Reprinted from: PHYSICS OF THE HOT PLASMA IN THE MAGNETOSPHERE
Edited by B. Hultqvist and L. Stenflo
Book available from: Plenum Publishing Corporation
227 West 17th Street, New York, New York 10011

AURORAL ELECTRON BEAMS NEAR THE MAGNETIC EQUATOR

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ABSTRACT

Intense beams of electrons travelling parallel to the local magnetic field have been observed at a magnetic latitude of 11° and a radial distance of 6.6 R_e. The distribution function for electrons travelling within 8° of the field line direction is typically flat or slightly rising up to a break point beyond which it decreases as v^{-5} to v^{-10}. The energy corresponding to the break point velocity is usually between 0.1 and 10 keV. These beams are found to occur on closed field lines at the inner edge of the plasma sheet and thus at the root of the earth's magnetotail. Beams with break point energies greater than 2 keV seem to occur only within the first 10 minutes after the onset of hot plasma injection associated with a magnetospheric substorm. Although the origin and destiny of these electrons is as yet unknown, considerations of the total energy and the number of particles transported guarantee that they must play a dominant role in many key magnetospheric processes.

INTRODUCTION

Before any direct particle measurements, ground-based observations of auroral arcs had already indicated that most of the auroral light was caused by energetic electrons entering the atmosphere from higher altitudes (Lenard, 1911; Störmer, 1955; Omholt, 1959). Since the first measurement of intense electron fluxes in and above an auroral arc (McIlwain, 1960), there have been a large number of such observations, including some at altitudes of up to 2000 km. The implications of the energy and angular distributions of these electrons are discussed in the contribution by D. Evans to these proceedings.

Many measurements have been made in the more distant regions of the magnetosphere with instruments easily capable of sensing the strong auroral electron fluxes, but no definite detection has been reported. This has led to the conclusion (1) that they occur only relatively near the earth, which in turn led to the tentative conclusion (2) that the acceleration processes must also occur only near the earth. Data presented in the present paper show that the first conclusion was incorrect, but that the second conclusion may still be correct.

The previous non-observation is easy to explain in retrospect. The high intensities occur only within a small (< .03 steradian) solid angle centered on the magnetic field direction. A sensor with poor angular resolution can thus underestimate the flux by more than a factor of ten, and a sensor with good angular resolution will rarely, if ever, be looking in the correct direction. In particular, there were no observations by the instruments on ATS-5 (DeForest and McIlwain, 1971) even though there must have been thousands of opportunities in the first 3 years of operation. The reason is simple. When auroral electron beams are present, the magnetic field is always tilted between 20 and 70 degrees with respect to the satellite's spin axis so that none of the sensors, which are pointed parallel and perpendicular to the spin axis, is never properly aligned with the magnetic field.

The present observations tend to confirm the speculation by Hones et al (1971) that the bumps sometimes found in the azimuthal dependence of electrons measured by the Vela satellites at 18 earth radii are due to field aligned electron beams. They assume that the bumps occur when the magnetic field direction is included in the 6° by 110° electron acceptance fan, and conjecture that a high resolution detector would measure 20 to 30 times higher fluxes.

THE AURORAL PARTICLES EXPERIMENT ON ATS-6

ATS-6 was launched in geosynchronous orbit (6.62 earth radii) on May 30, 1974 and is being kept near 94° west longitude for about 1 year, after which it is to be moved to 35° east. The orbital inclination is less than 2 degrees. At 94° west, the average magnetic latitude is $+10.5^{\circ}$, and it is estimated that variations in the geographic latitude and the changing aspect to the solar wind can make the distance from the magnetic equator as small as 6° and as large as 15°.

The scientific package on this satellite, the "Environmental Measurements Experiment", includes a good array of particle sensors and an excellent magnetometer, but, unfortunately, no electric field or high frequency wave sensors.

The University of California, San Diego (UCSD) auroral particles experiment on ATS-6 consists of 5 electrostatic analyzers. These measure both ions and electrons over the range of 1 to 80,000 eV with an energy resolution of about 0.2E plus 2 eV full width at half maximum. The analyzers are unique in two ways: the analyzing plates are ovoidal, i.e. have different curvatures in the parallel and perpendicular directions, and there is a short focal length electrostatic lens preceding the 0.3 cm diameter Bendix Spiraltron sensors. The result is a large geometric factor (over 0.001 cm^2 ster) in spite of the small sensor area and, at the same time, good angular resolution: 2.8° by 7° for a flat spectrum.

The spacecraft is three axis stabilized with the scientific package mounted behind the 10-meter diameter parabolic antenna which is normally kept pointed at the earth. To obtain the dependence of the plasma upon pitch angle, one pair of analyzers is mechanically swept from north up to radially out and on to the south covering a range of 220°. To obtain the dependence of the plasma on the azimuthal angle (for flow and gradient determinations) another pair of analyzers is swept back and forth from east up to radially out and on to west before reversing. In each case the motion is at 1.4 degrees per second so that a complete cycle takes 314 seconds. It is also possible to stop the sweeping motion so that time variations in a particular direction can be studied. The fifth analyzer is stationary and measures ions travelling westwards.

The energy range is normally covered in 64 steps taken 4 per second. In between these 16-second energy scans, the instrument can be commanded to dwell on any of the 64 energies for 0, 1, 2, 4, - - -, 128 seconds and to then follow the next scan by a dwell at an energy step that 0, 1, 2, - - - 32 steps higher and to continue this sequence 0, 1, 2, - - -, 64 times. This capability has proven invaluable in studying fast time variations and sharp angular dependences.

The sweeping of the "North/South" pair of analyzers takes the look direction 13° to the west of north instead of directly through north in order to avoid the large solar cell panels. At the 35° east longitude location, the average magnetic field is within a few degrees of this plane of motion. At the 94° west longitude location, the field is usually about 10° away from this plane so that particles with pitch angles less than 10° cannot be measured. Field-aligned currents do, however, sometimes give an azimuthal twist to the magnetic field so that smaller pitch angles can be viewed.

Instantaneous pitch angles are determined using magnetometer data kindly supplied by Dr. P. Coleman and Dr. R. McPherron of the

University of California, Los Angeles. Studies to determine the offsets due to spacecraft magnetic fields are still in progress, but the consistency of the particle data indicates that pitch angle errors are typically less than 4° using present procedures.

The absolute fluxes given in this paper are provisional. In particular, a known gradual rise of about a factor of two in the electron efficiency below 1 keV has not been incorporated in the present conversion algorithms.

FIRST DETECTION OF FIELD-ALIGNED FLUXES

Within the first day of operation, the UCSD plasma detectors encountered three events involving intense beams of electrons travelling along the local magnetic field direction heading toward the northern auroral zone. The differential number flux measured by the two electron sensors during one of these events is shown in Figure 1. For a brief time, the ambient magnetic field was perturbed so that very small pitch angles could be sampled. It is interesting to note that this fortuitous field perturbation could be reasonably explained by assuming the spacecraft encountered a sheet of electrons just like the ones being measured.

The spectrum at large pitch angles has both the shape and intensity typically found in the midnight region at 6.6 earth radii following each magnetospheric substorm (DeForest and McIlwain, 1971). The shape is close to Maxwellian with a temperature of 4000 eV, and the intensity corresponds to a density of 0.9 electrons/cm^3. By contrast, the shape of the spectrum at small pitch angles is unusually peaked, and the absolute differential intensity at 7 keV is believed to be higher than any previous observation in this region of space. On the other hand, this spectrum is both less peaked and less intense than some of the spectra observed (Albert, 1967; Evans, 1968A, 1968B; Westerlund, 1969; O'Brien and Reasoner, 1971; Bryant, Courtier, and Bennett, 1972; Arnoldy, Lewis and Isaacson, 1974) near the earth in association with auroral arcs. The number flux at small pitch angles is 1.5×10^9 electrons/cm^2 s ster) compared with 1.8×10^8 at large angles. The energy fluxes are 19. and 2.2 ergs/(cm^2 s ster) respectively. As will be shown, the beam occupies only a very small solid angle and thus does not make a large contribution to the omnidirectional fluxes. When these electrons approach the northern auroral zone, their pitch angles become much larger so that they would deposit energy at about the rate of 100 ergs/cm^2 sec provided they are not repulsed or further accelerated by parallel electric fields. This energy flux is sufficient to produce bright auroral light emissions.

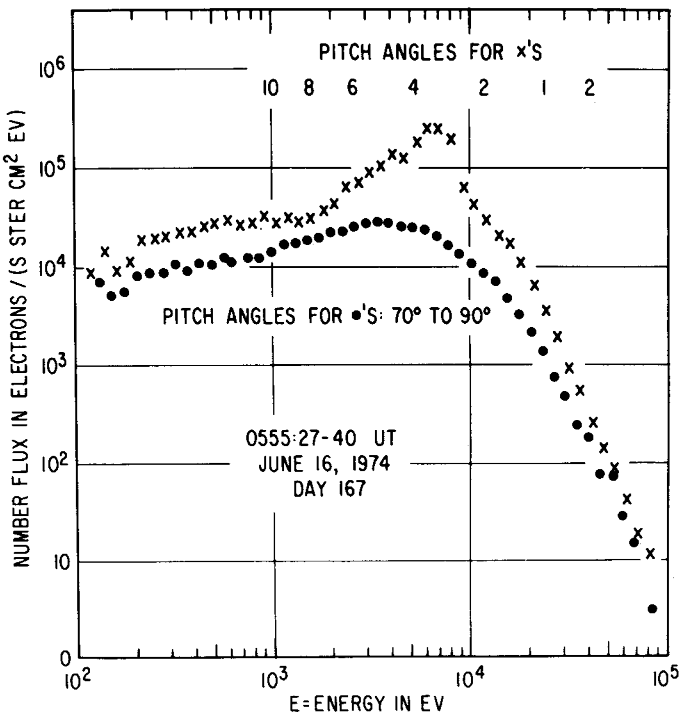

Figure 1 The differential number flux of electrons travelling close to the magnetic field direction measured during the first minutes of a magnetospheric substorm plasma injection.

Figure 2 is an energy-time (and angle) spectrogram of data taken by the pair of detectors sweeping past north and south each 5.23 minutes. The magnetic field is inclined between -40 and -65 degrees to the horizontal plane during this time period (as is normal for this region of space at the root of the geomagnetic tail and at a magnetic latitude of +11 degrees). The detectors thus view particles going along the magnetic field twice each sweep cycle (at about half-way between vertical and south). Particles travelling antiparallel to the field (heading for the magnetic equator and on toward the southern hemisphere) come up from below the spacecraft and cannot be observed. The dark vertical lines in the electron part of the spectrogram are produced by the deficiency in high energy electrons in the vicinity of the "loss cone". Also bright vertical lines can be seen at lower energies indicating the presence of what might be termed the "source cone". Arrows mark the three times that intense fluxes were seen in the source cone. The spectra shown in Figure 1 were taken at the time of the second arrow.

The two bright features at the bottom of Figure 2 are made by low energy ambient ions accelerated by a varying negative spacecraft potential. Most of the lowest energy electrons are believed to be spacecraft produced photoelectrons and secondary electrons that are returned to the spacecraft by a negatively charged sheath (Whipple, 1975). The periodic structure at the bottom of the electron portion of the spectrogram is an artifact produced by a 16-second dwell at 24 keV every 128 seconds (and by an unfinished computer program).

Figures 3 and 4 show the portions of the distribution function corresponding to the spectra in Figure 1. The shape seems to be one which should excite waves which would tend to flatten the peak. The peak is less than a factor of two higher than the minimum, indicating that such processes may have already modified the velocity distribution. The statistical accuracy in the vicinity of the peak is quite good. As will be shown later, the irregularities are probably due to fast time variations and not to fine structure in the instantaneous velocity distribution. It is not impossible that the distribution is in fact flat, with the relative minimum being an artifact of time and angle variations.

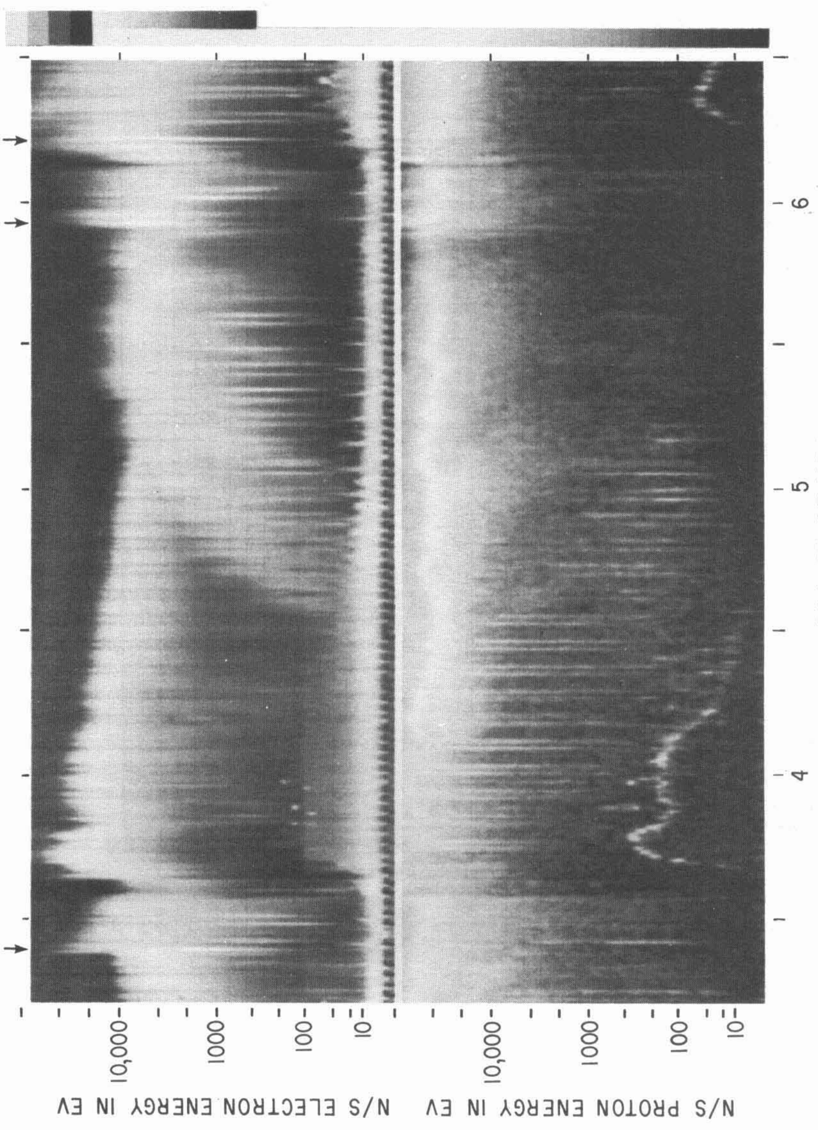

Figure 2 An energy-time spectrogram of 3 hours data obtained on June 16, 1974 by the North/South analyzers of the UCSD experiment on ATS-6. The periodic structure is due to the analyzers mechanically sweeping back and forth over a 220° range each 314 seconds.

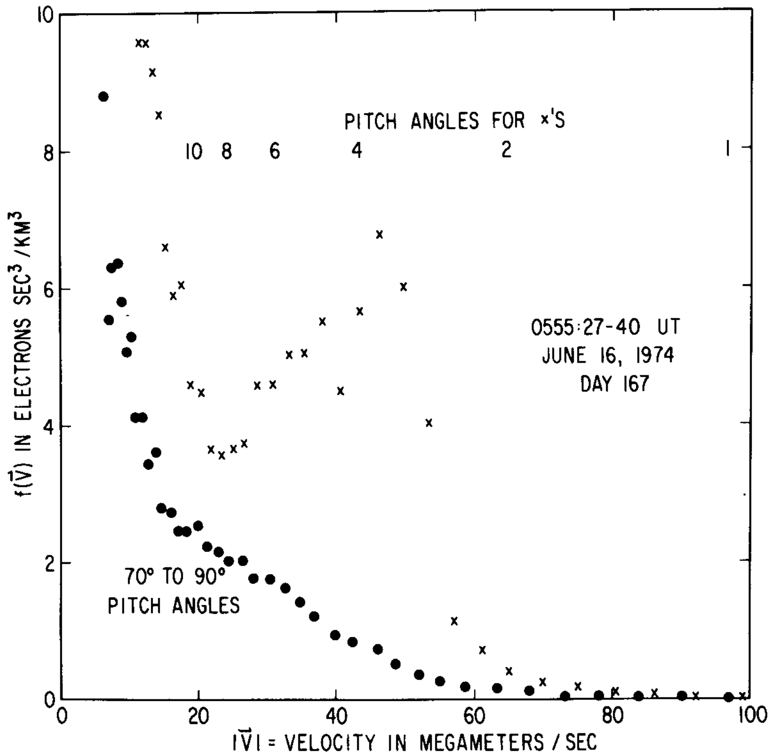

Figure 3 The portions of the distribution function $f(\vec{v})\ d^3x d^3v$, corresponding to the spectra shown in Figure 1.

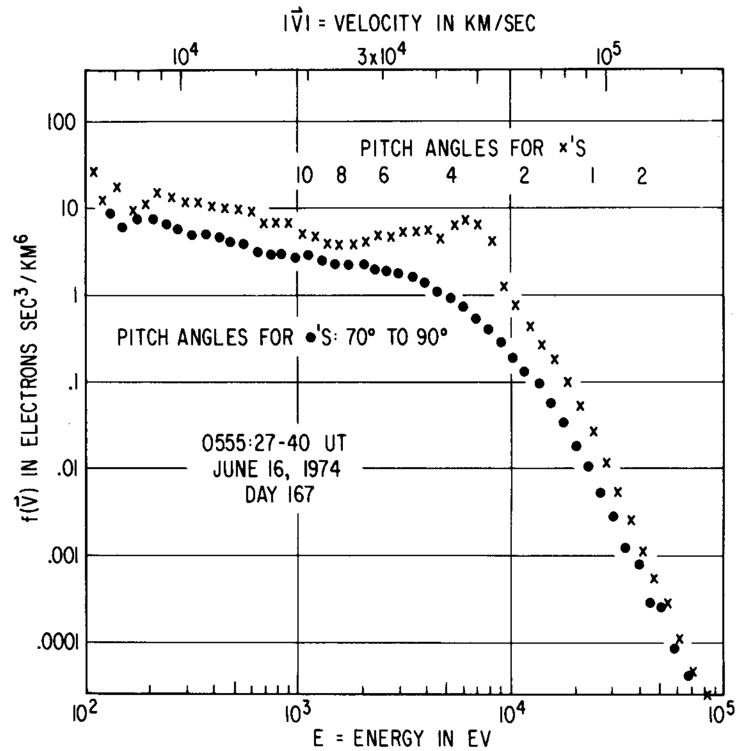

Figure 4 The distribution function replotted using logarithmic scales.

CONTEXT IN WHICH THE BEAMS ARE FOUND

Figure 5 shows the velocity distributions measured during an event on July 20, 1974. Again, the distribution is relatively flat or slightly rising up to a break point, beyond which it decreases very rapidly -- in this case approximately as $E^{-3.5}$ or v^{-7}.

To show the full context of this event, 24 hours of data from both ATS-6 and ATS-5 are shown in Figures 6 and 8. ATS-5 is also in synchronous orbit at a longitude of 105° west, which is 11° west of ATS-6. Analysis of these spectrograms in terms of drifting plasma clouds injected during each magnetospheric substorm (DeForest and McIlwain, 1971; McIlwain, 1972; McIlwain, 1974; Kamide and McIlwain, 1974) indicates that substorms occurred at about 0020, 0440, 0520, 0635, 1010, and 2020 UT. The number and intensity of the first five substorms is typical for the observed K_p magnetic index values of around 2. The similarity between the two data sets is striking, considering that the spacecraft are over a thousand kilometers apart. This confirms the previous conclusion that substorm injections occur almost simultaneously over a wide region of space (McIlwain, 1974).

ATS-6 encountered the first electrons associated with the plasma sheet at 0350 UT. If this "cold plasma" boundary were stationary in local time, ATS-5 would encounter it 4 x 11° = 44 minutes later, at 0434 UT (Mauk and McIlwain, 1974). The ATS-5 spectrogram shows that the boundary was encountered as expected, but that the 0440 UT substorm rapidly replaced this low energy residual of previous injections with a fresh hot plasma.

The very low energy ions visible at the lower left of Figure 6 can be used to measure the plasma flow velocity. Between 0 and 2 hours UT (18 and 20 hours local time), these ions do have a measureable drift velocity in the westward direction (relative to the 3 km/sec eastward motion of the spacecraft). Determination of the magnitude of the flow is greatly complicated, however, by variable large amplitude transverse Alfvén waves which are common at these local times. In this case, their period was 3 to 4 second, and their perturbations of the flow velocity were often comparable to the average flow rate. These waves were presumably driven by the anisotropic energetic ion population which was present at that time.

Figure 7 is an expanded version of Figure 6 which shows that the plasma injected by the 0440 UT substorm was almost isotropic over the measured pitch angle range of 17° to 135°. By 0505 UT, however, the high energy electrons had already developed a pronounced deficiency around the loss cone. The 0520 UT event was either localized at some distance from the two spacecraft or was something different than a regular substorm. At 0518 UT, there was a

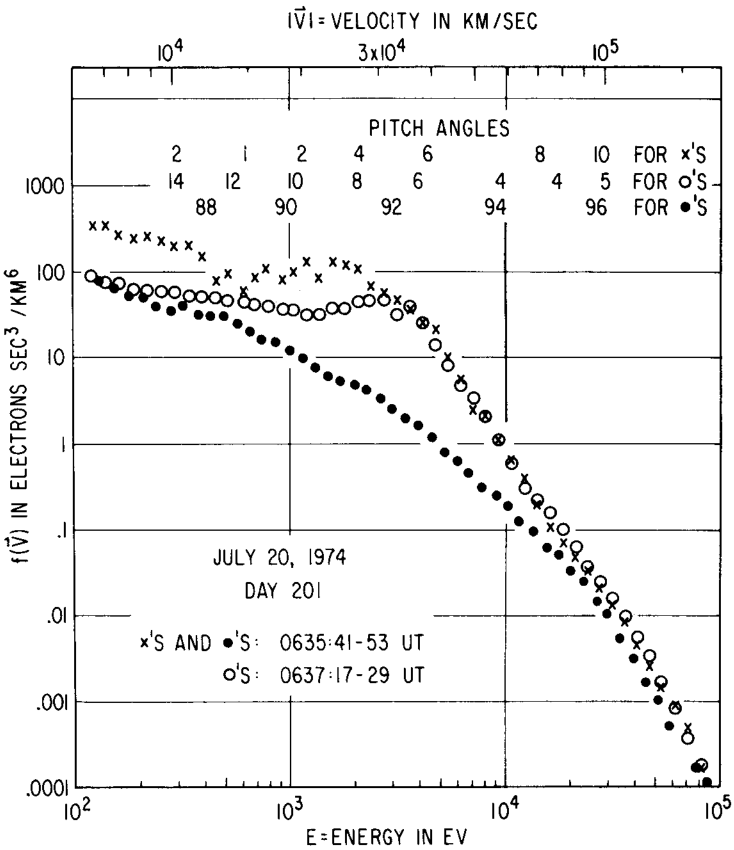

Figure 5 Distribution functions measured shortly after a substorm on July 20, 1974.

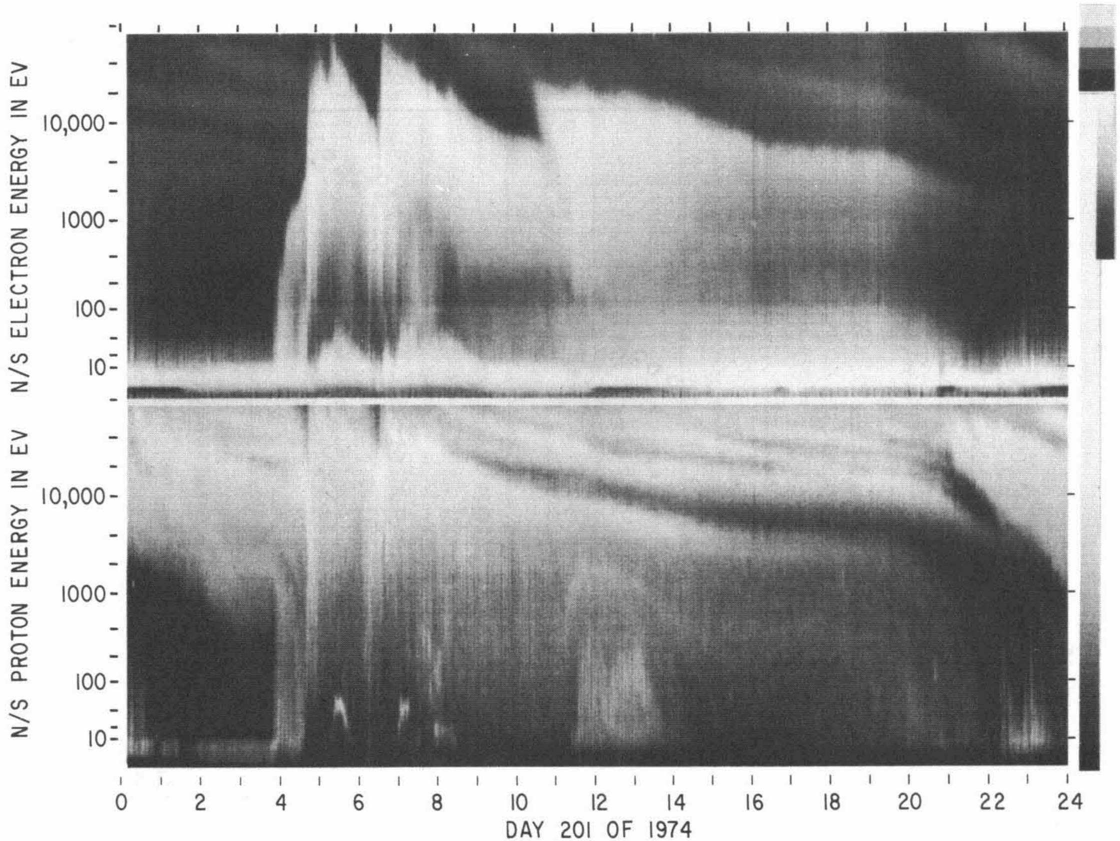

Figure 6. An energy-time spectrogram of 24 hours of data obtained on July 20, 1974 by the North/South analyzers on ATS-6. The structure due to the periodic motion of the analyzers is almost invisible on this time scale.

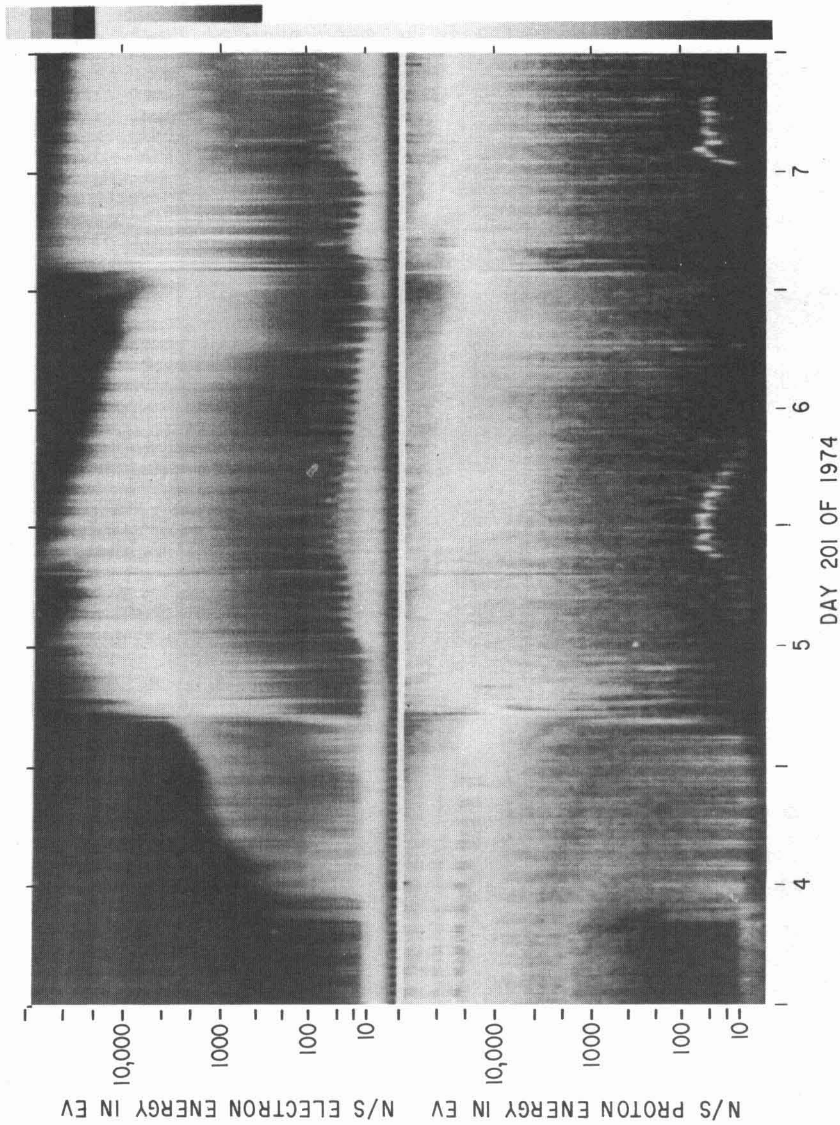

Figure 7 An energy-time spectrogram of 4 hours of data obtained on July 20, 1974 by the North/South analyzers on ATS-6. Details of particle behavior during the 0440, 0520 and 0635 substorms are visible.

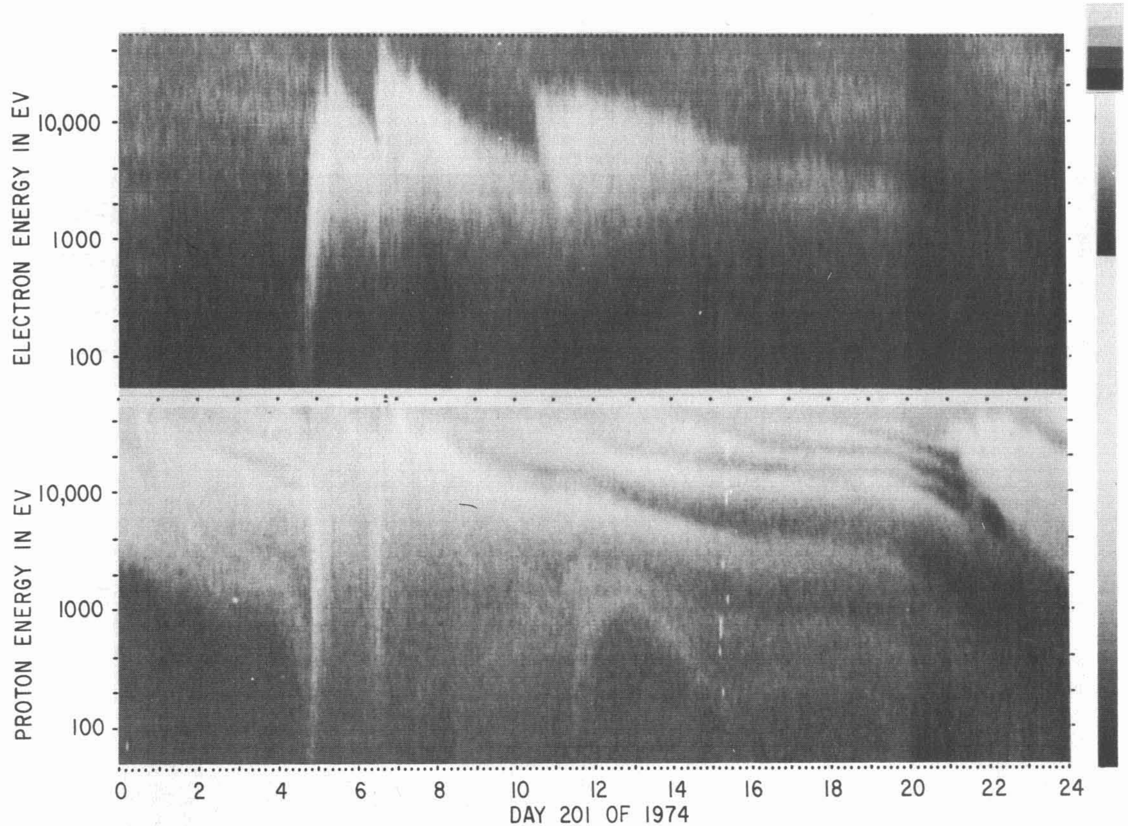

Figure 8 An energy-time spectrogram of 24 hours of data obtained on July 20, 1974 by the UCSD analyzers on ATS-5 measuring the electrons parallel to the spin axis and the ions perpendicular to the spin axis.

momentary factor of two change in both ion and electron fluxes and a simultaneous variation in the magnetic field. This suggests the data should be studied in terms of the passage of a solitary wave (soliton).

As can be seen in Figures 5 and 7, the 0635 event did produce a short lived intense beam of electrons. Within 15 minutes, however, the electron distribution was almost isotropic except for the usual empty loss cone region at high energies. This is about the time expected for the development of a loss cone when there is strong pitch angle diffusion (Schulz, 1974).

It is interesting to note that while the most energetic ions also develop an empty loss cone, the ions with energies less than 10 keV are enhanced at small pitch angles. In other words, their "source cone" region is filled. Field-aligned ion fluxes have also been observed near the ionosphere (Hultqvist et al, 1971).

Referring back to Figure 2, it can be seen that parallel beams of ions were present on day 167 with a slowly decreasing maximum energy between 0400 and 0500 UT. Around 0500 UT it can be seen that both parallel ions and electrons are present at low energies.

Simultaneous ion and electron beams at high energy, however, do <u>not</u> seem to occur. This strongly suggests that the beams are to be associated with parallel currents. Unfortunately, the net current cannot be measured using data taken at the 94° west longitude location, because particles with pitch angles around 180° are obscured by the spacecraft.

PITCH ANGLE DEPENDENCE AND RAPID TIME VARIATIONS

On July 3, 1974 (day 184), the auroral particles experiment was commanded to dwell successively at 1.6, 1.8, 2.1, and 2.4 keV for 128 seconds between the regular 16-second energy scans. Figure 9 shows a case in which the North/South detectors swept almost directly past the field line direction while dwelling at 1.6 keV. In the absence of a parallel electric field, particles with pitch angles less than 3° go to altitudes of less than 500 km in the northern auroral ionosphere. Ignoring an apparent offset of about 4°, the pitch angle distribution has a width at half maximum of about ± 10°. Figure 10 is a replot of the same data on a linear scale. Large fast fluctuations are present but <u>only</u> within the central ± 5°.

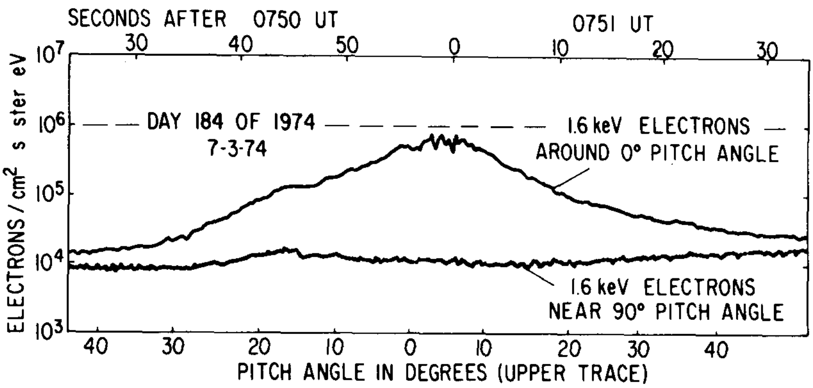

Figure 9 The time and pitch angle dependence of electrons measured during a long dwell at a fixed energy of 1.6 keV.

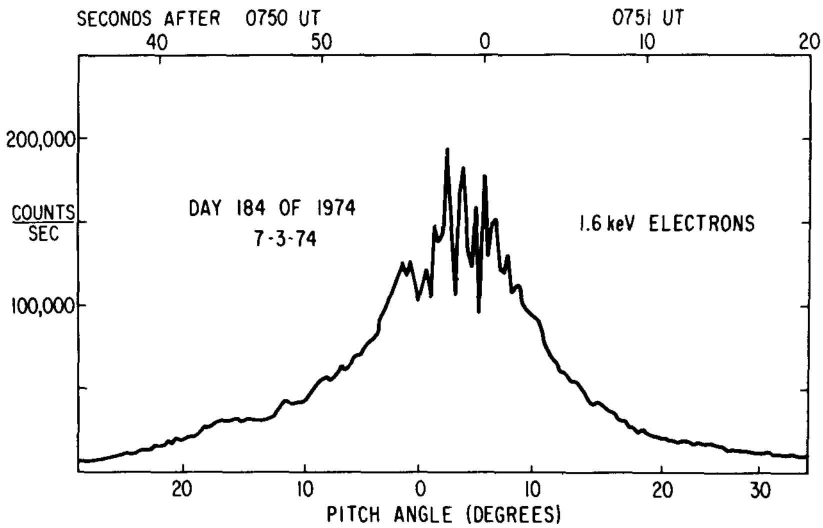

Figure 10 A replot of Figure 9 on linear scale to exhibit the fluctuations in the central $\pm 5^{\circ}$.

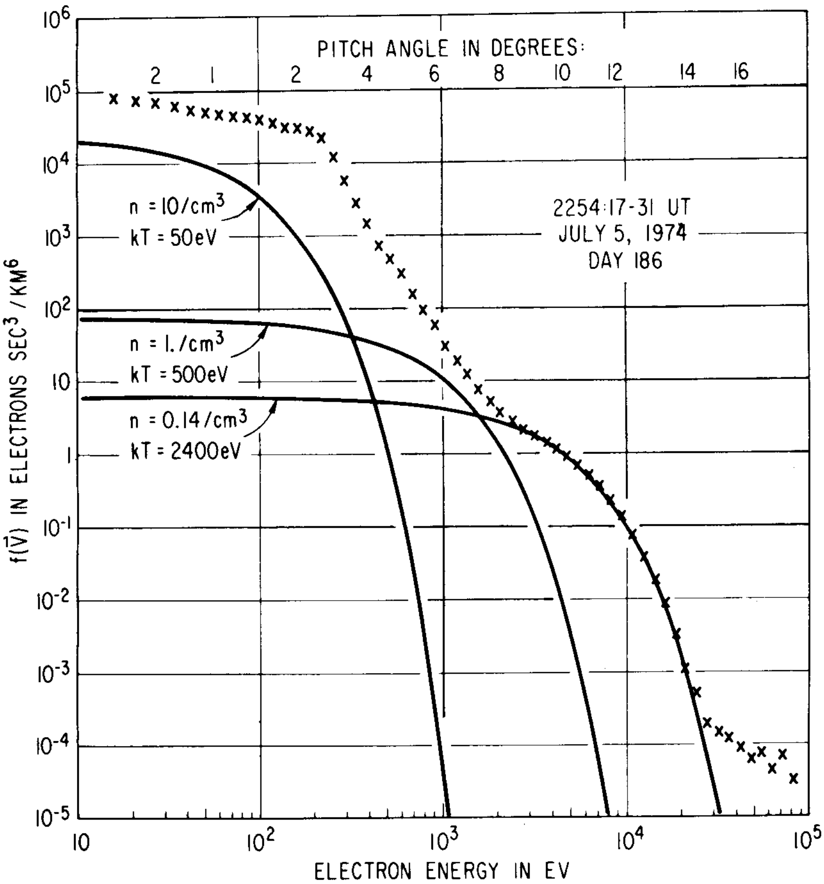

Figure 11 A distribution function measured at 17 hours local time during a magnetic storm. Also shown are 3 isotropic Maxwellian distributions. The $10/cm^3$ and $1/cm^3$ examples correspond roughly to the distributions found in the magnetosheath and in the plasma sheet respectively.

One possibility is to have an initial beam of field-aligned electrons which excites waves, which in turn scatter some of the electrons into neighboring pitch angles (where they can survive for longer periods of time). It seems difficult to account for all characteristics of the observed beams by means of simple convection driven Fermi acceleration (Axford, 1968). The addition of parallel electric fields to this process, however, might yield a viable theory (Fälthammar, 1972; Boström, 1974; Heikkila, 1974) In this case, the electrons in the neighboring pitch angles could be part of the parent population instead of scattered ones.

ORIGIN OF THE ELECTRONS

The distribution function of electrons normally found in the plasma sheet of the magnetotail reaches values of about 100 electrons sec^3/km^6. The distributions shown in Figures 4 and 5 could therefore have been produced by accelerated plasma sheet electrons. In other field-aligned events, however, much larger phase space densities have been observed. One such event was observed in the late afternoon during a large magnetic storm. Figure 11 shows that electrons with energies less than 200 eV had densities exceeding 10,000 sec^3/km^6. There are only two available sources of electrons with this density: the magnetosheath and the ionosphere.

At this point it must be remembered that the residence time of particles on the closed field lines in the 5 to 15 earth radii region can be many hours. This is quite long enough for substantial densities of ionospheric particles to accumulate by means of parallel current driven transport to great heights, and by concurrent wave scattering into trajectories with high altitude mirror points. The ATS-6 data provide strong evidence that this process does in fact occur, and that it may be operating almost continuously over a wide region of space.

CONCLUSION

The observed electron beams presumably carry a net current even though this cannot be proven using the present particle data. It seems probable, however, that the magnetic variations observed during the events can be used to resolve this question. A complete absence of electrons around 180° pitch angles is not to be expected because of pitch angle scattering within one-half of a bounce period caused both by waves and by collisions in the ionosphere.

Ignoring the opposing contribution of these electrons, current densities per unit solid angle of 2.5, 8., and 13. $\mu A\ m^{-2}\ ster^{-1}$ are obtained for the spectra observed at 0555 UT on day 167, at 0635 UT on day 201 and at 2254 UT on day 186 respectively. If confined to a 5^{o} half-angle cone, the current densities are only 0.06, 0.2, and 0.3 $\mu A/m^2$. When the beam approaches the ionosphere, the converging magnetic field increases the current density by at least a factor of 100 giving values greater than 6, 20, and 30 $\mu\ A/m^2$ respectively. These are similar to the current densities observed flowing in and out of the ionosphere (Vondrak, Anderson, and Spiger, 1971; Choy et al, 1971; Cloutier et al, 1973; Armstrong, 1974; Arnoldy, 1974; Zmuda and Armstrong, 1974). There is thus every reason to assume that the equatorial electron beams are part of a Birkeland current system.

While the observed electrons are capable of producing bright auroras, acceleration in or near the ionosphere does still seem to be required to explain the low altitude observations of field-aligned quasi-monoenergetic electrons (Arnoldy, 1974).

It is quite possible, however, that the electron beams observed near the equator in fact establish and maintain the potential differences believed to be responsible for electron acceleration near the ionosphere (Hultqvist, 1971; Evans, 1974).

ACKNOWLEDGMENTS

I thank R. LaQuey, R. Judge, W. Fillius, and E. Strein for their contributions in the design and construction of the ATS-6 Auroral Particles Experiment Detector; G. Peters and L. McDaniel for preparing computer programs; and S. DeForest and B. Mauk for their assistance in the ATS-6 calibrations and data analysis. This research was supported by NASA Grant NGL 05-005-007 and Contracts NAS 5-10364 and NAS 5-21055.

REFERENCES

Albert, R. D., Nearly monoenergetic electron fluxes detected during a visible aurora, Phys. Rev. Letters, 18, 369, 1967a.

Armstrong, J. C., Field aligned currents in the magnetosphere, Magnetospheric Physics, ed. B. M. McCormac, p. 155, D. Reidel Pub. Co.., Dordrecht, Holland, 1974. (Ref. in Zmuda, A. J., and J. C. Armstrong, The diurnal flow pattern of field-aligned currents, J. Geophys. Res. 79, 4611, 1974).

Arnoldy, R. L., Auroral particle precipitation and Birkeland currents, Rev. of Geophys. and Space Phys., 12, 217, 1974.

Arnoldy, R. L., R. B. Lewis, and P. O. Isaacson, Field-aligned auroral electron fluxes, J. Geophys. Res., 79, 4208, 1974.

Axford, W. I., Magnetospheric convection, Rev. of Geophys. 7, 421, 1969.

Boström, R., Ionosphere-magnetosphere coupling, Magnetospheric Physics, ed. B. M. McCormac, p. 45, D. Reidel Pub. Co., Dordrecht, Holland, 1974.

Bryant, D. A., G. M. Courtier, and G. Bennett, Electron Intensities over auroral arcs, Earth's Magnetospheric Processes, ed. B. M. McCormac, p. 141, D. Reidel Pub. Co., Dordrecht, Holland, 1972.

Choy, L. W., R. L. Arnoldy, W. Potter, P. Kintner, and L. J. Cahill, Field-Aligned particle currents near an auroral arc, J. Geophys. Res. 75, 8279, 1971. (Ref. in Zmuda and Armstrong, The diurnal flow pattern of field aligned currents, J. Geophys. Res. 79, 4611, 1974.)

Cloutier, P. A., B. R. Sandel, H. R. Anderson, P. M. Pazich, and R. J. Spiger, Measurement of auroral Birkeland currents and energetic particle fluxes, J. Geophys. Res., 78, 640, 1973.

DeForest, S. E., and C. E. McIlwain, Plasma clouds in the magnetosphere, J. Geophys. Res. 76, 3587, 1971.

Evans, D. S., Fine structure in the energy spectrum of low energy auroral electrons, in Atmospheric Emissions, eds. B. M. McCormac and A. Omholt, p. 107, Van Nostrand Reinhold, New York, 1969.

Evans, D. S., Observations of a near monoenergetic flux of auroral electrons, J. Geophys. Res. 73, 2315, 1968.

Evans, D. S., Precipitating electron fluxes formed by a magnetic field aligned potential difference, J. Geophys. Res. 79, 2853, 1975.

Fälthammar, C.-G., Magnetospheric processes, Earth's Magnetospheric Processes, ed. B. M. McCormac, p. 16-28, D. Reidel Pub. Co., Dordrecht, Holland, 1972.

Hall, D. S., and D. A. Bryant, Collimation of auroral particles by time-varying acceleration, Nature 251, 5474, 1974.

Heikkila, W. J., Outline of a magnetospheric theory, J. Geophys. Res. 79, 2496, 1974.

Hones, E. W., Jr., J. R. Asbridge, S. J. Bame, and S. Singer, Energy spectra and angular distributions of particles in the plasma sheet and their comparison with rocket measurements over the auroral zone, J. Geophys. Res. 76, 63, 1971.

Hultqvist, B., On the production of a magnetic-field-aligned electric field by the interaction between the hot magnetospheric plasma and the cold ionosphere, Planet. Space Sci. 19, 749, 1971.

Hultqvist, B., H. Borg, W. Riedler, and P. Christophersen, Observations of magnetic-field aligned anisotropy for 1 and 6 keV positive ions in the upper ionosphere, Planet. Space Sci. 19, 279, 1971.

Kamide, Y., and C. E. McIlwain, The onset time of magnetospheric substorms determined from ground and synchronous satellite records, J. Geophys. Res. 79, 4787, 1974.

Lenard, -, Über die Absorption der Nordlichtstrahlen in der Erdatmosphäre', S. B. Heidelberg. Adal. Wiss., Math. Naturw. Kl. 1911, No. 12.
(Ref. in International Monographs on Radio, ed. by E. Appleton and R. L. Smith-Rose, Oxford University Press, London, p. 192, 1955.)

Mauk, B. H., and C. E. McIlwain, Correlation of K_p with the substorm-injected plasma boundary, J. Geophys. Res. 79, 3193, 1974.

McIlwain, C. E., Direct measurement of particles producing visible auroras, J. Geophys. Res. 65, 2727, 1960.

McIlwain, C. E., Plasma convection in the vicinity of the geosynchronous orbit, Earth's Magnetospheric Processes, ed.

B. M. McCormac, p. 268, D. Reidel Pub. Co., Dordrecht, Holland, 1972.

McIlwain, C. E., Substorm injection boundaries, Magnetospheric Physics, ed. B. M. McCormac, D. Reidel Pub. Co., Dordrecht, Holland, 1974.

O'Brien, B., and D. L. Reasoner, Measurements of highly collimated, short-duration bursts of auroral electrons and comparison with existing auroral models, J. Geophys. Res. 76, 8258, 1971.

Omholt, A., Studies on the excitation of aurora borealis, 1, the hydrogen lines, Geofys. Publikasjoner, 20 (11), 1-40, 1959.

Schulz, M., Particle lifetimes in strong diffusion, Astrophys. & Space Science 31, 37, 1974.

Shook, G. B., R. D. Sharp, M. F. Shea, R. G. Johnson, and J. B. Reagan, Trans. Am. Geophys. U. 47, 64, 1966.

Störmer, C., The polar aurora, Oxford University Press, London, 1955.

Vondrak, R. R., H. R. Anderson, and R. J. Spiger, Rocket-based measurements of particle fluxes and currents in an auroral arc, J. Geophys. Res. 76, 7701, 1971.
(Ref. in Zmuda and Armstrong, The diurnal flow pattern of aligned currents, J. Geophys. Res. 79, 4611, 1974).

Westerlund, L. H., The auroral energy spectra extended to 45 eV, J. Geophys. Res., 74, 351, 1969.

Whalen, B. A., and I. B. McDiarmid, Observations of magnetic-field-aligned auroral electron precipitation, J. Geophys. Res. 77, 191, 1972.

Whipple, E. C., private communication, 1975.

Zmuda, A. J., and J. C. Armstrong, The diurnal flow pattern of field-aligned currents, J. Geophys. Res. 79, 4611, 1947.