The magnitude of this local-time variation decreases with increasing omnidirectional intensity J_o and for $J_o = 10^4$ $(cm^2 - sec)^{-1}$, $L \simeq 7$ and $\simeq 6$ near local noon and midnight, respectively (refer to summary of Figure 6). A geo-stationary satellite at 6.6 R_E should observe an average diurnal intensity variation by a factor ~ 50. Although the B-L coordinate system has been used here to organize the observations of electrons ($E > 1.6$ MeV), the data are taken near the geomagnetic equator $|\lambda_m| < 25°$ and detailed examination of passes at lower latitudes (refer to Figures 1 and 2) shows that the above L-values and the median L-values of Figure 6 may be interpreted as the geocentric radial distance in earth radii in the geomagnetic equatorial plane to the corresponding isoflux contours. Hence the isoflux contour $J_o = 10^2\ (cm^2 - sec)^{-1}$ is at $\simeq 10\ R_E$ at local noon and draws nearer to the earth by $\sim 2\ R_E$ near the geomagnetic equator at local midnight. Observed temporal variations in the maximum L-values at which a given electron ($E > 1.6$ MeV) omnidirectional intensity is observed are large, from $L \simeq 8$ to 11 and from $L \simeq 5$ to 10 near the local noon and midnight meridians, respectively, for $J_o = 10^2\ (cm^2 - sec)^{-1}$. The measurements of energetic electrons of similar energies by Pioneers 3 and 4 and Explorers 6 and 12 near the geomagnetic equator and at various local times (refer to discussions given in Frank, Van Allen, and Macagno [1963] and Frank and Van Allen [1964 a]) are consistent with the above extensive survey. Diurnal variations of the intensities of trapped energetic electrons ($E > 280$ keV) at low altitudes ~ 1100 km have been observed by Williams and Palmer [1965]; for example, their results show that the position of an isoflux curve at $L \simeq 9$ near local noon is at $L \simeq 7$ near local midnight during magnetic quiet in good agreement with the local-time dependence near the geomagnetic equator as determined by the present investigation.

The present observation of a local-time dependence of the intensities of electrons ($E > 1.6$ MeV) in the outer radiation zone beyond $L \simeq 6$ near the geomagnetic equatorial plane is presumably related to the distortion of the geomagnetic field by the solar wind. The motion of charged particles in a realistic model of the distorted geomagnetic field for $L \lesssim 10$ shows, for example, that if an electron $E \sim 1$ MeV with second adiabatic invariant of motion $I = 0$ (i.e., mirroring in the geomagnetic equatorial plane) is initially at 7.5 R_E at the local noon meridian, then the corresponding position along its longitudinal drift path at local midnight will be at ~ 6 R_E [Hones, 1963]. This result is in quantitative agreement with our present observations of the isoflux contours of electrons ($E > 1.6$ MeV) near the geomagnetic equatorial plane although the extension of the above theoretical result for the motion of a single particle to the present observation of isoflux curves demands, of course, that realistic equatorial pitch angle distributions as a function of radial distance be assumed in order to calculate the isoflux curves in a L-local time coordinate system. The assumption that the observed local-time effect is primarily a manifestation of the distortion of geomagnetic field by the solar wind is based upon the fact that the gradient drift velocity is proportional to the energy of the particle (or more precisely the first adiabatic invariant μ) and for charged particles $E \gtrsim 1$ MeV is considerably larger than the drift expected due to electric fields in any reasonable current magnetospheric model. A further tacit assumption is that rapid radial diffusion and/or a combination of loss and source mechanisms are not effective on a time scale of the longitudinal drift period in these regions ($\lesssim 10$ minutes); i.e., the electrons are durably trapped in the geomagnetic field. It is of interest to note that the termination of observable electron ($E > 1.6$ MeV) intensities (cf. Figures 2 and 3) corresponds closely with the position of the magnetospheric boundary near the local noon meridian [Frank and Van Allen, 1964 b].

The radial profiles of the intensities of electrons ($E > 1.6$ MeV) at low latitudes ($|\lambda_m| < 25°$) which provided the above local-time survey discussed above were usually characterized by monotically decreasing intensities beyond 5 R_E. Observations at higher magnetic latitudes (cf. Figures 2 and 3) during local day often displayed small multiple peaks of intensity from 5 to 12 R_E and may reflect an active acceleration mechanism for energetic outer zone electrons in these regions.

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FIGURE CAPTIONS

Figure 1. Relative response of the 302 G.M. tube for several passes of Explorer 14 through the outer radiation zone near the geomagnetic equator. Local time of the satellite apogee position is ~ 22:00. Cosmic ray background rate is 1.6 counts $(\mathrm{sec})^{-1}$.

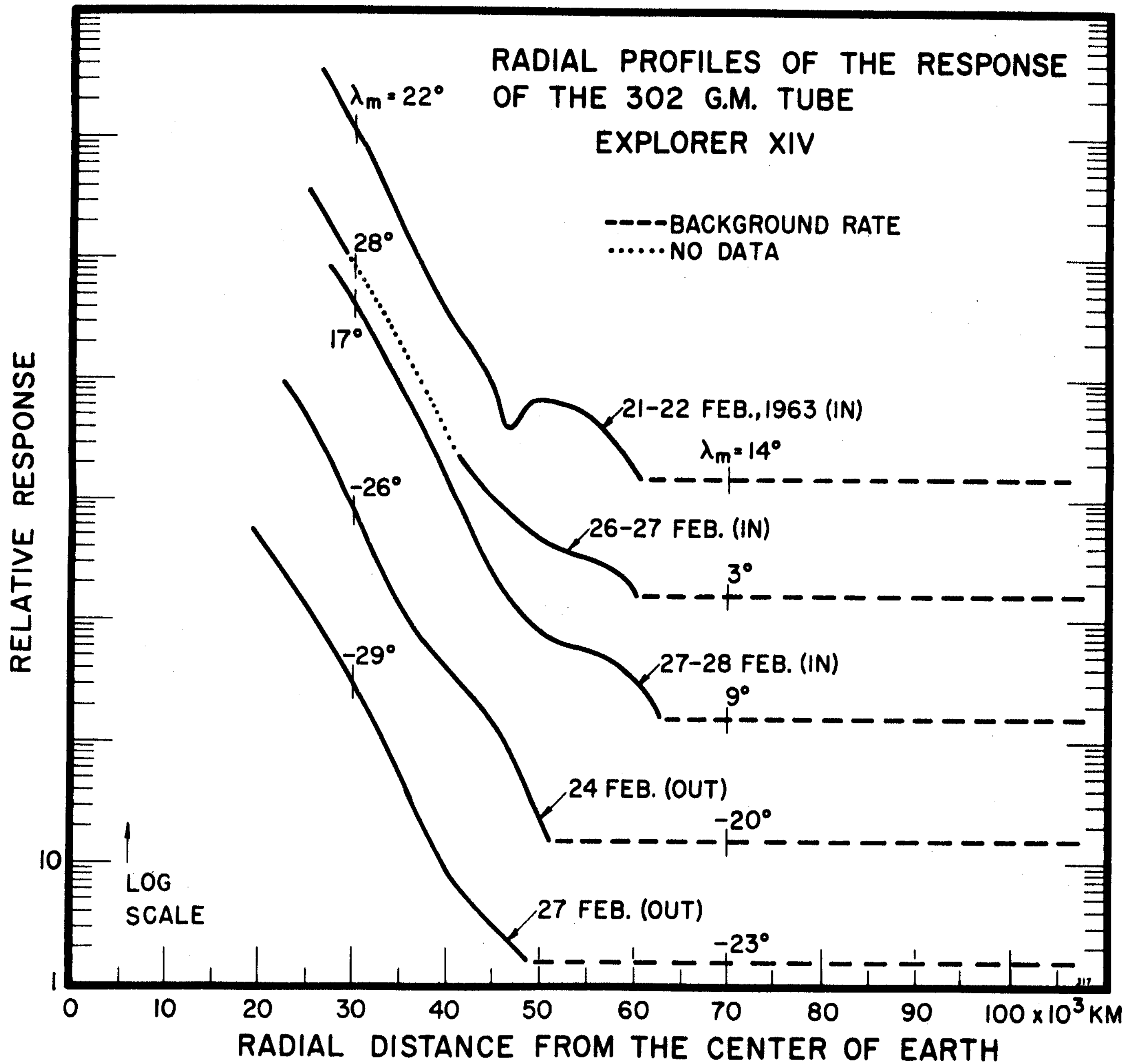
Figure 2. Continuation of Figure 1 for the period when the local time of the satellite apogee position is ~ 14:00.

Figure 3. Continuation of Figure 2 but for passes with higher magnetic latitudes.

Figure 4. The maximum L-value for which an electron ($E > 1.6$ MeV) omnidirectional intensity $J_c = 10^2\ (\mathrm{cm}^2 - \mathrm{sec})^{-1}$ was observed versus the local time of the observation. Each data point represents an individual pass of Explorer 14 through the outer radiation zone ($B/B_o \leq 2$).

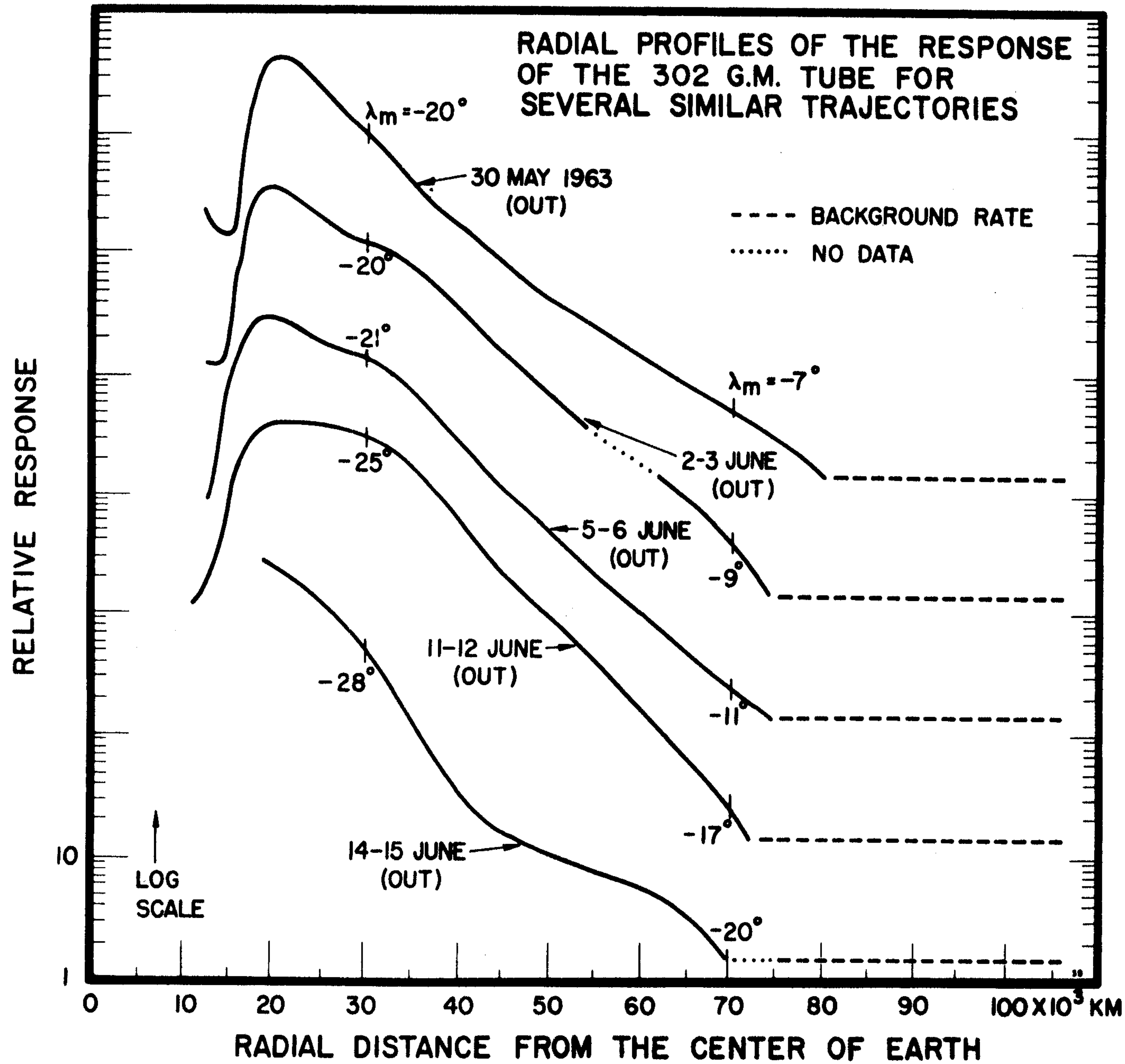
Figure 5. Scatter plot of parameters associated with the observations of Figure 4.
Left: Maximum L-value for which an omnidirectional electron ($E > 1.6$ MeV) intensity $J_o = 10^2\ (\mathrm{cm}^2 - \mathrm{sec})^{-1}$ was observed versus the corresponding Kp daily sum $\sum$ Kp.
Right: $\sum K_p$ versus the local time for each measurement.

Figure 6. Summary of the median L-values for omnidirectional electron ($E > 1.6$ MeV) intensities $J_o = 10^2$, 3×10^2, 10^3, and $10^4\ (\mathrm{cm}^2 - \mathrm{sec})^{-1}$ near the geomagnetic equatorial plane ($B/B_o \leq 2$) for two-hour local-time intervals.



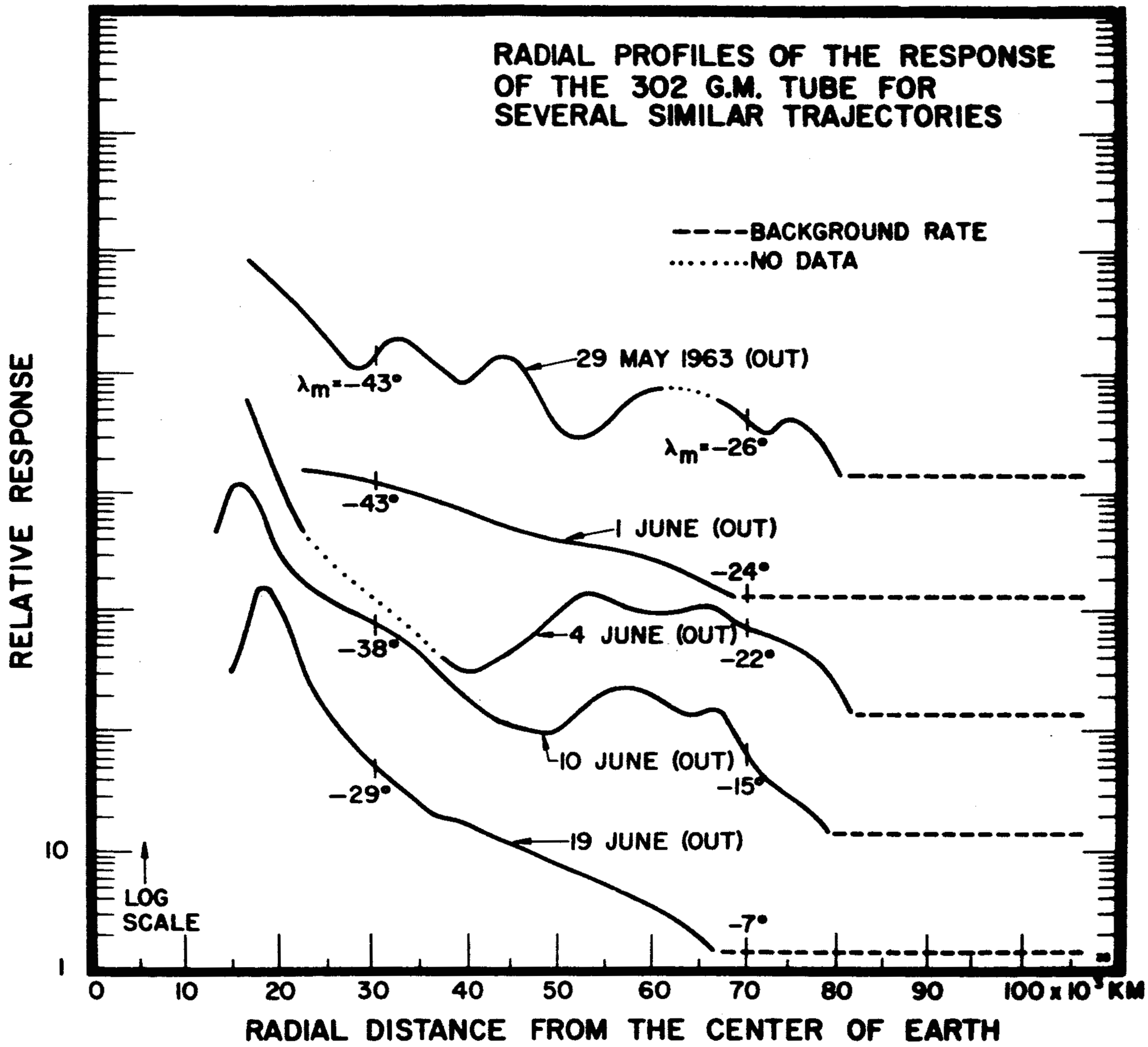
RADIAL PROFILES OF THE RESPONSE
OF THE 302 G.M. TUBE
EXPLORER XIV
BACKGROUND RATE
NO DATA
$\lambda_m = 22°$
28°
17°
-26°
-29°
21-22 FEB., 1963 (IN)
$\lambda_m = 14°$
26-27 FEB. (IN)
3°
27-28 FEB. (IN)
9°
24 FEB. (OUT)
-20°
27 FEB. (OUT)
-23°
RELATIVE RESPONSE
10
1
LOG
SCALE
0
10
20
30
40
50
60
70
80
90
100 x 10³ KM
RADIAL DISTANCE FROM THE CENTER OF EARTH

Figure 1



RADIAL PROFILES OF THE RESPONSE OF THE 302 G.M. TUBE FOR SEVERAL SIMILAR TRAJECTORIES
BACKGROUND RATE
NO DATA
$\lambda_m = -20°$
30 MAY 1963 (OUT)
-20°
-21°
-25°
-28°
2-3 JUNE (OUT)
5-6 JUNE (OUT)
11-12 JUNE (OUT)
14-15 JUNE (OUT)
$\lambda_m = -7°$
-9°
-11°
-17°
-20°
LOG SCALE
RELATIVE RESPONSE
10
1
0
10
20
30
40
50
60
70
80
90
100×10^3 KM
RADIAL DISTANCE FROM THE CENTER OF EARTH

Figure 2



RADIAL PROFILES OF THE RESPONSE OF THE 302 G.M. TUBE FOR SEVERAL SIMILAR TRAJECTORIES
----BACKGROUND RATE
........NO DATA
29 MAY 1963 (OUT)
λm=-43°
λm=-26°
-43°
1 JUNE (OUT)
-24°
4 JUNE (OUT)
-38°
-22°
10 JUNE (OUT)
-15°
-29°
19 JUNE (OUT)
-7°
RELATIVE RESPONSE
10
1
LOG SCALE
0
10
20
30
40
50
60
70
80
90
100 x 10³ KM
RADIAL DISTANCE FROM THE CENTER OF EARTH

Figure 3

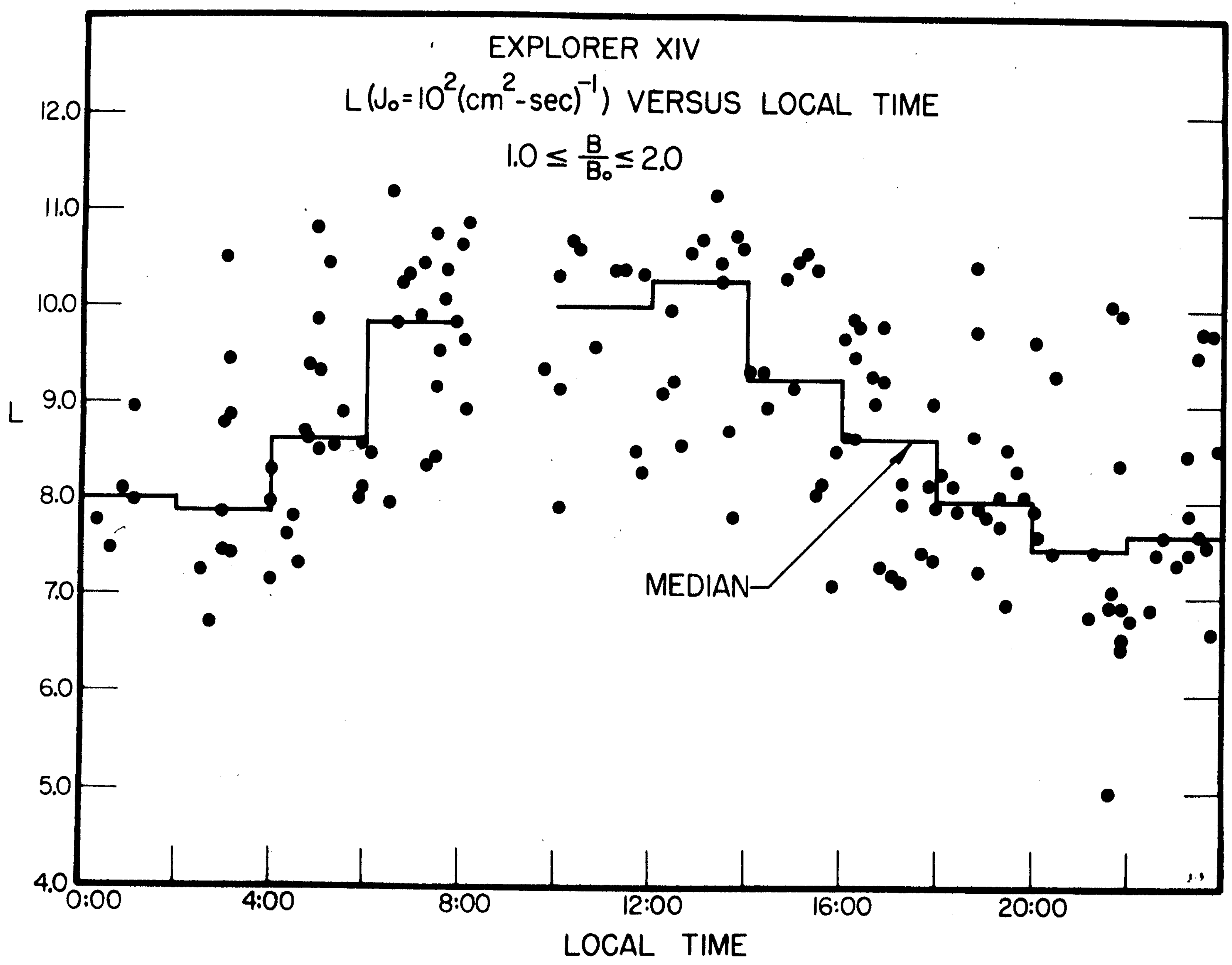
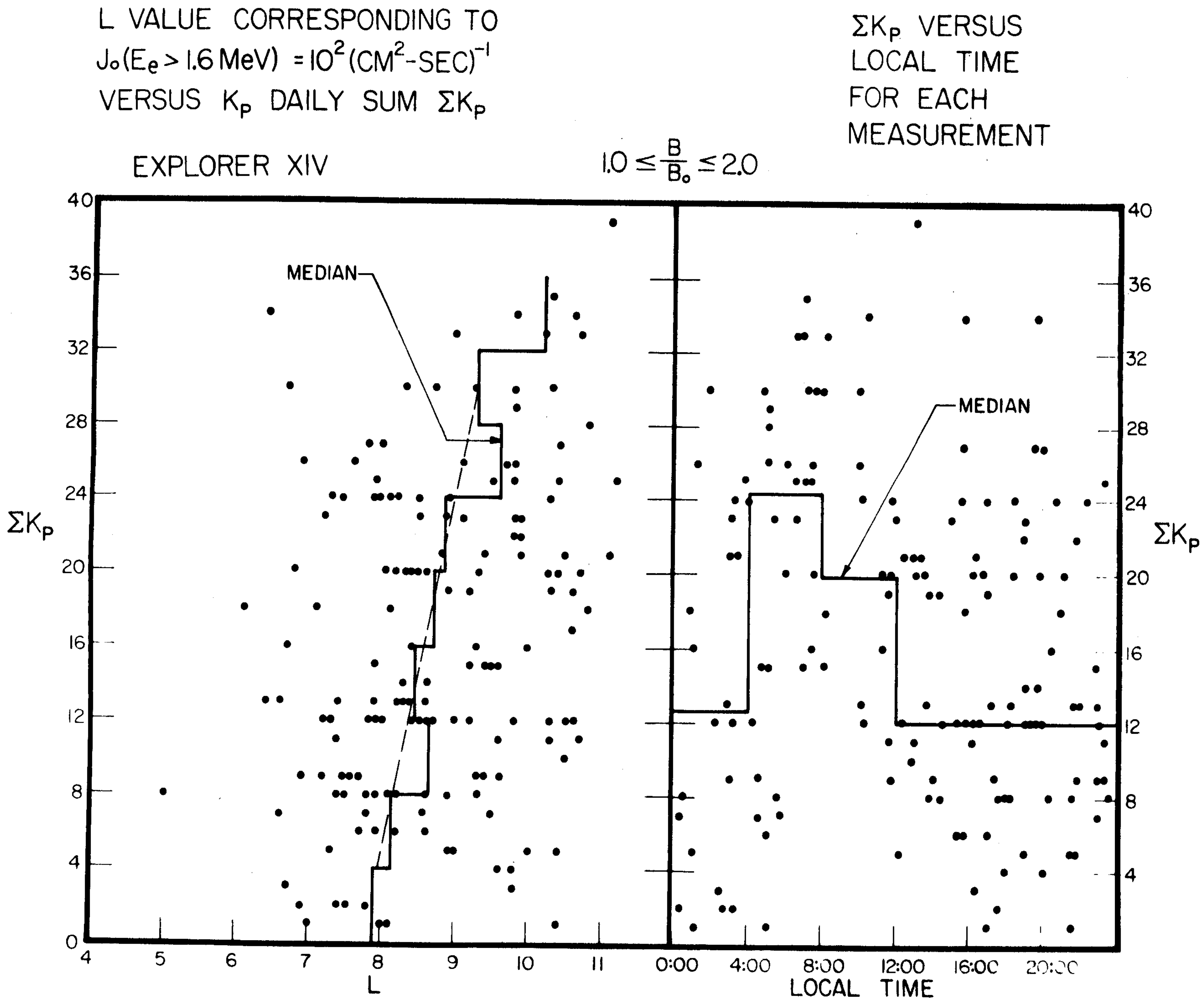

EXPLORER XIV
L (J_o=10^2(cm^2-sec)$^{-1}$) VERSUS LOCAL TIME
$1.0 \leq \frac{B}{B_o} \leq 2.0$
L
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
0:00
4:00
8:00
12:00
16:00
20:00
MEDIAN
LOCAL TIME

Figure 4



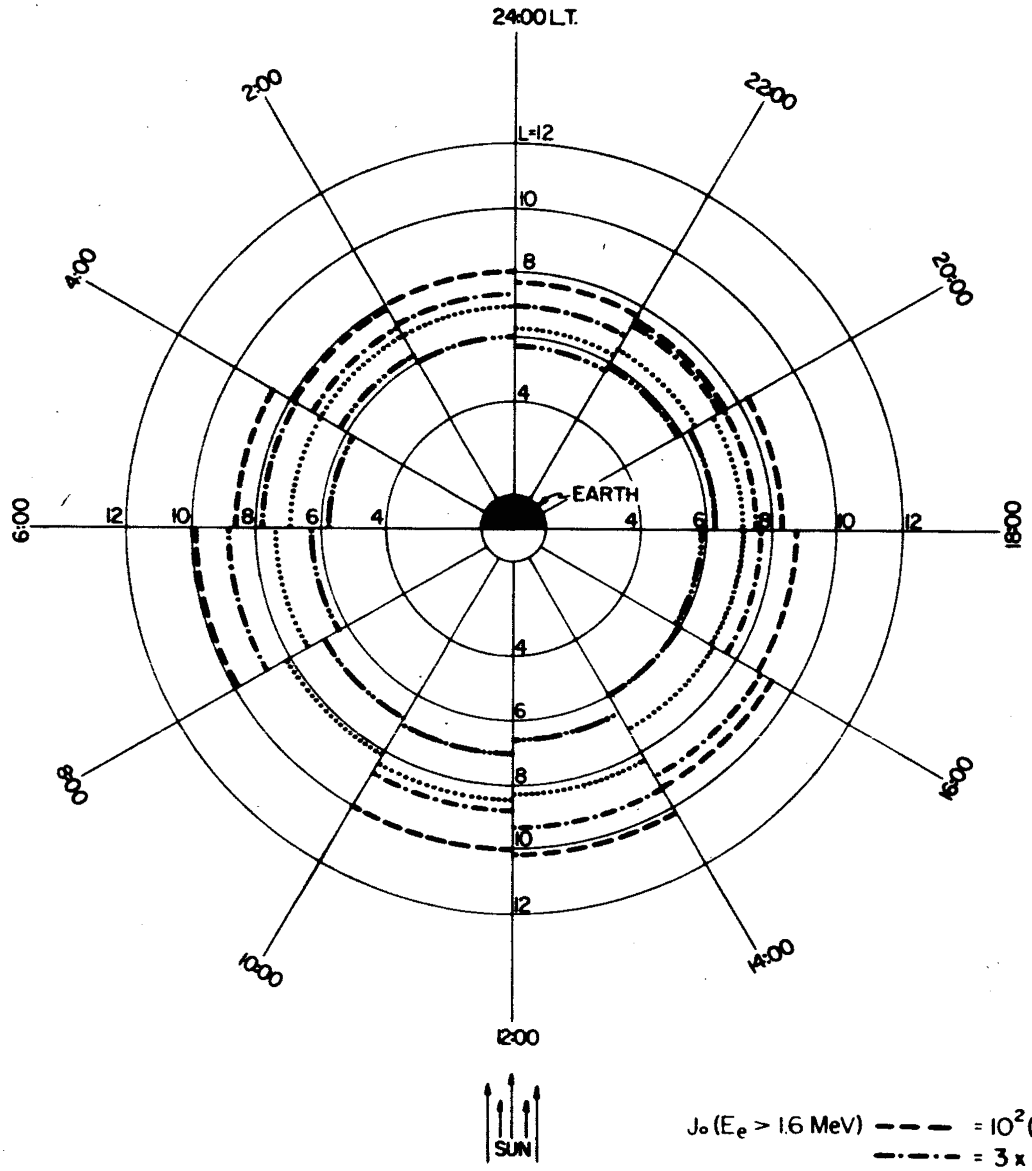
L VALUE CORRESPONDING TO
$J_o(E_e > 1.6\,MeV) = 10^2 (CM^2\text{-}SEC)^{-1}$
VERSUS K_p DAILY SUM ΣK_p
EXPLORER XIV
$1.0 \le \frac{B}{B_o} \le 2.0$
ΣK_p VERSUS
LOCAL TIME
FOR EACH
MEASUREMENT
MEDIAN
MEDIAN
ΣK_p
ΣK_p
L
LOCAL TIME
0
4
8
12
16
20
24
28
32
36
40
4
5
6
7
8
9
10
11
0:00
4:00
8:00
12:00
16:00

Figure 5

MEDIAN L VALUES FOR SEVERAL
ELECTRON (E_e > 1.6 MeV) ISOFLUX CONTOURS
AS A FUNCTION OF LOCAL TIME

$1.0 \le \frac{B}{B_o} \le 2.0$
2-HOUR L.T.
MEDIANS

EXPLORER XIV



J_o (E_e > 1.6 MeV) = 10^2 (cm^2-sec)$^{-1}$
= 3×10^2 (cm^2-sec)$^{-1}$
= 10^3 (cm^2-sec)$^{-1}$
= 10^4 (cm^2-sec)$^{-1}$

Figure 6

UNCLASSIFIED
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13. ABSTRACT

A study of approximately 10 months of Explorer 14 observations of energetic electrons (E > 1.6 MeV) in the outer radiation zone near the geomagnetic equator $|\lambda_m| < 25°$ shows that if the omnidirectional intensity measurements are organized in a B-L system based upon surface measurements of the geomagnetic field, a large local-time dependence of intensities on a given L-shell is observed beyond $L \simeq 6$. The 'average' isoflux contour $J_o = 10^2$ $(cm^2\text{-}sec)^{-1}$ in a L-local time coordinate system is at $L \simeq 10$ (maximum L) and at $L \simeq 8$ (minimum L) near the local noon and midnight meridians, respectively. For the contours of higher intensities (and hence smaller radial distances) this local-time variation weakens; for $J_o = 10^4$ $(cm^2\text{-}sec)^{-1}$, maximum $L \simeq 7$ near local noon, minimum $L \simeq 6$ near local midnight. A geostationary satellite at 6.6 R_E (earth radii) should observe an average diurnal variation in electron (E > 1.6 MeV) intensity by a factor ~ 50. At higher magnetic latitudes, $|\lambda_m| > 25°$, near local noon, the electron (E > 1.6 MeV) intensity profiles were often not monotonically decreasing with increasing radial distance beyond ~ 5 R_E as were the profiles at lower magnetic latitudes but displayed frequent secondary peaks of intensity from 5 to 12 R_E which may be indicative of an acceleration mechanism for energetic electrons $E \gtrsim 1$ MeV in the local day portion of the magnetosphere. The diurnal

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ABSTRACT (continued)

variations of electron ($E > 1.6$ MeV) intensities observed near the geomagnetic equatorial plane are consistent with the expected distortion of the geomagnetic field in these regions by the solar wind.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Outer Radiation Zone						

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