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Department of Physics and Astronomy

THE UNIVERSITY OF IOWA

Iowa City, Iowa 52242

U. of Iowa 75-23

ELECTRON ANGULAR DISTRIBUTIONS

ABOVE THE

DAYSIDE AURORAL OVAL*

by

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June 1975

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[See page following]

Abstract

An electrostatic analyzer, a LEPEDEA, was employed on the low-altitude satellite Ariel-4 in order to gain pitch angle distributions of electron intensities with good temporal resolution within the energy range 205 eV to 12.5 keV over the dayside auroral oval. Two major precipitation zones were encountered -- an equatorward zone of broad spectra with intensities $\sim 10^4$ electrons $(cm^2\text{-sec-sr-eV})^{-1}$ and a poleward zone, the polar cusp, with intensities typical of those of the magnetosheath. Angular distributions within the equatorward zone are generally isotropic outside of the atmospheric backscatter cone. The precipitation mechanism would appear to be pitch angle scattering near the distant magnetic equator. In contrast, pitch angle distributions within the polar cusp are often found to be strongly field aligned with intensities within the atmospheric loss cone greater by factors ~ 10 than the mirroring intensities. These angular distributions within the dayside polar cusp are qualitatively similar to those for the inverted-V precipitation events at later local times, and probably share a common acceleration mechanism with the inverted-V phenomenon.

I. Introduction

There is an increasing body of observational evidence indicating that the luminosities of the auroral oval are excited by two major charged-particle precipitation regimes [cf. Frank and Ackerson, 1972; Frank and Gurnett, 1971; Hultqvist, 1974; Craven and Frank, 1975]. Both precipitation zones are to be found at all local times along the auroral oval with overall temporal and spatial features which are strongly dependent upon the local-time sector of the observation. In brief summary, the equatorward zone of precipitation of electron intensities exhibits filling of the loss cone, and hence 'precipitation', to intensities which approach isotropy or less over the upper hemisphere of pitch angles. This precipitation region is threaded with geomagnetic field lines which are closed within the terrestrial magnetosphere and is fed by the distant plasma sheet and ring current located in the vicinity of the magnetic equatorial plane. The dominant mechanism responsible for the precipitation of these electron intensities appears to be strong pitch angle scattering into the loss cone as effected at or near the equator [cf. Coroniti and Kennel, 1970; Craven and Frank, 1975; Frank et al., 1975]. The corresponding luminosity feature of the auroral oval has been recently identified as the 'diffuse aurora' via global imaging with satellite-borne photometers [Lui and Anger, 1973].

The second, and poleward zone of major electron precipitation is characterized by the presence of the remarkable 'inverted-V' events and strongly field-aligned electron intensities. Traversals of inverted-V events by a satellite at low-altitudes are readily identifiable in energy-time spectrograms of electron intensities as an increase in average electron energy to a maximum energy with a subsequent decrease of these average energies, whence comes the descriptive 'inverted-V' [Frank and Ackerson, 1971]. This poleward zone of electron precipitation is generally contiguous with the aforementioned, less intense equatorward zone; their common boundary is positioned approximately at the 'trapping' boundary for higher energy electrons with $E \geq 40$ keV and a reversal of convection electric fields [Gurnett and Frank, 1973]. Plasma convection velocities are dominantly sunward and antisunward in the equatorward and poleward precipitation regimes, respectively. The discrete auroral arcs which extend from the local noon sector and gain prominence in the local evening and midnight sectors [Buchau et al., 1970] are probably the luminous signature of inverted-V precipitation events. Quasi-static electric fields directed along the geomagnetic field and positioned somewhere in the altitude range of about 1000 kilometers to several earth radii are viable possibilities for accounting for this striking precipitation phenomenon [cf. Kindel and Kennel, 1971; Block, 1972].

Inverted-V electron precipitation events at local evening and midnight are typically broad in latitude width, one to several hundreds of kilometers, and energetic, in the range of kiloelectron volts, relative to their counterparts in the local noon and morning sectors where these parameters usually are merely tens of kilometers and roughly hundreds of electron volts. The corresponding spatial region in the local noon sector is the dayside polar cusp [cf. Frank, 1971; Heikkila and Winningham, 1971; Frank and Ackerson, 1972]. Because of the aforementioned diminutive parameters for the electron precipitation features near local noon it has been difficult to establish the nature of the angular distributions of electron intensities in this sector -- and hence to verify that the mechanism for accelerating electrons is in fact similar to that for the well-developed inverted-V events at later local times. The low-altitude, nearly polar satellite Ariel-4 is well suited to discern these angular distributions of electron intensities due to its short spin period and ground-commanded ability to orient its spin axis nearly perpendicular to the local geomagnetic field for comprehensive surveys of pitch angle distributions.

Plasma analyzers, or LEPEDEA's, were included within the satellite's instrumentation to exploit this opportunity. Indeed, as we shall show here, the angular distributions of electron intensities within the low-altitude polar cusp are similar to those of inverted-V events in the local evening and midnight sectors and appear to share a common acceleration mechanism with their more intense counterparts found at these later local times.

II. Observations

Our measurements of the angular distributions of electron intensities at low altitudes within the dayside polar cusp were acquired with plasma instrumentation on the satellite Ariel-4 of the United States-United Kingdom Cooperative Satellite Program. Ariel 4 was launched on December 11, 1971 into an orbit with initial perigee and apogee altitudes of 472 and 587 km, respectively, and an inclination 83°. Two features of the satellite were especially useful for gaining the measurements of angular distributions reported here. The first advantage was the relatively high spin rate of 32 rpm at launch, which slowly declined to 22 rpm for the period of observations reported here, mid-March 1972. The second useful feature was the inclusion in the satellite hardware of a ground-controlled magnetic torquer which allowed alignment of the spin axis nearly perpendicular to the local geomagnetic field vector at auroral latitudes and hence yielded comprehensive sampling of pitch angle distributions with a single detector. A general description of Ariel 4 and its complement of scientific instruments has been given by Dalziel [1975].

Two plasma analyzers, or LEPEDEA's, were mounted on the Ariel-4 satellite such that the fields-of-view of one analyzer (LEPEDEA 'A') were aligned parallel to the spin axis; those of the second analyzer (LEPEDEA 'B') were directed perpendicular to this spin axis. These electrostatic analyzers are each capable of providing measurements of the directional, differential intensities of protons and electrons, separately and simultaneously, within the energy range 35 eV to 26 keV and with adequate dynamic range and sensitivities for auroral and polar cap phenomena. Each of these two LEPEDEA's was accompanied by a collimated thin-windowed Geiger-Mueller tube with a conical field-of-view of full angular width 30°, which was directed parallel to that of its respective analyzer. These Geiger-Mueller tubes responded primarily to directional intensities of electrons with $E > 40$ keV at auroral latitudes. A more complete description of this instrumentation has been recently presented by Craven and Frank [1975].

This plasma instrumentation could be operated in a variety of telemetry modes available via ground command; and each such mode was tailored to effectively study specific plasma regimes above the auroral oval and polar cap. For the temporal resolution required to discern angular distributions of electron intensities within the polar cusp, the most suitable mode employs almost full dedication of the available telemetry to the electron channel of LEPEDEA 'B' with fields-of-view directed perpendicular to the satellite spin axis and a minor telemetry allotment to its companion Geiger-Mueller tube. This particular mode allowed the electrostatic analyzer to sample the electron energy spectra over the range 205 eV to 12.5 keV with 9 energy passbands centered at 244 eV, 400 eV, 644 eV, 1.07 keV, 1.67 keV, 2.78 keV, 4.38 keV, 6.96 keV and 10.8 keV. These energy passbands were sampled cyclically for 1.745 seconds with 36 telemetered responses for each passband. However, the dwell time on every third passband listed above was twice as long, 3.490 seconds. The satellite motion during the determination of pitch angle distributions within a single energy passband was approximately 14 kilometers. During the period of interest here the spin rate of the satellite was such that samples of electron intensities were telemetered each 6° of rotation and a total rotation of 225° occurred during the passband dwell time of 1.745 seconds. The angular dimensions of the fields-of-view for the LEPEDEA were 8° x 30°, approximately of rectangular geometry, and with the 8° dimension lying in a plane perpendicular to the satellite spin axis. Whereas several such instruments have been previously flown at low altitudes with good energy resolution at a few, fixed pitch angles [cf. Frank and Ackerson, 1971], the principal purposes of the Ariel-4 analyzers were to gain unique pitch angle observations with the necessary sacrifice of energy resolution.

Nonetheless, energy range and coverage were sufficiently maintained to properly identify the major plasma regimes of the auroral zone and polar cap.

The overall character of the principal series of observations presented herein is given by the latitude profiles of electron intensities at selected energies of Figure 1. These measurements were obtained near local noon MLT (magnetic local time) and at altitudes of about 550 km on March 14, 1972. The signatures of electron intensities are typical of many such crossings of the two major precipitation regimes in the local noon sector -- (1) large intensities of low-energy electron intensities at poleward latitudes corresponding to those of the polar cusp, invariant latitudes $\Lambda \simeq 76°$ to $80°$, and (2) less intense, but more energetic electron intensities in a broader zone at $\Lambda \leq 76°$. The pitch angles for these observations are $\alpha = 90°$ (locally mirroring). High-latitude terminations of measurable intensities of electrons with $E > 40$ keV, or 'trapping' boundaries, during this orbit and the two previous orbits at $\sim$ 2145 and 2320 U.T. of the prior day were positioned at $\Lambda \simeq 75°$. The magnetic disturbance index K_p was 2 for the period of observations of Figure 1 during one of the five magnetically quiet days of March. This series of observations was chosen specially for relatively unstructured, quiescent conditions of the polar cusp in order to avoid compromising of the angular distributions via severe temporal and spatial variations of intensities. Of specific interest here are the angular distributions of electron intensities at latitudes both poleward and equatorward of $\Lambda \simeq 76°$.

The distinct characters of electron intensities in these two contiguous precipitation zones are further emphasized by their energy spectra which are summarized in Figure 2. Two differential spectra of electron intensities for pitch angles $\alpha = 90°$ for the precipitation zone equatorward of the polar cusp are shown in the left-hand panel of Figure 2. These spectra are broad with typical maximum intensities $\sim 10^4$ electrons $(cm^2\text{-sec-sr-eV})^{-1}$. Intensities of electrons with $E \geqslant 2$ keV at poleward latitudes are lesser than those encountered at lower latitudes, i.e., a 'softer' spectrum. The background spectra for $E \leqslant 800$ eV identified by vertical dashes in both panels of Figure 2 are present at all latitudes when the spacecraft is sunlit and are presently believed to be due to photoelectrons from the satellite external surfaces. This background intensity is also evident for electron intensities at $E = 244$ eV at $\Lambda \leqslant 76°$ as displayed in the previous Figure 1. In striking contrast to the spectra at lower latitudes are the steep electron spectra with relatively large intensities at low energies within the polar cusp. Three such spectra are given in the right-hand panel of Figure 2. Again the pitch angles for these observations are 90°. There is evidence for an increase of higher energy electron intensities at $E \geqslant 1$ keV within the center of this precipitation zone [cf. Figure 1], which is at least remotely reminiscent of the character of inverted-V electron events found at later local times. Intensities of electrons for this encounter of the low-altitude cusp are roughly similar to those found in the distant magnetosheath [Montgomery *et al.*, 1970]. The electron spectra of Figure 2 clearly demonstrate one of the important features in which these two precipitation zones differ.

These two electron regimes also display disparate character with regard to their angular distributions. Angular distributions of electron intensities in the equatorward zone are either (1) generally isotropic at pitch angles outside of the atmospheric backscatter cone for the higher energies and isotropic over all pitch angles for lower energies or (2) with maximum intensities at $\alpha = 90°$ for the higher energies. Exemplary pitch-angle distributions for the latitude segment $\Lambda = 72.8°$ to $74.1°$ of Figure 1 are shown in Figure 3. For electron energies ≤ 1.67 keV the angular distributions are isotropic over all pitch angles. Medians of intensities are shown for latitude 'buckets' of 20°. For higher electron energies, $E \geq 2.78$ keV, intensities within the backscatter cone at $\alpha \geq 120°$ decrease relative to the isotropic intensities at lesser pitch angles. At the highest energy sampled in this instrument mode, 10.8 keV, an indication of an intensity maximum at $\alpha = 90°$ is barely discernible with the appearance of a slight lessening of intensities in the atmospheric loss cone at $\alpha \leq 60°$. This anisotropy typically increases with decreasing latitude as demonstrated for this particular series of observations in Figure 4. At latitudes $\Lambda \leq 66.1°$ intensities of electrons precipitating into the atmosphere have decreased by factors $\sim$ 200 to detector threshold levels, a decrease which is also accompanied by a similar, but less dramatic lessening of mirroring intensities at $\alpha = 90°$. For this traversal of the equatorward precipitation zone, and many other such observational series which we have examined, there was no evidence of strongly field-aligned intensities, i.e., with $j\ (\alpha = 0°) > j\ (\alpha = 90°)$.

Strongly field-aligned electron intensities were encountered within the poleward precipitation zone, the low-altitude polar cusp. These observations were taken within the latitude range 76.7° to 80.5° (cf. Figure 1) and are shown in Figure 5. Since electron intensities fluctuate substantially on time scales of an instrument passband cycle (21 seconds) we have plotted the ratios of intensities during a single angular scan (1.7 seconds) in order to partially obviate the effects of these spatial and/or temporal variations on discerning the angular distributions. These ratios are the differential intensities, dJ/dE, at α to those at $\alpha = 90°$ (locally mirroring). Different symbols in each of the four panels indicate individual pitch-angle scans. The field-aligned intensities are found at low energies in the low-altitude polar cusp. For the observations at 244 eV of Figure 5 this anisotropy is approximately 10 in favor of $\alpha = 20°$. At 400 eV and 644 eV, intensities are more or less isotropic outside of the backscatter cone and, at somewhat higher electron energies of 1.07 keV, intensities decrease from such isotropy in the atmospheric loss cone at $\alpha \leq 60°$. A second category of pitch angle distributions within the polar cusp is demonstrated in Figure 6. These measurements were gained during the next encounter of the dayside polar cusp during the orbit 1409 following the above extensively discussed observations. The angular distributions at 644 eV display two relative maxima of intensities, field-aligned at $\alpha \leq 30°$ and mirroring at $\alpha = 90°$. Open and closed circles indicate measurements during two angular scans, respectively. At lower energies, 244 eV, only one relative maximum of intensities is apparent -- the field-aligned intensities at $\alpha \leqslant 30°$. Thus strongly field-aligned intensities are found in the polar cusp, but dominantly at the lower energies, hundreds of eV or less.

III. Discussion

We have reported herein a series of exemplary observations of the energy spectra and angular distributions of electron intensities at low altitudes over the dayside auroral oval. The satellite Ariel-4 was particularly useful for these studies with its high spin rate and its favorable spin-axis orientations for pitch angle surveys. During these measurements the electrostatic analyzers, or LEPEDEA's, were operated in a mode which spanned the energy range 205 eV to 12.5 keV with fast temporal resolution of pitch angle distributions. Two major precipitation regimes are readily discerned with these observations -- an equatorward zone positioned below the trapping boundary on closed field lines and a poleward zone identified as the low-altitude polar cusp.

The equatorward electron precipitation zone is characterized by isotropy of electron intensities at pitch angles outside of the atmospheric backscatter cone. As the latitudes of the observations decrease this isotropy evolves to an anisotropy which favors pitch angles at 90° (locally mirroring) and the levels of electron intensities decrease. The energy spectra are broad in the energy range of about 1 to 10 keV and with maximum intensities of roughly

10^4 electrons $(cm^2\text{-sec-sr-eV})^{-1}$. The overall character of this electron precipitation region is generally similar to those encountered at similar latitudes in the local evening sector [Craven and Frank, 1975] and local morning sector [Frank et al., 1975]. No evidences of strongly field-aligned intensities, $j(\alpha = 0°) > j(\alpha = 90°)$, were found. The observed anisotropies yield a weak, diffuse current of the order of $0.25\ \mu a(m)^{-2}$, a Birkeland current flowing upwards from the ionosphere. This precipitation zone is believed to be the 'foot-print' of the electron intensities of the ring current and plasma sheet lying near the distant magnetic equator at geocentric radial distances ~ 5 to $10\ R_E$ (R_E, earth radii). This identification is largely based upon the magnitudes of electron intensities, energy spectra and geomagnetic latitudes of their location [cf. Vasyliunas, 1968; Schield and Frank, 1970; McIlwain 1972]. We would associate this electron population with that stimulating the 'mantle aurora' in the local morning sector as reported by Hoffman and Burch [1973]. The overall nature of the pitch angle distributions and energy spectra of electron intensities in this equatorward zone in the local noon sector as reported here, and in the evening and morning sectors as discussed elsewhere, is in substantive agreement with electron precipitation via pitch angle scattering driven by high-frequency wave turbulence near the equator as outlined by Coroniti and Kennel [1970].

The poleward electron zone features strongly field-aligned intensities precipitating into the upper atmosphere. The electron intensities are similar in magnitude to those of the distant magnetosheath. This zone is in fact the low-altitude polar cusp. Intensities at pitch angles $\alpha \simeq 20°$ were factors often as high as 10 greater than locally mirroring intensities. The angular distributions are remarkably similar to those for inverted-V events in the evening and midnight sectors [cf. Craven and Frank, 1975]. The major differences between these two regions, polar cusp and inverted-V, are merely that characteristic electron energies and latitudinal widths are markedly lesser within the polar cusp -- features which also increase the difficulties of obtaining definitive measurements. Field-aligned intensities were found only at electron energies of hundreds of eV in the dayside polar cusp with indications that field-aligned intensities also occurred at lower energies, ≤ 200 eV, than the particular energy passband range employed in the present survey. Such field-aligned currents are often detected at electron energies of several keV within inverted-V events in the local evening sector. Typical currents directed out of the ionosphere carried by the field-aligned electron intensities in the low-altitude polar cusp are $\sim 5\ \mu a(m)^{-2}$.

We have searched the literature and have not found reports of other low-altitude satellite measurements of such field-aligned intensities clearly associated with the polar cusp [cf. Winningham, 1972]. Such anisotropies have been inferred for the more distant polar cusp, at altitudes $\sim 5\ R_E$ [Fredricks et al., 1973]. Currently the most promising mechanism for generating these field-aligned intensities appears to be quasi-static electric fields, aligned parallel to the geomagnetic field and positioned above the satellite position. These geoelectric fields may be sustained perhaps by anomalous resistivity [Kindel and Kennel, 1971] or electrostatic double-layers [Carlqvist and Bostrom, 1970; Block, 1972]. Assuming the existence of this electric field and employing a rudimentary atmospheric model for electron scattering, Evans [1974] has shown that field-aligned angular distributions substantially similar to those reported here can be expected from such geoelectric fields. These calculated distributions include the significant, scattered electron intensities at pitch angles $\sim 90°$, which are effectively trapped at lower altitudes between their mirror points and the electrostatic barrier. Presently there is no overwhelming feature of field-aligned currents in the dayside polar cusp or the inverted-V region in the evening and midnight sectors, which precludes the existence of these parallel geoelectric fields.

Hence we have found that the two major electron precipitation zones over the dayside auroral oval are similar with respect to their angular distributions and apparent acceleration mechanisms to their counterparts at later local times. The equatorward zone is characterized by precipitation via an isotropic angular distributions outside the atmospheric backscatter zone. The more intense poleward zone, located in the dayside polar cusp and evening inverted-V bands, features strongly field-aligned currents.

Acknowledgments

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Figure Captions

Figure 1. Directional, differential intensities of electrons at E = 244 eV and 4.38 keV (upper panel) and directional intensities of electrons with E > 40 keV (lower panel) as functions of invariant latitude Λ at low altitudes over the dayside auroral oval, which were gained with a LEPEDEA on the satellite Ariel-4 at ~ 0100 U.T. over the Northern hemisphere on March 14, 1972. The pitch angles for these observations were $\alpha = 90°$. The vertical grey bar identifies the approximate location of the boundary between the equatorward precipitation zone of energetic electron intensities below the 'trapping boundary' and the region of lower energy electrons of the polar cusp.

Figure 2. A comparison of electron spectra for the two major precipitation zones encountered over the dayside oval

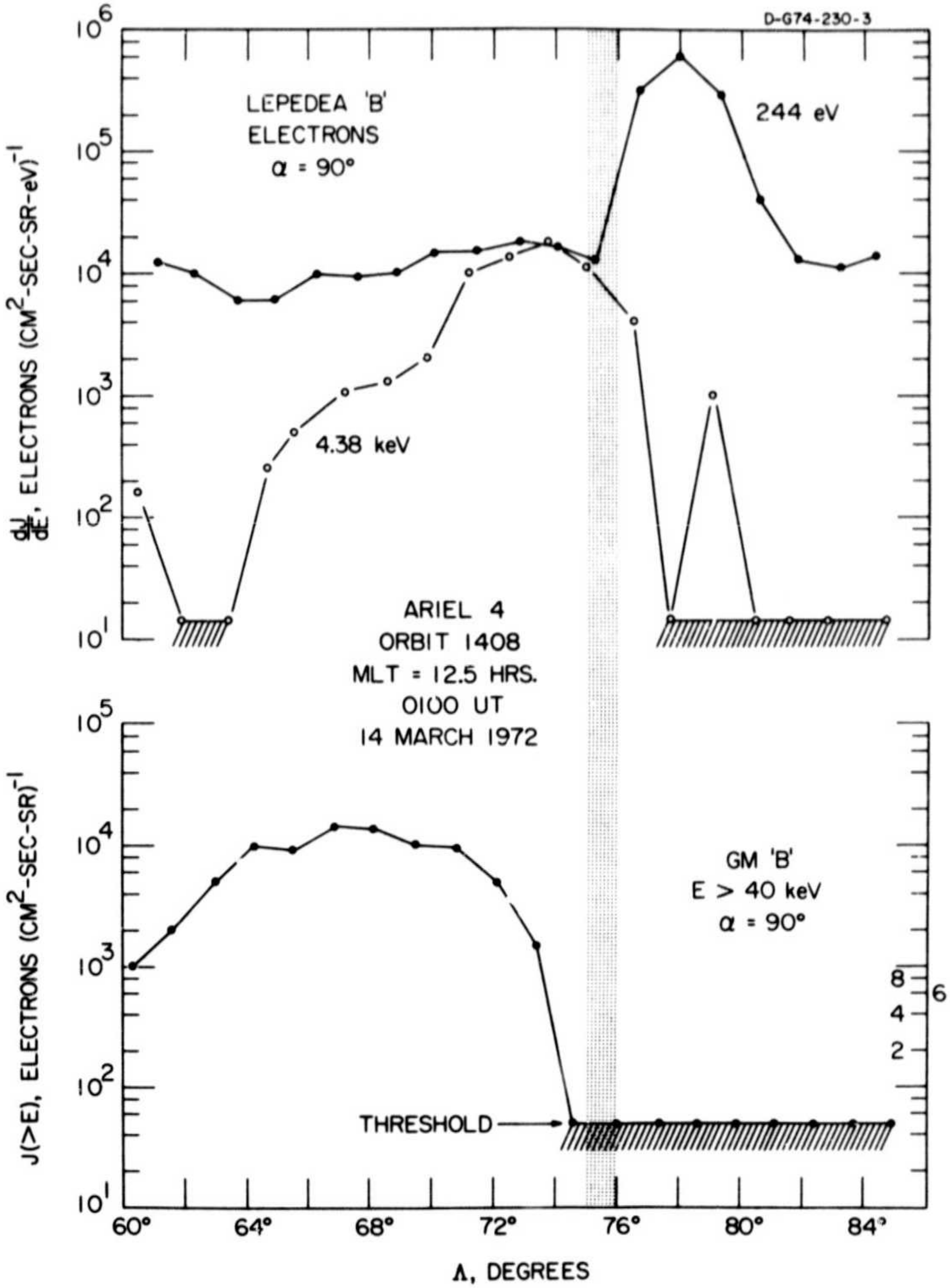
for the series of observations of Figure 1. The pitch angles for these observations were $\alpha = 90°$.

Figure 3. Pitch angle distributions of electron intensities at various electron energies for latitudes equatorward of the trapping boundary during the observations of Figure 1.

Figure 4. Continuation of Figure 3 for electron intensities at 10.8 keV as functions of invariant latitude.

Figure 5. Pitch angle distributions of electron intensities (normalized to intensities at $\alpha = 90°$) at four energies for latitudes poleward of the trapping boundary, and within the polar cusp, during the observations of Figure 1.

Figure 6. Continuation of Figure 5 but with absolute intensities, again within the polar cusp, during the following orbit at $\sim$ 0235 U.T.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LEPEDEA 'B'
ELECTRONS
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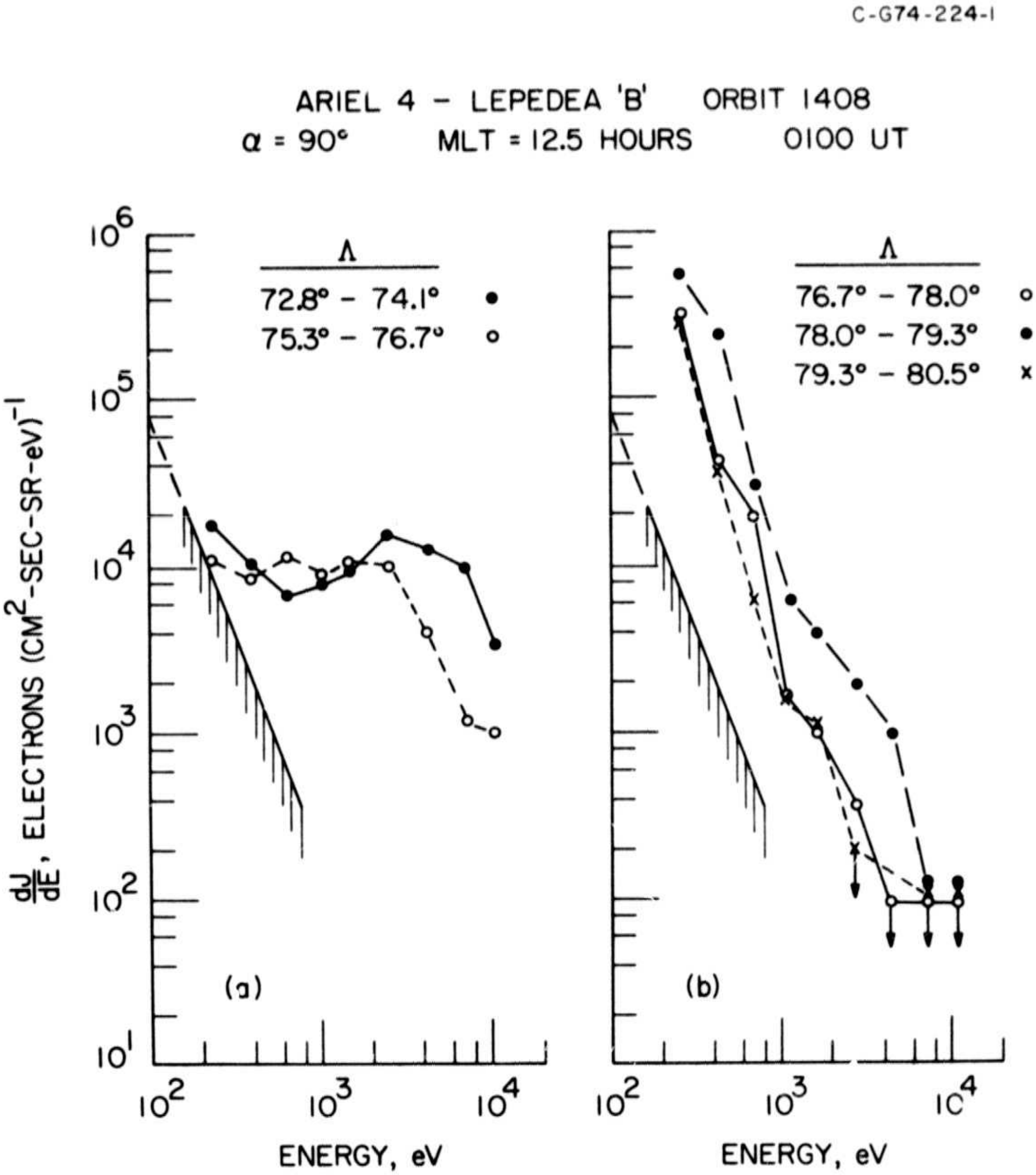
244 eV
4.38 keV
dJ/dE, ELECTRONS (CM²-SEC-SR-eV)⁻¹
ARIEL 4
ORBIT 1408
MLT = 12.5 HRS.
0100 UT
14 MARCH 1972
GM 'B'
E > 40 keV
α = 90°
J(>E), ELECTRONS (CM²-SEC-SR)⁻¹
THRESHOLD
Λ, DEGREES

Figure 1.


C-G74-224-1
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α = 90° MLT = 12.5 HOURS 0100 UT
Λ
72.8° - 74.1° ●
75.3° - 76.7° ○
76.7° - 78.0° ○
78.0° - 79.3° ●
79.3° - 80.5° x
dJ/dE, ELECTRONS (CM2-SEC-SR-eV)-1
(a)
(b)
ENERGY, eV
ENERGY, eV

Figure 2.

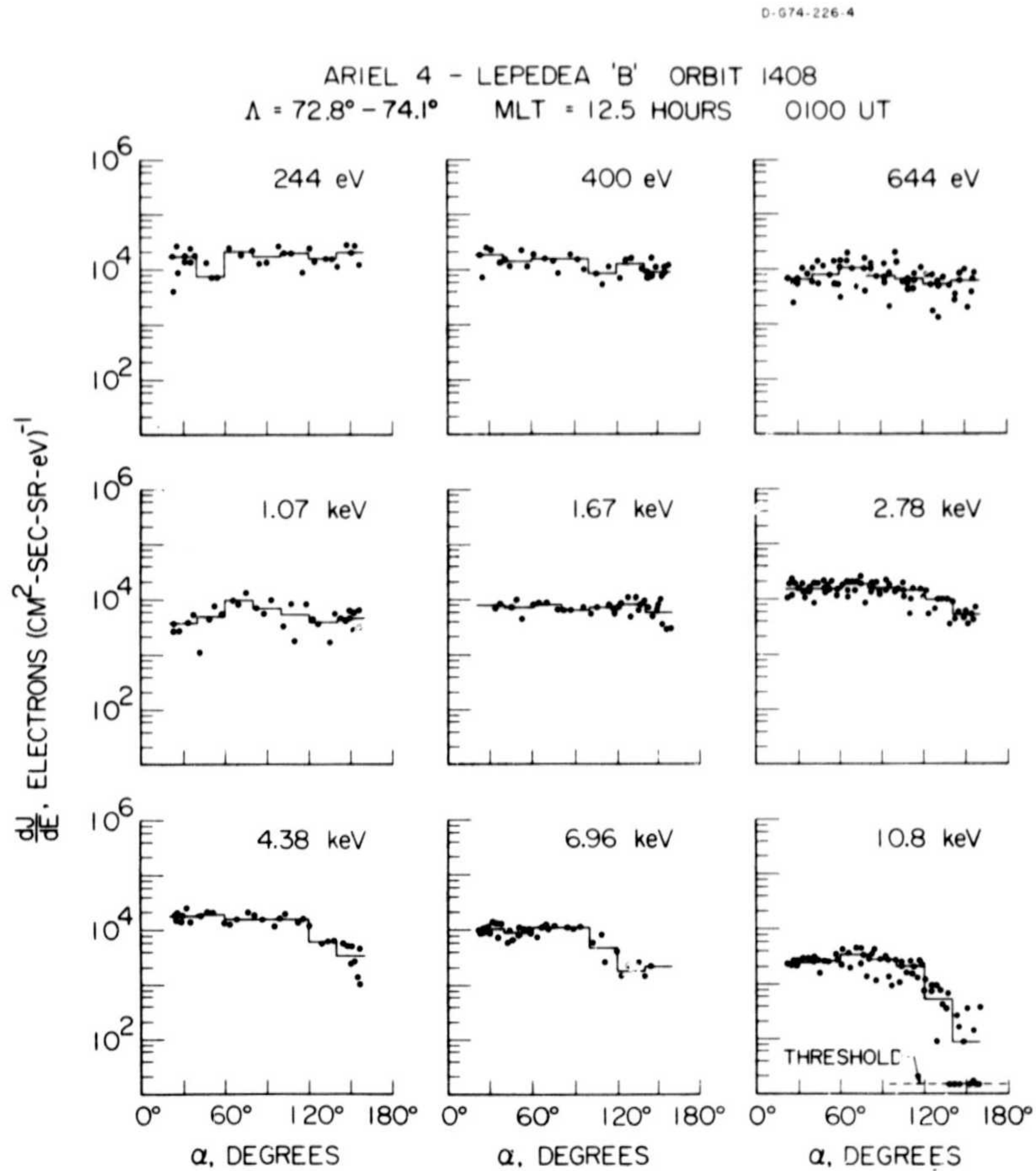
D-G74-226-4
ARIEL 4 - LEPEDEA 'B' ORBIT 1408
Λ = 72.8° - 74.1° MLT = 12.5 HOURS 0100 UT
244 eV
400 eV
644 eV
1.07 keV
1.67 keV
2.78 keV
4.38 keV
6.96 keV
10.8 keV
THRESHOLD
dJ/dE, ELECTRONS (CM²-SEC-SR-eV)⁻¹
10⁶
10⁴
10²
0°
60°
120°
180°
α, DEGREES

Figure 3.

A-G75-86-2

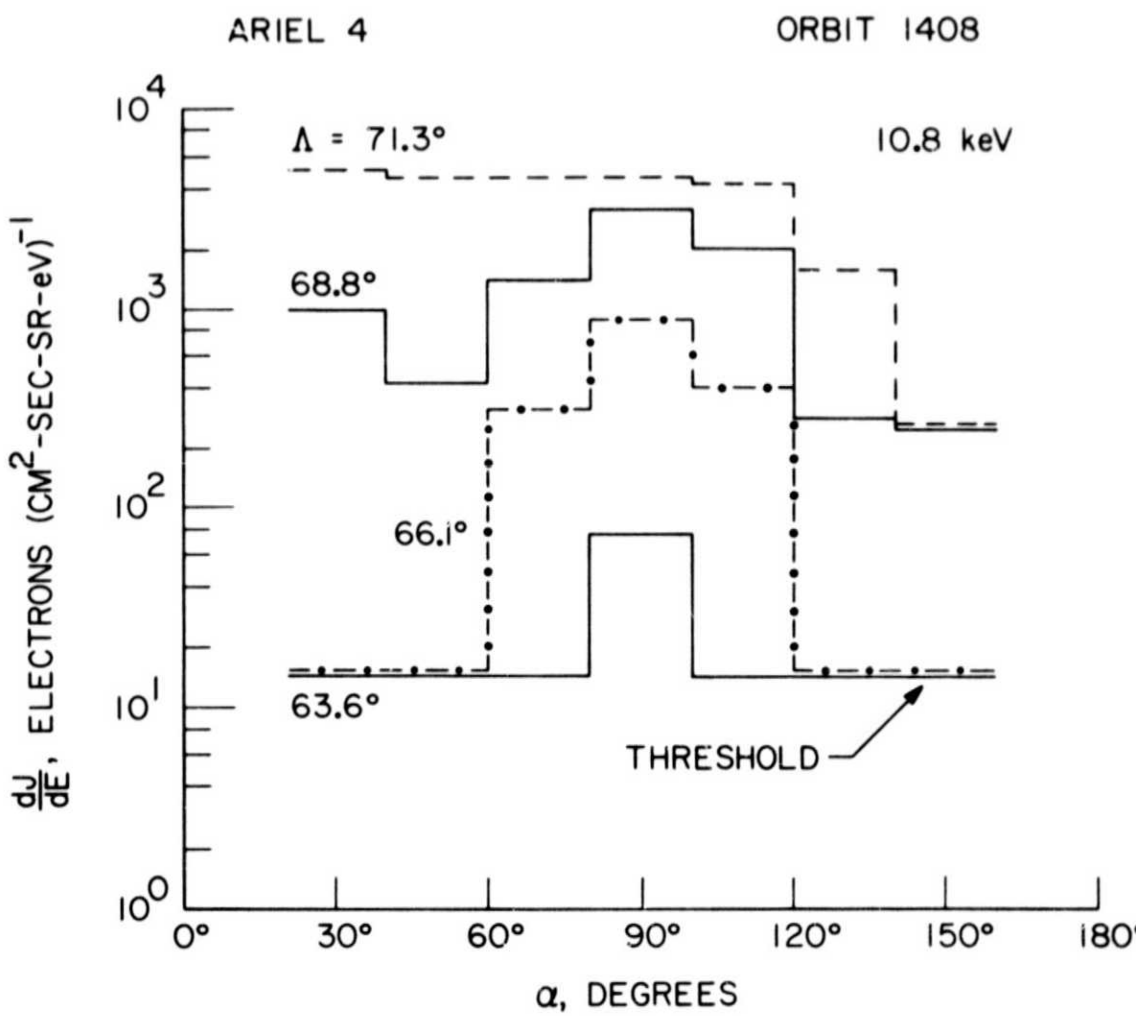

Figure 4.

C-G74-225-2

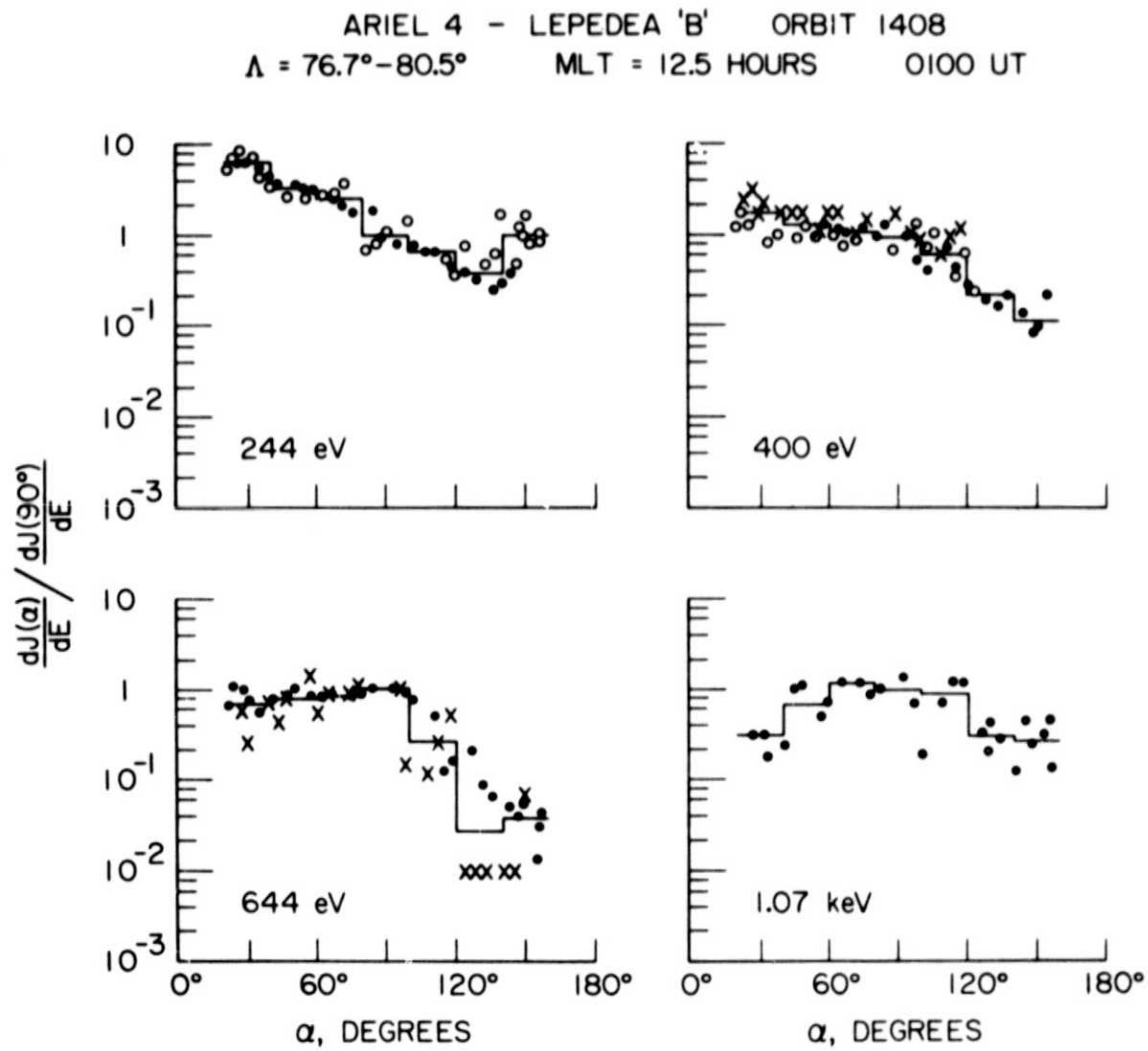

Figure 5.

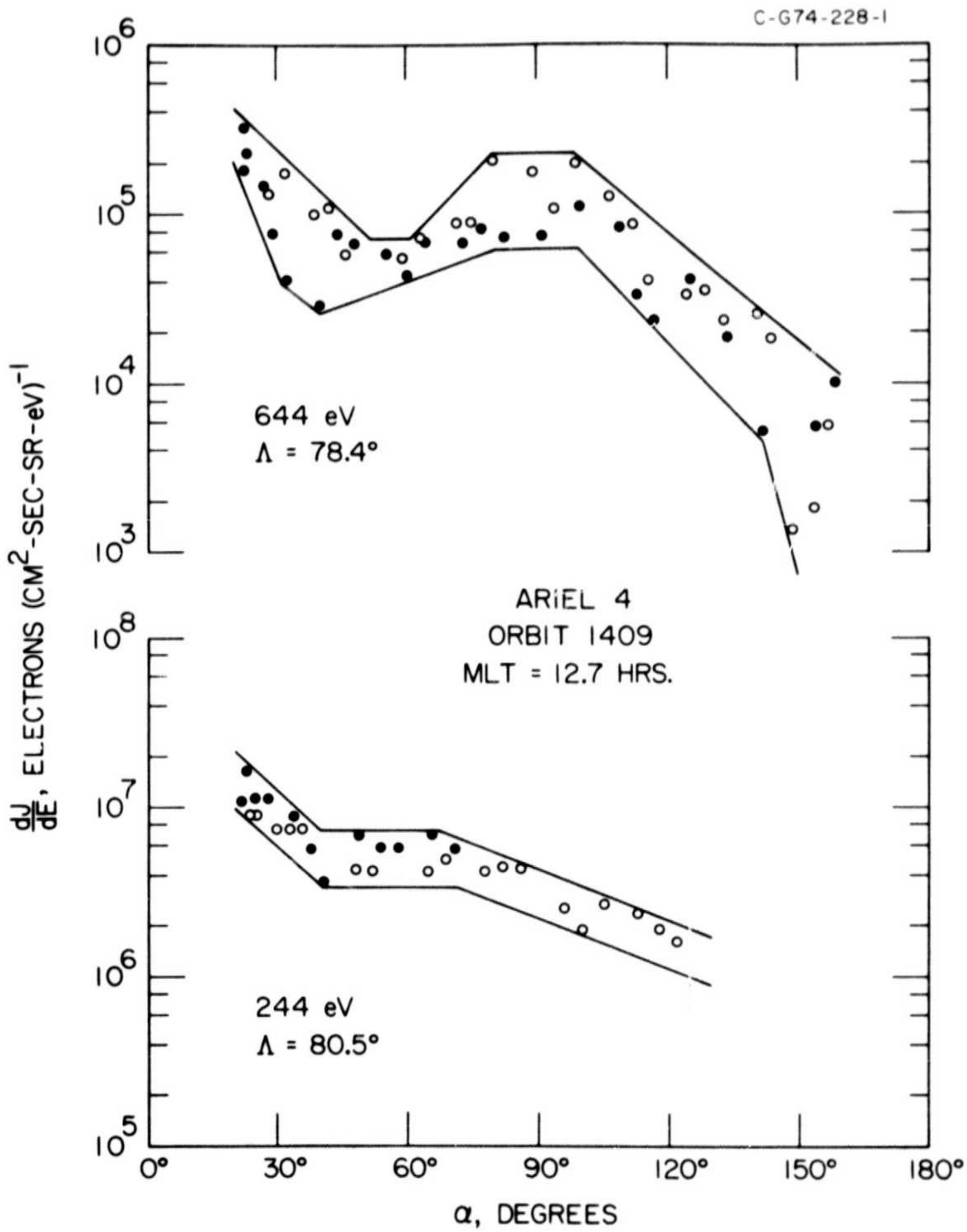
C-G74-228-1
10^6
10^5
10^4
10^3
644 eV
Λ = 78.4°
ARIEL 4
ORBIT 1409
MLT = 12.7 HRS.
10^8
10^7
10^6
10^5
244 eV
Λ = 80.5°
dJ/dE, ELECTRONS (CM²-SEC-SR-eV)⁻¹
0°
30°
60°
90°
120°
150°
180°
α, DEGREES

Figure 6.