

AD-A106 153 AEROSPACE CORP EL SEGUNDO CA SPACE SCIENCES LAB F/6 4/1
 LOW-ENERGY ION PITCH-ANGLE DISTRIBUTIONS IN THE OUTER MAGNETOSP--ETC(U)
 UNCLASSIFIED SEP 81 J F FENNELL, D R CROLEY, S M KAYE F04701-80-C-0081
 TR-0081(6960-05)-15 SD-TR-81-81 NL

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Low-Energy Ion Pitch-Angle Distributions in the Outer Magnetosphere: Ion Zipper Distributions

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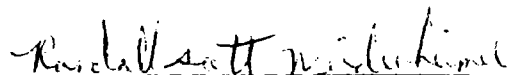
Prepared for
SPACE DIVISION
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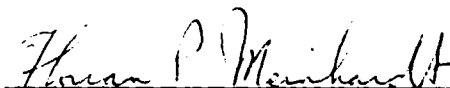
This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-80-C-0081 with the Space Division, Deputy for Technology, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by G. A. Paulikas, Director, Space Sciences Laboratory. Lt R.S. Weidenheimer, SD/YLV, was the project officer for Mission-Oriented Investigation and Experimentation Programs.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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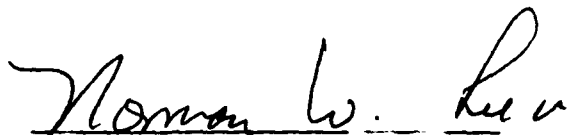


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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-81-81	2. GOVT ACCESSION NO. AD-A1406	3. RECIPIENT'S CATALOG NUMBER 153
4. TITLE (and Subtitle) LOW-ENERGY ION PITCH-ANGLE DISTRIBUTIONS IN THE OUTER MAGNETOSPHERE: ION ZIPPER DISTRIBUTIONS.	5. TYPE OF REPORT & PERIOD COVERED 14	
	6. PERFORMING ORG. REPORT NUMBER TR-0081(6960-05)-15	
7. AUTHOR(s) J. F. Fennell, D. R. Croley, Jr., and S. M. Kaye	8. CONTRACT OR GRANT NUMBER(s) F04701-80-C-0081/V	
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Air Force Systems Command Los Angeles, Calif. 90009	12. REPORT DATE 28 September 1981	
	13. NUMBER OF PAGES 31	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 151	15. SECURITY CLASS. (of this report) Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Alfuen Boundaries Outer Magnetosphere Pitch Angle Distributions Substorm Phenomena Synchronous Environment		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Ion pitch-angle distributions, measured in a near synchronous orbit, are predominantly field-aligned at low energies and predominantly peaked perpendicular to the magnetic field at higher energies. The transition from field-aligned fluxes to fluxes peaked predominantly perpendicular to the magnetic field occurs over a very narrow energy range. These ion distributions have been observed at all local times between 5.3 R_e and 7.8 R_e . This transition energy correlates between the ion transition energy and magnetic local time, L, Kp, or Dst.		

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

However, the transition energy does respond to observed particle injections. The transition energy decreases prior to injection, increases abruptly at injection by as much as 10 to 20 keV and then decreases slowly after injection. Fresh low-energy ions are supplied at injection and decrease in intensity over several hours to instrument threshold level. Ion drift trajectory calculations indicate that the low-energy component below the transition energy drifts in from the night-side plasma sheet via local morning to the day side. The high energy component, above the transition energy, arrives on the day side via local evening.

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PREFACE

We wish to thank all those who have worked so hard to make the P78-2 satellite and experiments successful. We especially thank the members of the Air Force Space Test Program Office and Satellite Control Facility for their efforts. We would like to thank Janet Luhmann and Margaret Kivelson for many useful discussions. We also thank the many individuals who labored to build the Aerospace experiments with special thanks to Sam Imamoto, Claude King, Don Katsuda and Gloria Roberts of SPL.

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INTRODUCTION

In the past few years much attention has been focused on determining the angular distributions of the low-energy particles in the magnetosphere. This has lead to the observation that low energy ions are often found to have field-aligned components in the regions of the outer magnetosphere near the equator (Mauk and McIlwain, 1975; McIlwain, 1975; Borg et al., 1978; Geiss et al., 1978; Young, 1979; Horwitz, 1980; Comfort and Horwitz, 1980; Horwitz et al., 1980) and at high latitudes near the earth (Mizera and Fennell, 1977; Sharp et al., 1977; Whalen et al., 1978; Ghielmetti et al., 1979; and Klumpar, 1979).

At the near synchronous altitudes the observation of the field-aligned ions has been, for the most part, discussed in terms of low altitude sources and acceleration mechanisms modified by pitch angle scattering or perpendicular acceleration at altitudes greater than 3 Re in the near auroral regions (Horwitz, 1980). The field-aligned ion (FAI) distributions measured on the ATS-6 satellite (Horwitz, 1980 and references therein) are the most complete set to date. These observations emphasized the low energy ions, less than 1 keV. The manner in which the data were obtained generally precludes conveniently measuring the energy spectrum and angular distribution of the ions simultaneously.

Recently The Aerospace Corporation Space Sciences Laboratory has flown ion and electron electrostatic analyzers on the near synchronous orbiting, spin-stabilized P78-2 satellite (Stevens and Vampola, 1978). The P78-2 satellite was placed into an elliptical orbit with an apogee of ~ 7.8 Re and a perigee of ~ 5.3 Re geocentric on February 3, 1979 and the final orbital maneuvers occurred on February 5, 1979. The orbit has an inclination of ~ 7.9

degrees with apogee and perigee in the earth's equatorial plane. The orbital period is somewhat less than 24 hours, giving rise to an apogee drift in geographic longitude of 5.1 degrees per day eastward. Apogee was initially at $\sim 200^\circ$ east longitude and 7.5 MLT on February 5, 1979. The satellite is spin stabilized with the spin axis in the orbital plane and maintained normal to the satellite-sun line within five degrees. The spin period is nominally 60 sec but varied from ~ 35 to ~ 62 sec in the first month of operations and has been ~ 57 sec since then.

The Aerospace particle analyzers are mounted with their view directions perpendicular to the spin axis allowing a reasonably complete angular distribution to be obtained continuously. The performance characteristics of the particle spectrometers used for this publication are summarized in Table 1. The operating mode of the units can be modified to a limited extent by ground command. The number of energy channels selected can be 7, 14 or 21. A complete spectrum is obtained in three seconds with the set of 21 energy channels, while the interlacing of the channels gives a simpler 7 channel spectrum in one second. For this study the instrument was in either a 21 or 14 channel program mode.

TABLE 1

Aerospace Low-Energy Particle Spectrometers

<u>Channel</u>	<u>Electron Energy, keV</u>	<u>Ion Energy, keV/charge</u>
1	0 (background)	0 (background)
2	.006	.006
3	.017	.018
4	.040	.037
5	.087	.074
6	.19	.15
7	.32	.26
8	.45	.36
9	.61	.49
10	.82	.66
11	1.1	.88
12	1.4	1.2
18	1.9	1.6
14	2.6	2.1
15	3.4	2.7
16	4.5	3.6
17	5.9	4.8
18	8.2	6.6
19	10.9	8.8
20	14.4	11.6
21	19.4	15.6

Sample rate = 7 sps

Sample duration ~ 100 ms

$\Delta E/E \sim 0.07$ for electrons, ~ 0.08 for ions

Geometric factor ($\text{cm}^2 \text{ ster}$) $\Delta E/E = 1.62 \times 10^{-4}$ for electrons
 $= 6.3 \times 10^{-4}$ for ions

Angular Response (full width at 10% maximum response) is $\sim 9^\circ \times 7^\circ$ for electrons and $16^\circ \times 9^\circ$ for ions in planes parallel and perpendicular, respectively, to the spin axis.

OBSERVATIONS

Figure 1 is a spectrogram containing twelve hours of electron and ion data taken on April 4, 1979 in the dayside magnetosphere. These data represent the locally mirroring particles ($\alpha = 90^\circ \pm 10^\circ$). The electrostatic analyzers were collecting data in a mode utilizing 14 energy channels ranging from 0.087 to 19.4 keV for electrons, shown in the top panel, and 0.074 to 15.6 keV/charge for ions, shown in the bottom panel. Note that ion energy increases downward.

The data displayed in Figure 1, a subset of the total data set, are similar in appearance to the data observed by the ATS satellites (McIlwain, 1972). Notice the presence of a deep minimum in the ion flux running through the data, a feature commonly seen in ATS data, extending from 0400 UT, at an energy of approximately 5 keV, to 0800 UT, where the energy has decreased to nearly 2 keV. The deep minimum crosses over to the electron data where it levels off at about 4 keV after 0900 UT. A similar deep minimum feature can be seen in the parallel ion flux about 2 keV higher in energy. (Although a spectrogram of parallel fluxes is not shown, the deep minima in the parallel and perpendicular fluxes can be seen in the spectra presented in Figure 3.) Other structures are visible in the data but the deep minimum is one of the most recognizable. Pc5 oscillations are evident between 0400 and 0800 UT in the data (Figure 1).

Figure 2 is a segment of the total ion data covering about 1400 seconds near 0700 UT on April 4, 1979. The added detail of the complete pitch angle coverage is immediately apparent. The data are plotted as a function of time and clearly show pitch-angle modulation. The deep minimum observed in Figure

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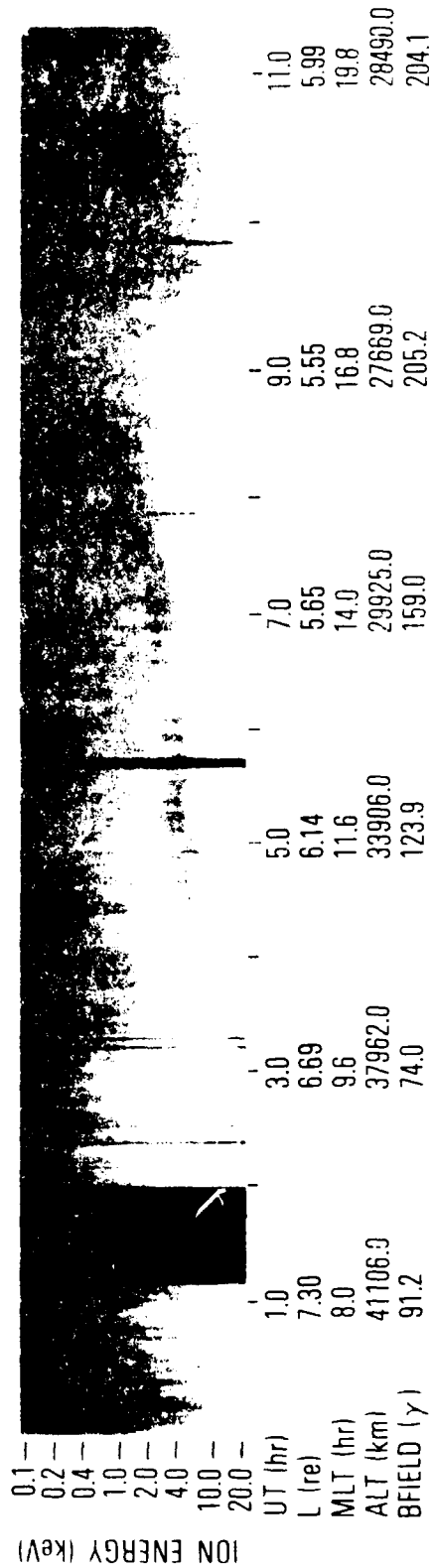
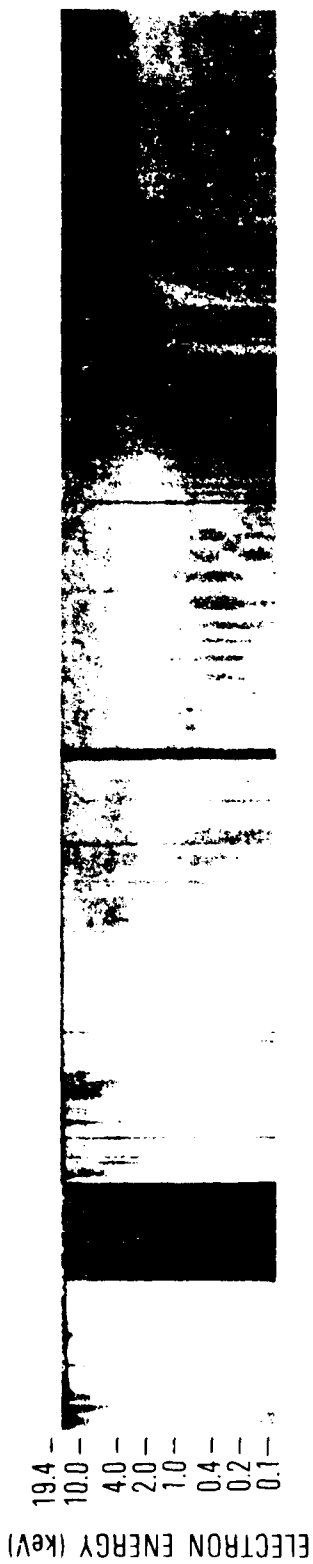


Fig. 1. Electron (upper panel) and ion (lower panel) spectrograms for 00 UT to 12 UT, 4 April 1979, from the Aerospace plasma analyzer on the P78-2 satellite. The intensity is proportional to the particle energy flux. The electron energies increase upward and the ion energies increase downward in their respective panels. The measurements are of locally mirroring ($\alpha \sim 90$ deg) particles.

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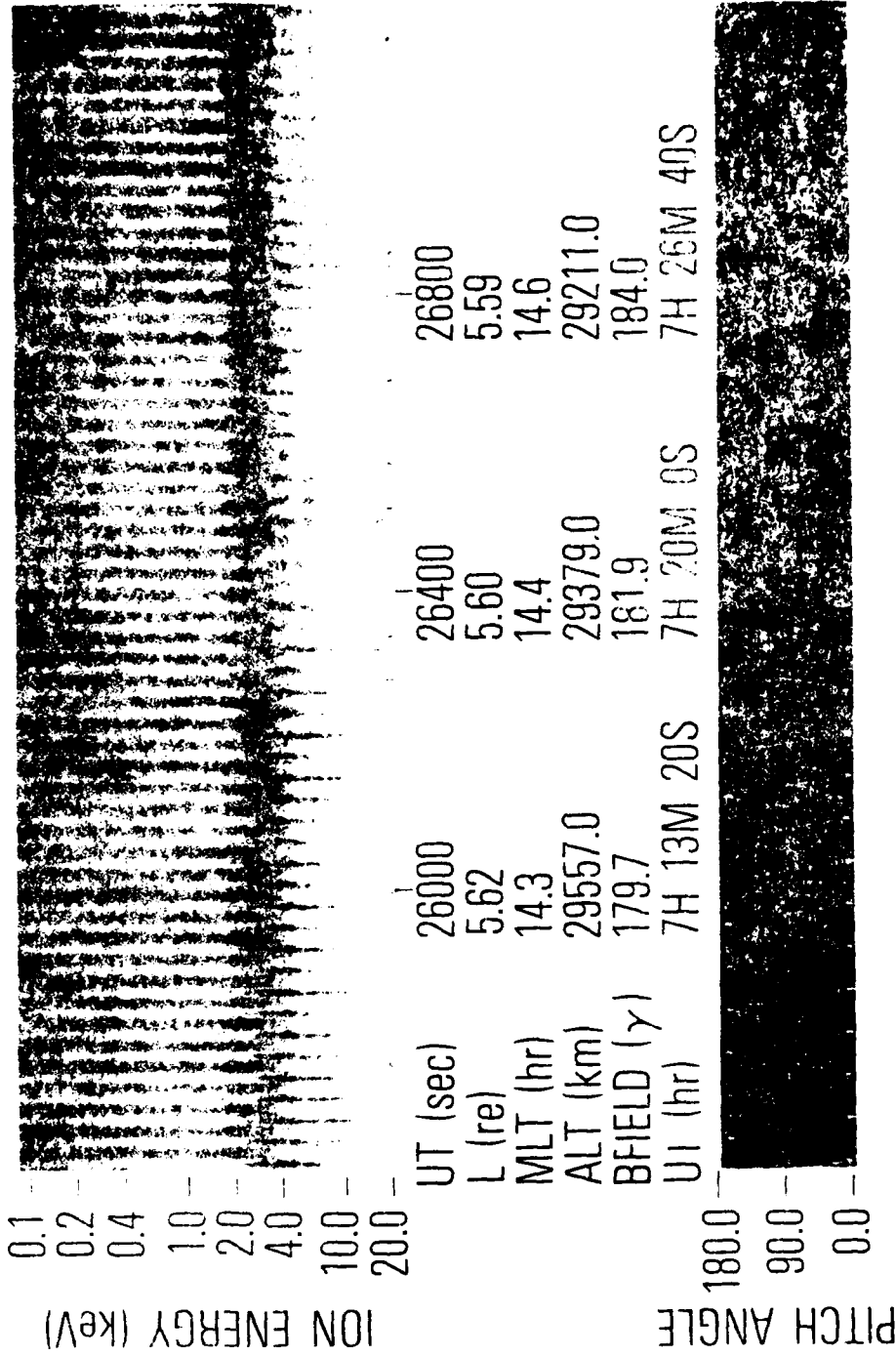


Fig. 2. Ion spectrogram from 0706:40 to 0723:26 UT, 4 April 1979, showing the transition from predominantly field-aligned fluxes below ~ 2 keV to predominantly trapped distributions. The pitch angles sampled are noted at the bottom.

1 is seen here also, but as a function of pitch angle. The darkening of the spectrogram near the energy interval 2 to 4 keV represents the change in energy of the deep minimum from approximately 4 keV for field-aligned ions to approximately 2 keV for mirroring ions. The most striking feature is the observation that the pitch-angle distributions at high energies (bottom of the spectrogram) are very different from those at low energies (top of spectrogram). Whereas the low-energy ions are predominantly peaked along the magnetic field direction ($\alpha \sim 0^\circ$ and $\alpha \sim 180^\circ$), the higher energy ions are predominantly peaked perpendicular to the magnetic field ($\alpha \sim 90^\circ$). The transition from the field-aligned distribution to the mirroring distribution occurs over a narrow range of energies, giving the appearance of a "zipper" in the ion distribution on the spectrogram data presentation. The energy, observed on the spectrogram Figure 2, at which the field-aligned ion distribution changes to a mirroring distribution is defined as the transition energy.

Figure 3 is a plot of ion data in velocity-space for one complete satellite revolution taken near 26016 seconds UT. The distribution function contours below 600 km/sec are observed to have an elliptical shape extending along the V_{\parallel} axis. Above that velocity the contours are elongated in the perpendicular direction. Ion flux spectra in the parallel and perpendicular directions are plotted at the right side of Figure 3. Here a deep minimum in the ion fluxes is clearly seen with a 2 keV energy separation between its location in the parallel and perpendicular fluxes. The transition energy lies between the two. In some observations the pitch-angle distribution at the transition energy is isotropic. An ion distribution similar to that presented in Figure 3 has been observed in the ISEE-1 data by Frank, et. al. (1978) in the day side ring current.

IONS SC2 3
 4 APR 1979 DAY 94
 L 5.617
 UT 26016.42 sec
 MLT 14.283 hr
 ALT 29549.3 km
 B-FIELD 179.83 gamma

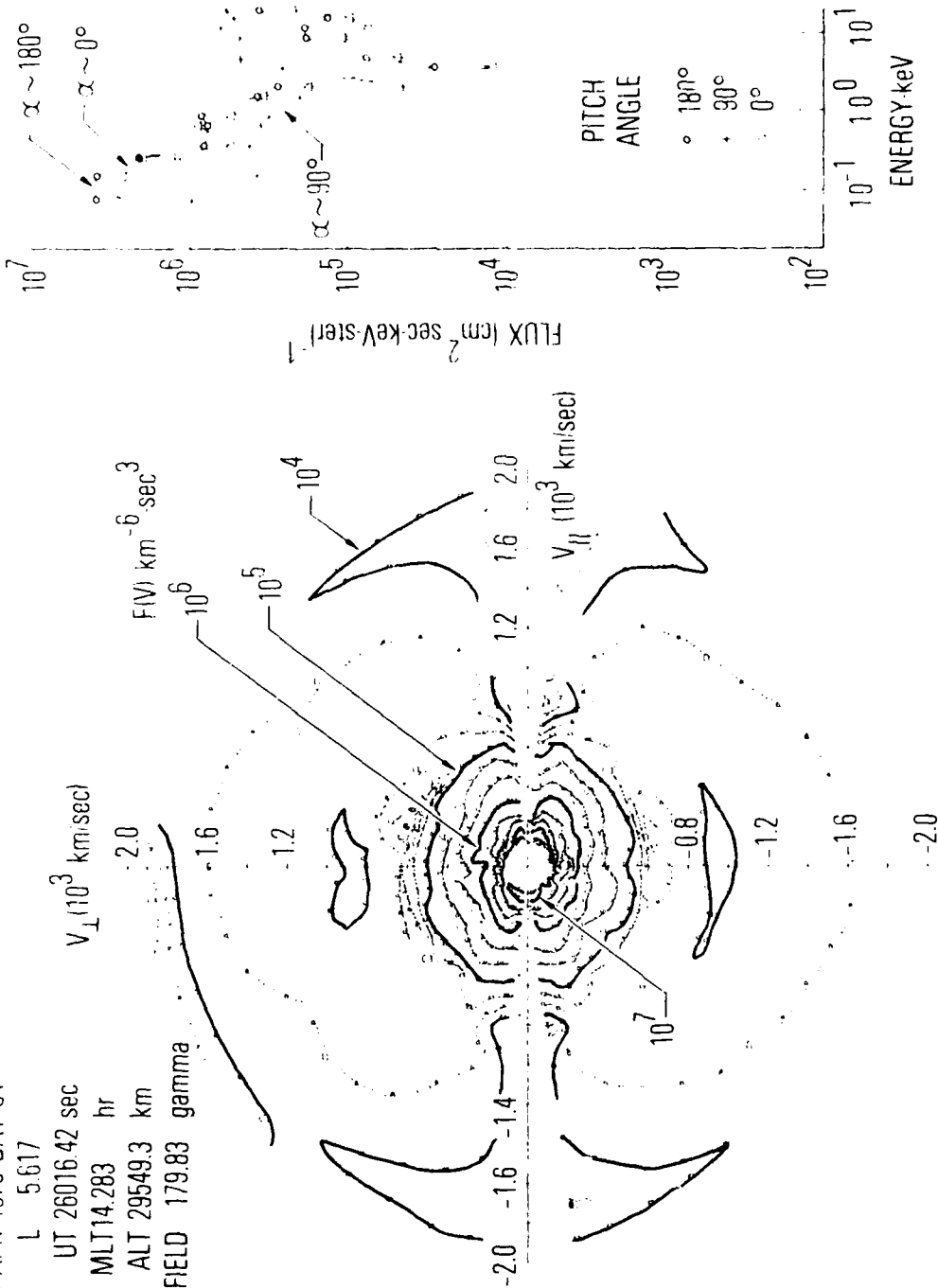


Fig. 3. Contours of constant ion (proton) distribution function in velocity-space (left panel) and ion spectra at large and small pitch angles for 0713 UT, 4 April 1979.

Ion spectra taken at two different local times on April 4, 1979 are shown in the two left panels of Figure 4. Ion spectra taken on two different days, 11 February 1979 and 12 February 1979, at the same local time and L-value are shown in the two right panels. April 4 was a disturbed day ($\Sigma K_p=34$ and Dst reached -197γ), while February 11 was a quiet day ($\Sigma K_p=19+$) and February 12 was a moderate day ($\Sigma K_p=23+$ and Dst reached -58γ). Each set of spectra shown in Figure 4 exhibits the predominantly field-aligned ion fluxes at low energies and locally mirroring ion fluxes at higher energies. The variety of spectral shapes shown in Figure 4 does not lead to any easy identification of the source population.

The field-aligned ions with peaked spectra observed on April 4, 1979 near 0250 UT were observed for more than 3 hours spanning magnetic local times of 7.3 to 10.4 hours and L-shells from ~ 6.5 to 7.6 Re. During this period, the S3-3 satellite observed upward flowing ions near 13 and 02 hours magnetic local time between 4700 and 6500 km altitude spanning the L-shells covered by the P78-2 satellite. The ion beams measured by the S3-3 satellite were mostly low energy (<1.2 keV) with fluxes from 10^6 to 10^7 ($\text{cm}^2\text{-sec-ster-keV}$) $^{-1}$ near 100 eV. Thus the early April 4 P78-2 observations are not unlike the low altitude auroral measurements of ion beams. Furthermore, the field-aligned fluxes at $\alpha \sim 0^\circ$ do not peak at the same energy as those at $\alpha \sim 180^\circ$ (Figure 4, left panel).

This evidence strongly suggests an auroral-like source operating at both ends of the field line. Kaye et al., (1979) and Lennartsson and Reasoner (1978) have suggested previously that the low-energy ions observed at synchronous orbit are of ionospheric origin. More recently, Kaye et al. (1981) have shown that the ion populations below and above the transition energy clearly have different composition. The low-energy population in the

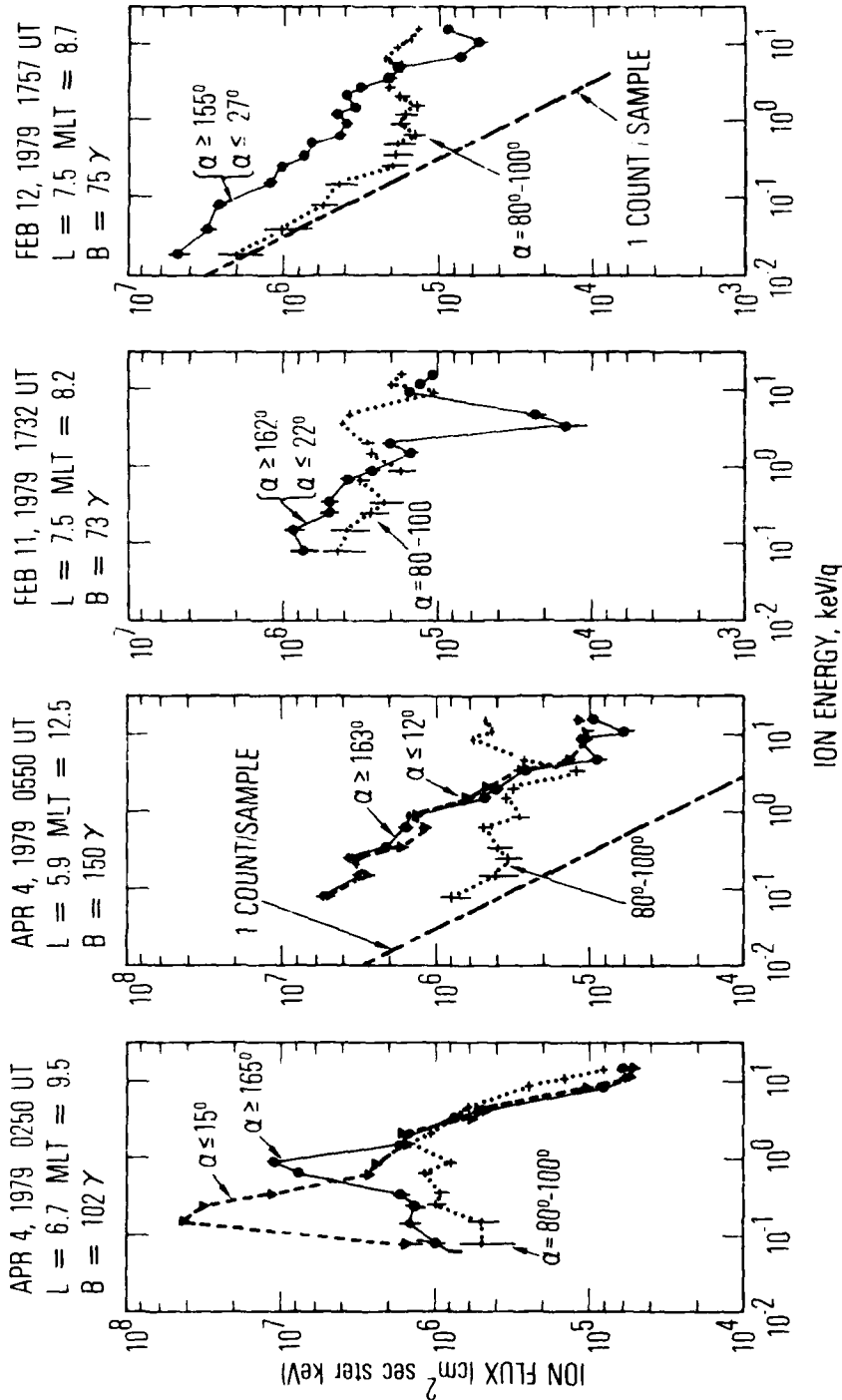


Fig. 4. Selected ion spectra taken at small and large pitch angles from three different days.

parallel direction is composed primarily of O^+ , and to a lesser extent, H^+ and He^+ while the higher energy perpendicular population is primarily H^+ . This in itself suggests a local ionospheric source for the ions below the transition energy. The source for the particles above the transition energy is most probably the plasmashield.

If the February 11, 1979 ion spectra in Figure 4 are compared with the ion spectra in Figure 3, the deep minimum is seen in the parallel flux in both cases; but the February 11 perpendicular spectrum exhibits a maximum instead of a minimum, a feature seen often in the data. From the variety of spectral shapes it can be seen how a small change in a spectrum can cause the transition energy to change drastically.

The transition energy observed in Figure 2 spans in energy the parallel and perpendicular flux minima in the ion spectra. This relationship of transition energy to deep minimum location is not the only one observed in the data base. The transition energy can vary from coincidence with the deep minimum, as observed in Figure 2, to tracking the deep minimum in the parallel ion flux but at several keV below. The deep minimum in the parallel ion flux is a more regular feature of the data than is a deep minimum in the perpendicular flux. Many observations exhibit the feature only in the parallel flux. The general observation to date has been that the transition energy is below the deep minimum in the parallel ion flux, with the deep minimum acting as an upper limit.

The appearance of the "zipper" distribution in the ions in the near synchronous region is a persistent feature of the data. At one time or another it is seen at all local times around the orbit. On any given orbit it will be observed for a period of several consecutive hours. The "zipper"

distribution has been observed at all local times with transition energies varying between a few hundred eV to approximately 20 keV. Figure 5 is a plot of the transition energy (solid line) as a function of local time over the three day period 11-13 February 1979. The location of the deep minimum in the parallel ion flux is also plotted in Figure 5 (dashed line). These three days were fairly quiet magnetically. Kp and Dst are plotted on the top panels of Figure 5. The arrows on Figure 5 mark the local times of particle injections. On 11 February there was only one injection event at ~ 0130 MLT. On 12 February there appeared to be several injections between dusk and dawn. On 13 February there were no injections observed. (For a discussion of plasma injections see Kivelson, Kaye and Southwood (1979).)

Particle injections have a dramatic effect on the transition energy. The change in the ion distribution as characterized by the transition energy on 11 February 1979 during a single injection event is shown in Figure 5. Prior to injection the transition energy decreased to several hundred eV. At the time of the injection the transition energy abruptly increased to ~ 10 keV. Following injection the transition energy decreased to a steady state value of 2 keV at about 0600 MLT. At the same time the low-energy field-aligned component was slowly decaying in intensity. By 1100 MLT the low energy field-aligned ion intensity had fallen below instrument threshold (Energy flux $< 1.6 \times 10^4$ keV/cm²-sec-ster-keV). On 12 February 1979 there were several injections on the night side, the most dramatic occurring at about 0430 MLT. The transition energy first increased to about 15 keV and then decreased to a steady value of 4 keV by 0900 MLT, where it remained throughout the rest of the day. On 13 February the transition energy decreased to 2 keV and the low-energy component decayed in intensity until the middle of the day on February 13 when it was no longer observable. During the multiple injections which

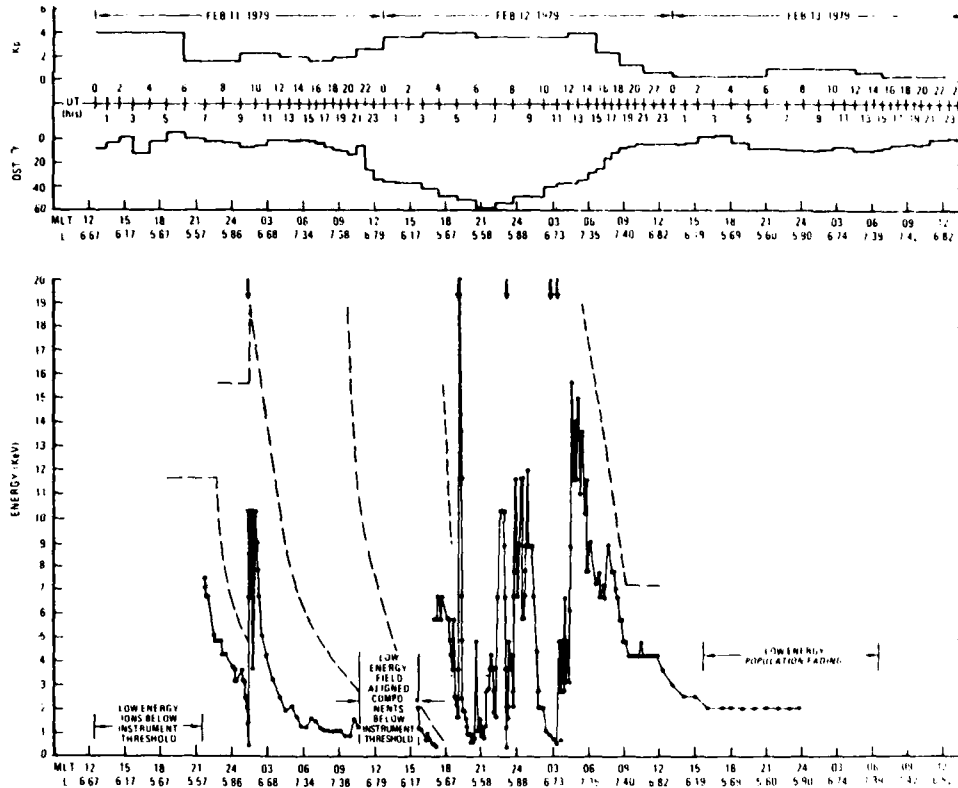


Fig. 5. The energy of transition from predominantly trapped to field-aligned ion fluxes (solid curve with points), the energy of the parallel ion flux deep minimum (dashed line), and the Kp and Dst indices (upper two panels), as a function of magnetic local time for 11-13 February 1979. The universal times are given in the top panel. The arrows denote times of substorm injections.

occurred on 12 February 1979, the transition energy was highly variable and at times became unrecognizable as a phenomenon.

The changes observed in the transition energy accompanying injection are related to changes in spectral shape of the ions. The following sequences are clearly seen with the injection on 11 February 1979. Prior to injection the low-energy perpendicular flux increased relative to the parallel flux, resulting in a decrease of the transition energy. At the time of injection the perpendicular flux hardened significantly relative to the parallel flux, raising the transition energy. The decrease in transition energy after injection was accompanied by the decay of the low-energy field-aligned component of the ions relative to a fairly stable perpendicular flux.

During the latter half of 13 February and the first half of 11 February, the low-energy ion component was not observed. Between the injection event on 11 February and those on 12 February, during a 5-hour period near 12 MLT, there was no observable low-energy ion component. Subsequently, injections appeared to resupply the near synchronous regions with a low-energy field-aligned ion population. The particle injections caused pitch-angle dependent spectral-shape changes in the ion distribution in such a way as to produce a signature in the transition energy as seen in Figure 5. Lennartsson and Reasoner (1978) note that low-energy predominantly field-aligned ion fluxes often increase in connection with "substorm injections" of high-energy particles.

Because there is an apparent relationship between the transition energy and the energy of the deep minimum in the ion flux and because the deep minimum is a feature of the magnetospheric convection system (McIlwain, 1974; Kivelson, 1979), the transition energy has been examined to see if it also is

a feature of magnetospheric convection. The trajectories of ions observed at the satellite position have been traced backwards in time to $10 R_e$. If a dipole magnetic field and a uniform cross-magnetospheric electric field is assumed (Kaye and Kivelson, 1979) it can be shown that ions convect inward from the plasmashet (Ejiri, 1978; Southwood and Kaye, 1979). The observed plasmopause position on February 12, 1979 is used to estimate a cross-magnetospheric potential drop of approximately 75 kV. The resulting ion trajectories, calculated using this potential for ions arriving at $L=7.4$ near 0900 MLT are shown in Figure 6. In Figure 6a it is shown that field-aligned ions below 5 keV have drifted from the plasmashet to the satellite position via local dawn. Field-aligned ions above 5 keV arrive at the satellite via local dusk. Note that this energy, 5 keV, corresponds to the transition energy at the satellite positions for that local time (Figure 5).

A similar trajectory calculation for locally mirroring ions ($\alpha \sim 90^\circ$) produces trajectories which separate at an energy of 3 keV (Figure 6b). The observation that the locally mirroring ions ($\alpha=90^\circ$) are not dominant below ~ 5 keV is probably a reflection of low flux intensities of these ions in the plasma sheet population (Figure 4).

In summary, the characteristics of the ion pitch-angle distributions observed in the near synchronous region are:

1. The low-energy ions are predominantly field-aligned, whereas the higher energy ions are predominantly peaked perpendicular to the magnetic field. The transition from the former distribution to the latter occurs over a very narrow energy range, giving the appearance of a "zipper" on an E-t spectrogram.
2. These ion distributions have been observed at all local times between $L=5.5$ and $L=7.5$.

CROSS MAGNETOSPHERE
ELECTRIC FIELD 75 kV

FEBRUARY 12, 1979

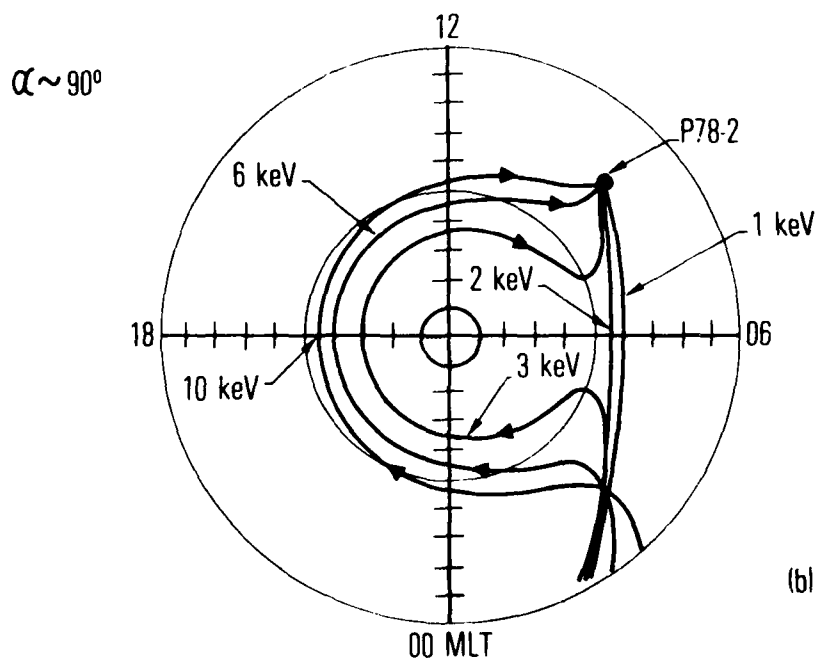
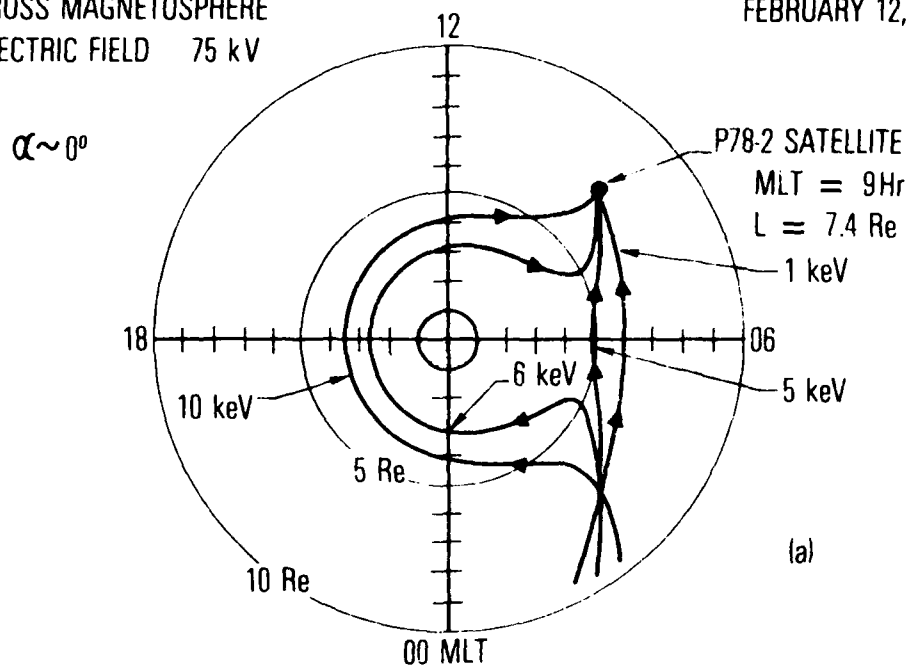


Fig. 6. Ion trajectories in a dipole magnetic field model with a uniform cross-magnetospheric electric field of ~ 75 kV for a range of energies. The trajectories of small pitch-angle ions (a) and large pitch-angle ions (b) are traced from the position of the P78-2 satellite, indicated by the large dot.

3. The transition energy follows the trends in the deep minimum in the parallel ion flux spectra, if a trend is observed in the data, at an energy less than or equal to the energy of the deep minimum in the parallel ion flux.
4. Particle injections cause rapid changes in the ion spectra as a function of pitch angle. These changes are characterized by systematic changes in the transition energy, which is a dominant feature in the particle E-t spectrograms.
5. On very quiet days the low-energy field-aligned component is often not observed above the instrument threshold energy-flux level of 1.6×10^4 keV/cm²-sec-ster-keV.
6. Particle injections resupply the near synchronous region with low-energy field-aligned ions. These ions have a composition similar to ionospheric composition.
7. Following an injection the low-energy field-aligned ion fluxes decay in less than 24 hours to the instrument detection threshold. The higher-energy perpendicular ions persist indefinitely.
8. Although the transition energy of the ion distribution responds to particle injection events, there is no obvious observable relationship between transition energy and magnetic local time, L, Kp or Dst in the data examined to date.

DISCUSSION

The ion flux deep minimum and the lowest ion energy observable at a given L and local time have been explained by the drift of particles in combined magnetic and large-scale quasi-static electric fields (McIlwain, 1972). Particles moving on both open and closed drift paths can be organized in terms of boundaries called Alfvén layers, which depend on models of global magnetic and electric fields (Kivelson et al., 1979; Southwood and Kaye, 1979; Kivelson and Southwood, 1975; Wolf, 1970; Chen, 1970; Ejiri, 1978; Cowley and Ashour-Abdalla, 1976). Calculations predicting the spatial Alfvén boundaries have been used to approximate the particle observations of Explorer 45 (Kaye and Kivelson, 1979; Southwood and Kaye, 1979; Kivelson and Southwood, 1975) and the ATS data (McIlwain, 1972). Most of the analyses so far have been concerned with equatorially mirroring particles, although some calculations have been done for particles at small pitch angle (Ejiri, 1978; Cowley and Ashour-Abdalla, 1976).

The appearance of distinctly different ion pitch angle distributions between high and low energy ions, the observation that the transition energy follows the deep minimum in the ion spectra, and the fact that ion spectral shapes exhibit considerable variability when compared in time, local time, magnetic activity and L-value, strongly suggests that the source populations are being restructured by the influence of a global convection electric field. Preliminary results from ion trajectory analysis in model fields show that low-energy ions are on open drift paths. Their source is the near-earth plasma sheet. Ions with both large and small pitch angles are predicted to have access to the spacecraft orbit at energies below the transition energy. Since there is little or no ion flux at large pitch angles, one must conclude that the plasma-sheet ions are predominantly field-aligned, a process acting

in the tail beyond 7.5 Re efficiently transports the field-aligned component only, or that the regions are populated by a source of parallel low-energy ion fluxes, such as the ionosphere, along drift paths intercepted by the spacecraft. The ion composition measurements (Kaye et al., 1981) support the latter hypothesis.

We can use adiabatic theory to ascertain whether the parallel and perpendicular fluxes originated from a common source distribution in the tail. In a dipole magnetic field the energy change a particle would experience during convection from the magnetotail would vary as L^2 for field-aligned particles and L^3 for particles perpendicular to the magnetic field. These relationships predict that the particles observed with energy E at near synchronous altitude by P78-2 would have the following energies in the plasmashet at $\sim 20 R_E$: field-aligned particles would have energy $\sim E/9$ and particles perpendicular to the magnetic field energy $\sim E/28$. The result of applying this analysis to the ion data presented in Figure 4 is that the perpendicular spectra and the parallel spectra do not transform to a common spectrum in the magnetotail. In fact, the energy shifts are such that the spectra differ even more. One concludes, then, that the observed ion distributions are not explained by energization during convection from the magnetotail but are characteristic of their different primary sources.

One ionospheric source for the field-aligned ion component in the plasmashet is the auroral source discussed above in relation to S3-3 observations. Such a source would provide predominantly field-aligned ions. Also the composition would be essentially that measured by the GEOS experiments in the outer magnetosphere (Ghielmetti et al., 1978; Ghielmetti et al., 1979; Geiss et al., 1978; Young, 1979). Such a source would also be in agreement with the results of Kaye et al. (1981).

Explanation of the data will undoubtedly require correctly identifying the source populations and compositions as a function of energy and pitch angle, and subsequently following these populations through their appropriate drift orbits while simultaneously accounting for losses such as charge exchange and modifications such as pitch-angle scattering.

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