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BY THE POGO ION CHAMBER EXPERIMENT.

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High Latitude Ionization Spikes
Observed by the POGO Ion Chamber Experiment

by ^{miss}
James E. McCoy

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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Ph.D.

Thesis Director's Signature

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INTRODUCTION

INTRODUCTION

Magnetosphere

The gross structural features of the magnetosphere predicted by theory have been confirmed by satellite experiments and it is now possible to describe the general shape and extent of the magnetospheric cavity in the solar wind [O'Brien, 1966], including the "tail" streaming behind $>80 R_E$ [Dessler, 1964; Ness, 1965; Behannon, 1968], the hydromagnetic shock in front [Ness et al, 1964], and the major temporal variations in the shape and location of the magnetospheric cavity in response to variations in the solar wind, with full confidence that any errors in the description are confined to structural details and do not affect the basic model. Using this established basic model (Figure 1), various authors have investigated refinements to the primary B,L coordinates developed to conform to particle motions in a dipole field [McIlwain, 1961]. Of particular importance are the inclusion of the effects of the magnetopause and magnetotail neutral sheet currents in limiting the extent and distorting the symmetry of the region of the closed, dipole-like field lines [Mead, 1964; Williams and Mead, 1965; Shield, 1968], L-shell "splitting" due to the departure from a true dipole field [Roederer, 1967] and displacement of "L-shells" from their normal location in space during magnetic disturbances [Kavanagh, 1968]. As yet untested theories have also been evolved to deal with energy transfer across the magnetopause [Dessler and Walters, 1964], the distant structure

of the tail with open [Dessler, 1964] or closed field lines [Axford and Hines, 1961], and plasma convection within and through the magnetosphere. These models provide a necessary and reliable framework on which to organize the observations made on the charged particle populations in space.

Trapped Particles

Since the original discovery of the trapped radiations about the Earth [Van Allen, 1959], extensive satellite experiments have added much data regarding charged particle populations, particularly those associated with the magnetosphere. The original Van Allen belts have been mapped in detail [Owens and Frank, 1968; Vette, 1966; and many others]. The inner zone has been found to be highly stable. Observations of the Starfish fission electrons showed decay rates in the region $L = 1.2$ to 1.5 to be of the order of 300 days [Walt, 1964]. Population changes occurring during magnetic disturbances can be accounted for on the basis of adiabatic compression and expansion of the magnetosphere with no new particle populations being injected. Diffusion across L shells is very slow, if present at all. The Explorer 14 data [Frank, 1965] shows apparent diffusion rates for 1.6 Mev electrons of ~ 0.007 L/day at $L \approx 3.2$, while the Explorer 4 data [Van Allen et al., 1959] places an upper limit of ~ 0.002 L/day at $L = 2.1$. The decay of galactic and solar cosmic ray albedo neutrons probably provides a source for more energetic inner radiation zone particles [Hess, 1966; Hess and Killeen, 1966], but cannot account for all, particularly those of lower energies [O'Brien, 1966].

In contrast, the outer zone has been found to vary greatly with time. The energetic (>1 Mev) electron populations in this region are observed to be enhanced following a few days after magnetic storms [Freeman, 1964]. They are observed to decay during periods of magnetic quiet with an exponential time constant of from 2 to 7 days, the rate of decay decreasing with L from L = 6 to L = 4.0 respectively [Williams and Smith, 1965]. These electrons seem to diffuse inward from high L, conservation of the magnetic moment leading to particle energies increasing as L^{-3} . Nakada and Mead [1965] and Hess et al., [1964] have calculated the particle spectra and intensities which would result from such diffusion according to the Fokker-Planck equation. Their calculations predict an L^{-8} dependence of diffusion rates resulting from magnetic disturbances. The predictions of this theory are found to agree very well with observations by Frank [1965] for an assumed mechanism injecting ~150 kev electrons through the magnetopause at times of strong magnetic disturbance. It has also been shown to agree with observed outer zone proton distributions, if the proton injection is assumed continuous in time, rather than intermittent like the assumed 150 kev electron injection [Nakada and Mead, 1965]. The boundary of stable trapping for energetic particles has been found to be normally around L = 8 from observations of energetic electrons, both in the equatorial plane by Explorer 12, ATS, and IMP and at high latitudes by low altitude polar orbiting satellites (Injun 1, 3, and 4, Alouette, anonymous USAF launches).

The fluxes simultaneously observed at similar L values near the equator correlate closely with those at high B values' [Craven, 1966] .

The observed boundary of trapping varies with geomagnetic activity, normally being depressed to lower invariant latitudes during magnetic storms [Ness and Williams, 1966; Rosen, 1965] . The boundary of trapping has also been shown to exhibit a day-night asymmetry due to the solar wind, occurring at lower invariant latitudes at local midnight than local noon [O'Brien, 1963; Williams and Mead, 1965; Freeman, 1964; Frank et al., 1963] .

Precipitated Particles

Low altitude polar orbit satellite and auroral zone sounding rockets have detected energetic particles following trajectories leading to immediate loss in the atmosphere on a majority of passes through L values of 3.5 to 8, as well as occasional occurrences in the polar cap [O'Brien, 1964; Blake et al., 1966; Sharp and Johnson, 1968] . Fluxes of precipitated electrons with energies ≥ 40 kev ranging upwards of $10^5/\text{cm}^2 \text{ sec}$ ster have been observed, pitch angles tending toward isotropic distribution for higher flux values and rapid fluctuations with time [O'Brien, 1963; Mozer, 1966; Cummings et al., 1966] . The energy spectrum of the precipitating particles has been observed to be softer near local midnight during a visible aurora than near local dawn when precipitation was occurring with no associated visible aurora [Cummings et al., 1966] . Mozer [1966] has observed the break-up phase of an IBCI aurora and found the electrons

were being energized in a single bounce. Associated with the concurrently observed anti-correlation between precipitating proton and electron fluxes, this observation implies the existence of electric potentials of kilovolts acting along the field lines at the time of precipitation.

Precipitated fluxes of higher energy electrons ($E > 1$ Mev) are also observed, and exhibit space and time variations independent of those affecting the lower energy electrons. O'Brien [1964] observed fluxes of electrons with $E_{\beta} \gtrsim 1$ Mev, which remained unperturbed while electrons with $E_{\beta} \gtrsim 40$ kev were being strongly precipitated at the same location. Mozer [1966] also observed what he termed electron "groups" with energies greater than 400 kev, which varied independently of the simultaneously observed auroral electrons.

Particles in the Tail and Distant Radiation Zones

The existence of large intermittent fluxes of electrons (electron "islands") in the magnetotail has been discovered by experiments aboard IMP I [Anderson et al., 1965; Anderson, 1965; Murayama, 1966] and confirmed and further studied with the Explorer 14 [Konradi, 1966] and Vela 2 [Montgomery, 1968] satellites. The results of these investigations indicate that electrons and protons are impulsively injected into tail field lines. These particles are not believed to be trapped in any fixed relationship to the Earth, as they are observed in the tail at radial distances up to $80 R_E$ with no discernible dependence on distance. Their occurrence is observed to concentrate

preferentially within a few R_E of the neutral sheet and toward the dawn side of the tail. Frequency of occurrence also shows a strong dependence on K_p .

The flux "islands" are observed to normally (in about 70 percent of all occurrences) show a characteristic "fast-slow" behavior, the flux increasing to its peak value in less than five minutes and decaying with time constant greater than 15 minutes. The order of occurrence (fast-slow rather than slow-fast) does not depend on position or whether inbound or outbound in orbit. Peak fluxes are frequently in the range of 10^5 to $2 \times 10^7 \text{ cm}^{-2}\text{sec}^{-1}$ for electrons with energies greater than 40 keV. Their energy spectrum is generally represented by a power law distribution with exponent of 4 ± 2 . Simultaneous proton fluxes are often observed, with peak values of $\lesssim 10^4 \text{ cm}^{-2}\text{sec}^{-1}\text{ster}^{-1}$ at energies greater than 125 keV and differential power law spectra $\delta \sim 5 - 8$.

Two other distinct regions in the distant radiation zone have been identified by experimenters [Anderson, 1965; Murayama and Simpson, 1968].

The "Cusp" region is located at about $12 \pm 2 R_E$ on the night side immediately outside the apparent boundary of stable trapping for the Van Allen particles, and confined to approximately $\pm 20^\circ$ MLAT. Electron fluxes in this region are variable, but remain consistently high ($J(E_\beta \gtrsim 40 \text{ keV}) \sim 10^5\text{-}10^8 \text{ cm}^{-2}\text{sec}^{-1}$). They display a much softer spectrum than the Van Allen particles, as do the other distant radiation zone electrons (in the "skirt" and magnetotail regions). They are distinguished from the electron "islands" observed in the tail by the absence of the characteristic "fast-slow" behavior described for the electron "islands".

The "Skirt" region is located on the day side of the magnetosphere, between the boundary of stable trapping and the magnetopause. Fluxes of soft electrons are observed in this region, extending around the edges of the magnetosphere to at least 120° satellite-earth-sun angle. These fluxes are distinguished from those in the tail "islands" and the "cusp" by their extremely sharp fluctuations with radial distance which do not show any sign of the characteristic "fast-slow" variation of the "island" fluxes. These features appear to be a temporal effect due to large scale oscillation of the location of the magnetopause [Anderson et al., 1968] .

Both the IMP I and Vela 2 experiments saw instances of apparent strong modulation of particle fluxes by MHD waves, with characteristic periods of 5 or 6 minutes.

McDiarmid and Burrows [1965] , using the Alouette I polar satellite, have observed spikes of electrons with intensities up to $J(E_\beta \gtrsim 40 \text{ kev}) \sim 10^9 \text{ cm}^{-2}\text{sec}^{-1}\text{ster}^{-1}$. They report these spikes normally have widths (in invariant latitude) of less than 2° and occur predominantly in the night hemisphere. The energy spectrum for electrons in the spikes is much softer than that found in the normal outer zone electrons (power law exponent of 4 - 7 in spikes vs. 2 - 4 for the outer zone). They argue that these spikes are the same particles seen in the tail as "islands".

OBJECTIVE OF THIS RESEARCH

The basis for this research paper is the reduction and analysis of ion chamber data returned by an experiment flown on the POGO earth satellite. This data is processed to obtain total ionization values due to radiation penetrating 0.2 gm/cm^2 as a function of position and time.

The data thus obtained cover a range of altitude $\sim 1,000 \pm 500$ km for all values of latitude and longitude. There are several areas in which this body of data is of particular interest:

- 1) Cosmic ray propagation through the magnetosphere
- 2) Distribution of high energy trapped radiations at low altitude
- 3) Study of solar proton propagation into the polar caps
- 4) Study of location of boundary of trapping for high energy particles
- 5) Study of anomalous flux enhancements near the boundary of trapping

The last named area of investigation was chosen for detailed analysis and comparison with current theoretical models of the outer magnetosphere environment. The behavior of energetic charged particles in this particular region, near the boundary of magnetic trapping, is of great current theoretical interest. The POGO data provides a large body of new information related to the high energy particle fluxes in this region.

The expected behavior of energetic particles in current theoretical models of the magnetic field configuration near the boundary of magnetic trapping is examined for particular situations. This expected behavior is compared with the actual POGO observations. Recent concepts such as L-shell splitting are shown to have a very important bearing on the latitude and local time dependence of high energy particle fluxes near the boundary of trapping.

The POGO results are also compared with related studies by other experimenters, particularly those of Anderson showing electron "islands"

present in the tail and the observation of electron flux spikes at low altitude/high latitude by McDiarmid and Burrows.

THE EXPERIMENT

POGO

The OGO-C spacecraft was launched into polar orbit October 14, 1965, becoming the first Polar Orbiting Geophysical Observatory (POGO), also known as OGO-2. The initial orbit was inclined 87.4 degrees to the Earth's equatorial plane with perigee of 413 km, apogee of 1512 km, and period of 104.3 minutes. The orbital plane lay near the dawn-dusk meridian, with the ascending node precessing $-.284$ degrees/day from its initial position of 280.5° R.A. The argument of perigee was initially at 144.2 degrees and precessing $+3.05$ degrees/day.

The POGO spacecraft was designed to be stabilized with respect to the Earth horizon, but a malfunction of the control system resulted in loss of stabilization due to pre-mature control gas exhaustion after 10 days in orbit. Partial stabilization was still obtained from the inertial system, however optimum orientation of the solar power panels was no longer possible. This resulted in intermittent shut-down of telemetry and/or experiments due to lack of adequate power, particularly during periods of eclipse. Since the ion chamber experiment is essentially an omnidirectional measurement insensitive to actual orientation of the instrument, our experiment was unaffected by the loss of spacecraft orientation other than by the loss of data during periods of low power. Very little data was obtained during periods while the orbital plane was within 30 degrees of the noon-midnight meridian due to the almost continuous under-powered status of the spacecraft at these times.

The ion chamber experiment continued to operate satisfactorily during the times power was available from October 14, 1965 until April 1, 1966,

at which time the telemetry word for Experiment 007 began to indicate random ionization values which no longer bore any discernable resemblance to the usual variations. No further usable data has been returned since April 1.

The location of the ion chamber at the end of an extendable boom on the POGO spacecraft is shown in Figure 2.

"Neher" Ion Chambers

The POGO ion chamber experiment consisted of an integrating ion chamber employing a quartz fiber electrometer to measure the ion current collected from the argon filling gas [Neher, 1953; Neher and Johnston, 1956; Neher, 1961]. The particular instrument flown on POGO consisted of a steel sphere with 0.2 gm/cm^2 thick walls, filled with 10 atmospheres of argon gas. The chamber was sensitive via direct penetration to protons with $E > 10 \text{ Mev}$ and electrons with $E \geq 1 \text{ Mev}$. The chamber was also weakly sensitive via bremsstrahlung to electrons of energy less than 1 Mev.

The quartz fiber electrometer was designed for operation in either of two sensitivity modes. In addition to the usual direct charge collection by the quartz fiber electrometer, application of a secondary voltage to a second electrode on this chamber provides a high sensitivity mode where the electrometer recycles after only about 0.1 as much charge has been collected from the gas. In operation, the ion chamber generates a pulse signal after a fixed amount of charge has been collected from ionization of the filling gas. Ionization rate is therefore inversely proportional to the time interval, Δt , between pulses.

A cross-sectional drawing of the Neher type ion chamber and electrometer is shown in Figure 3. The POGO instrument is similar to these ion chambers as flown on Mariner II and Mariner IV, employing a modified electrometer plus greater filling pressure of argon gas to obtain a higher electrometer pulse rate for better time resolution. For clarity of explanation, construction of the simpler single mode type of electrometer will be described first, then the POGO configuration will be treated as a modification.

The electrometer mechanism, consisting of the collector, fiber and support arm, is made of quartz fused into a single piece. The fiber is $\sim 10 \mu\text{m}$ in diameter by 9 mm long and is mounted so as to lie ~ 0.38 mm from the collector when no electrical forces are present. An aquadag coating applied to the collector makes it conducting, and the conducting portion is insulated from the remainder of the instrument. Before the fiber and support arm are joined to the collector, a silver band is evaporated on the fiber at the point of contact with the collector. Platinum is then evaporated onto the fiber and tip of the support, and a conductive coating is applied to the support so that the resistance along the fiber to the point which touches the collector during operation is ~ 10 megohm. This limits the peak current conducted to the collector during the recharging cycle, and extends the life of the electrometer to $> 3 \times 10^8$ pulses. The fiber is connected to a header pin by a PtIr wire.

After assembly the chamber is evacuated, baked several hours at 350°C and then cooled and filled with argon. In operation a potential

$V_0 \simeq +300$ to $+400$ volts with respect to the shell is applied to the inner shielding can, and through an external load resistor of $\simeq 0.2$ megohm to the fiber. The fiber is attracted to the collector, charges it to V_0 and returns to its rest position. Ion and electron current between the grounded shell and the collector discharges the latter, and the fiber is gradually pulled toward the collector until the potential between the two reaches a critical value (~ 150 V) such that with a further decrease in the separation of the fiber and collector, the attracting electrostatic force increases more rapidly than the restoring mechanical force. The fiber then whips against the collector, recharging it, and producing a voltage pulse across the external load resistor.

The above basic instrument design has been used successfully on the Mariner spacecraft and on numerous Caltech balloon flights. In order to increase the electrometer discharge rate to obtain sufficient spatial resolution with the POGO experiment, which orbits the earth in 100 minutes, the filling gas pressure was increased to 10 atmospheres and the electrometer was modified to provide two sensitivity modes. The POGO electrometer has two parallel electrodes inside the inner shield. The fiber, now connected to the collector, is perpendicular to the electrodes and located between them as described by Neher [1961]. A potential $V_0 \simeq 400$ volts is applied to one electrode and $V_0 - \Delta V$ to the other. When $\Delta V \simeq 0$, the electrometer operates like the single mode instrument. But if $\Delta V \simeq 150$ volts, the electrometer recycles after 0.1 to 0.05 s as much charge has been collected from the gas. On each cycle, the fiber first is attracted to contact the electrode with

V_0 . It is then immediately attracted to the second electrode which discharges it to $V_0 - \Delta V$, thereby "biasing" it by the amount ΔV toward the critical value at which it will recycle to the first (V_0) electrode.

This higher sensitivity varies linearly with ΔV over a restricted range, the calibration changing 5%/volt. On POGO, the instrument can be commanded into either sensitivity mode.

Calibration

Calibration of the POGO ion chamber was performed by H. R. Anderson and H. V. Neher, using standard reference ion chambers and Co 60 sources at Caltech.

Several identical instruments were fabricated for the POGO experiment, from which the primary flight instrument was chosen. Operation of the ion chambers under various environmental conditions were measured using convenient sources of radiation as stimuli. Each flight instrument was calibrated in a standard flux of Co 60 γ -rays reproducible to ± 0.2 percent when account is taken of decay, then subjected to an environmental test and recalibrated. Non-linearity at high rates is determined with an x-ray beam, and the calibration changes due to gravitational acceleration and with temperature are measured with Co 60 γ -rays.

The flight instruments are operated for several months prior to launching, both on and off the spacecraft. They are recalibrated in the standard γ -ray flux several times during this period as a check on long term stability. A summary of the ion chamber characteristics is presented in Table I, from Anderson et al. [1967] .

Table I - Response of Ion Chamber to Environment

Parameter	Response or Quantity	Comment
Filling pressure vs. pressure $\times \Delta t$	-0.8%/atm.	1-10 atm. of argon, 300 V applied
Δt vs. collection voltage, V_0	< 0.002%/V	10 atm. of argon, 200-500 V applied
Δt vs. ΔV	5%/V	High sensitivity mode
Δt vs. temperature	0.01%/°C	Normal sensitivity
	0.1%/°C	High Sensitivity -25°C to +75°C
Stability of calibration	$\frac{\Delta k}{k} \leq +0.05\%$	Includes 3 or more months of test and operation
rsm deviation of Δt	$\leq 0.3\%$	Mariner instrument - deviations result from random effects in the mechanical electrometer
Dynamic range of pulse rates	3×10^{-5} to 10^2 /sec	
Δt vs. acceleration in direction of fiber motion	4% per g	Normal sensitivity
	22% per g	High sensitivity
Lifetime	$> 3 \times 10^8$ pulses	
Calibration const. K	$\sim 150,000$	Normal sensitivity
	$\sim 15,000$	High sensitivity
Volume of chamber	10^3 cm^3	
Filling pressure	10 atm. abs.	

The absolute calibration of the ion chambers is made by measuring their pulsing rate, $(\Delta t)^{-1}$, in a flux of Co 60 γ -rays with known ionizing power. This ionization rate, I , is measured in units of ion pairs $\text{sec}^{-1} \text{cm}^{-3}$ (of STP air) by a set of standard ion chambers maintained at Caltech. The calibration constant, K , of the flight instruments is calculated from the expression

$$K = I \Delta t \frac{\text{ion pairs}}{\text{sec} \cdot \text{cm}^3 (\text{STP air})} \text{ sec}$$

where Δt is the time interval between pulses from the quartz fiber electrometer.

Calibration of the ion chamber response to electrons was performed over the range of 0.5 to 1.35 Mev by direct bombardment of the chamber with mono-energetic electrons selected by a magnetic spectrometer. Data were normalized at 1.35 Mev to the minimum ionizing value of ~ 70 ion pairs $\text{sec}^{-1} \text{cm}^{-3}$ (STP air) calculated from dE/dx energy loss data. Calibration of response to non-penetrating electrons with energies of 40-100 kev was measured by exposing the instrument to the bremsstrahlung produced by a monoenergetic electron beam impinging upon 0.15 and 0.32 g/cm^2 steel targets in an apparatus described by Frank [1962]. The ion chamber's response to an isotropic electron flux incident directly upon it was calculated from the measured response to unidirectional electrons incident on the target and from the measured absorption in the steel targets. Figure 4 shows the result of the electron calibration.

Anderson et al [1967] calculated the total rate of energy loss in the filling gas from monoenergetic protons incident upon a 12.7 cm diameter

ion chamber containing argon at 4 atm. abs. pressure. This calculation was based on the known dE/dx collision loss rates for protons and included a correction for the additional ionization due to secondary particles created by nuclear interactions in the chamber walls and filling gas. The result is shown in Figure 5 and is considered valid for the 10 atm. chamber on POGO.

The X-ray sensitivity of the instrument was measured using a constant potential X-ray machine producing 50-300 keV photons. The X-ray flux was measured with a $2" \times 2"$ Na (Tl) crystal and pulse height analyzer. Photons with energies above 300 keV were obtained from γ -ray sources. The ionization rate per unit omnidirectional photon flux was found to vary between 0.3 - 0.7 over the range of photon energies 30 - 1,000 keV.

Since the ion chamber has an isotropic sensitivity, none of these calibrations depend upon the angular distribution of the incident radiation, but only upon the total flux, $4\pi j$.

THE DATA

Handling

The ionization chamber data consists of individual voltage pulses from the electrometer whose separation in time, Δt , is inversely proportional to the ionization rate being observed. Δt is the time required for the electrometer to collect the fixed amount of charge necessary to generate a pulse. After suitable amplification and shaping, these electrometer output pulses are accumulated in a four bit binary register and stored until read out to the spacecraft telemetry system. For read-out, the four bit accumulated count is transferred to the first, second, third, and fifth bit locations of a nine bit shift register, which comprises the complete Experiment 5007 data word for the spacecraft telemetry format. The fourth bit indicates the sensitivity mode in which the experiment is being operated and the remaining bits, normally "0" when power is on to the experiment, are used only as an "on-off" indication.

The 9 bit data word is read out twice during each spacecraft telemetry frame, as words 19 and 83 of the 128 word frame. At the usual 4 kilobit/sec telemetry rate, this results in obtaining the Experiment 5007 data word at equi-spaced intervals of 0.144 seconds. Alternate telemetry rates of 16, 32, and 64 KB are also used for real-time data return. The 4 KB rate is always used for recording data on the spacecraft tape recorders, which are each capable of storing two orbits of continuous data.

Real-time and play-back (tape recorder) data are received and recorded together with simultaneous WWV time signal at several ground stations around the world. These tapes are sent to NASA Goddard Space Flight Center (GSFC)

for preliminary reduction and analysis. At GSFC the ground station tapes are sorted to separate real-time and play-back data and assembled into chronological order on master tapes. Greenwich Mean Time is calculated for each data word from the spacecraft clock and ground station WWV time records. The data words for each particular experiment are then stripped off of the master tape onto "decom" tapes, together with GMT and spacecraft status ("housekeeping") information, and sent to the individual experimentors for further reduction and analysis. Also sent to the experimentors are orbit/altitude tapes containing spacecraft position and altitude at one minute intervals during each orbit.

Upon receipt at Rice, the ion chamber experiment "decom" tapes are computer processed in four steps to obtain data in the form of (1) ionization rates versus GMT on magnetic tape and computer print-outs, with position parameters of latitude, longitude, local time, B, L, B/Bo, MLAT, range, and altitude calculated and listed for each data point and (2) ionization rates and spacecraft altitude versus invariant latitude in the form of machine plots covering one half orbit each.

The first step takes the GSFC "decom" tapes and calculates Δt . At low ionization rates this involves calculating the time interval between successive non-zero words. At higher rates, where more than one pulse is recorded per word Δt is calculated from the number of pulses in each word divided into the period between words. To condense the volume of data at high ionization rates, pulses recorded are totaled for ten consecutive words to calculate a single average value of Δt . Also, values of Δt are

checked for doubling due to missed ion chamber pulses, i.e. pulses which occurred during transfer of the count to the 9 bit output registers and were not recorded. Values of Δt which differ from adjacent values by a factor of 2 are rejected. From these values of Δt , approximate values for ionization rate, I , are calculated for reference. Each value calculated is assigned a line number for reference purposes and printed out on a computer listing together with associated telemetry and spacecraft operating information as well as recorded on magnetic tape.

The second step in the reduction of the data is to examine the computer output from the first stage for periods when pulse rates exceeded 12 per word, indicated status or sensitivity mode of the instrument conflicted with spacecraft command log records, or frequent occurrence of bit errors indicated the data were unreliable. Control cards were punched with the line numbers of such data lines and a second computer run made to delete all such lines and correct the remaining ionization values for temperature and non-linearity of the instrument. The general philosophy followed in deletion of data was to delete only those lines which were clearly in error, judged by erroneous status indicator values or bit parity errors, and those groups of data where more than 25% of the lines in the group were in error, but avoided any biasing of the data by preferential removal of data not conforming to the experimenters' preconceived expectations. We consider the mostly random effects of errors due to telemetry problems and other mechanical difficulties to be preferable to the systematic exercise of the experimenters' prejudices as to the "reasonableness" of a data value.

The result of the second step in data reduction was the generation of a tape containing correct values of ionization versus GMT. The third step was to merge these with the position vs. GMT information contained on the Orbit Altitude Tapes to obtain our final data tapes. A fourth (actually, additional) step was to use these final data tapes to generate machine plots of ionization rate and spacecraft altitude versus invariant latitude (or "L"), identified with orbit number, date, time, and spot values of longitude and local time.

Method of Analysis

A notable feature of the ionization plots is the frequent occurrence of ionization spikes at high latitudes. These features consist of a brief increase in the observed ionization rates above the normal ionization versus latitude profiles. For the purpose of studying the frequency and conditions of occurrence of these features, the data in the form of machine plots of ionization rate vs. invariant latitude were examined in segments extending from the point of maximum ionization in the outer zone into the polar cap region, resulting in four such segments per complete orbit. Each segment examined was classified into one of the following six categories:

- 1) Definite spike present: Data points show a definite minimum value before increasing to form a secondary peak (spike). This peak must be defined by a minimum of three consecutive data points. This is necessary to rule out the possibility of an erroneous value for a single point due to telemetry error, etc. See Figure 8.
- 2) Possible spike present: The data points show a definite bulge in the profile of the edge of the outer zone ($I_{\text{actual}} \geq 140\% I_{\text{projected}}$) which appears to be a spike merging with the rest of the outer zone, but now showing a distinct relative minimum. Also included are any other features which could be spikes, but do not satisfy all our criteria for one case (1). See Figure 7.
- 3) Definite absence of spikes: The data points are smoothly varying with latitude (with the possible exception of a few apparent bad points due to counting errors) and show no sign of the presence of any spikes. If a spike were present it would be smaller than

about 10% increase in average ionization over a distance of several kilometers. This is the normal outer zone profile on quiet days. See Figure 6.

- 4) Large spike-"new" particles: Peak ionization rate in the spike exceeds the levels observed at that L value at higher altitudes. Such a spike could not be due to a lowering of mirror points, relatively greater loss of particles on adjacent field lines, or other redistribution of local particle populations. It must be the result of injection of substantial numbers of new energetic particles not previously present at nearby values of B and L. See Figure 9.

- 5) Multiple spikes: More than one spike is present in the same data segment. See Figure 8.

- 6) Unable to classify: Edge of outer zone, or the entire zone is very ragged in appearance, outer zone intensity greatly reduced at location of a particular segment, or many apparently erroneous data points would likely mask the presence of a spike.

Features falling into categories 4 or 5 above were also counted in category

1. Not all spikes would be recorded, as some would be masked by the effect of digitization in recording Δt , from which I is calculated (See Figure 6).

Also, non-linearity of the ion chamber at rates above $I \approx 10^6$ when in the high sensitivity mode made useless some of the data near the peak ionization regions of the outer zone.

A total of 710 data segments were examined, taken from intervals of more or less continuous data during the period from Orbit 13 (October 15, 1965) to Orbit 2326 (April 1, 1966), chosen so as to include segments from all local times as the spacecraft orbit precessed. Due to the power shortage resulting from the loss of spacecraft orientation, very little data was available for local times near noon and midnight.

Results of Analysis

The spikes are most often observed near the boundary of trapping for outer zone particles, and may occur on approximately half of the spacecraft's passes through these areas. Frequency of occurrence appears to be the same in both hemispheres. No dependence on local time has been noted for those spikes occurring at or inside the boundary of trapping. For those spikes occurring outside the boundary a strong predominance of events in the dawn hemisphere is noted. No dependence on geographic longitude was found. Relative amplitude of spike over ambient ionization varies up to more than two orders of magnitude, often exceeding 10^6 ion pairs/sec cm^3 (STP air) increase over adjacent latitudes. Width of the spikes varies from a few degrees of latitude to less than $\frac{1}{4}$ degree (the resolution limit of our data), typically $\frac{1}{2}$ to 1 degree. It is not possible to determine whether a particular spike is the result of temporal or spatial variation, however it seems clear that at least some of them are spatial features which persist and are identifiable in both hemispheres for one or two complete orbits.

Of the 710 data segments examined, 58 were in category 6 (unable to classify), leaving 652 useful segments. The results of their classification are shown in Table III.

Category	Number of Segments	Percent of Total
1. Definite spike	221	34
2. Possible spike	218	33
3. No spike	213	32
4. Large spike	47	7
5. Multiple spike	70	11

} included in category #1

Table III. Classification of data segments by occurrence of spikes.

Comparison between occurrence of spikes and the 3 hour magnetic disturbance index K_p showed a marked correlation with magnetic activity (See Figures 10 & 11). Occurrence of spikes increased from 8% of segments examined when $K_p = 0$ (very low magnetic disturbance) to 68% of segments examined when $K_p \geq 5$ (high magnetic disturbance). Although K_p exceeded 4 during only 3% of the data segments examined, these segments included 17% of the total number of large spikes observed.

A plot of invariant latitude, Λ , at which spikes were observed versus local time is shown in Figure 13. Their occurrence seems evenly distributed in local time for values of Λ below about 70° , the normal boundary of trapping falling between $67-70^\circ$. Occurrence at higher (polar cap) latitudes shows a preference for the morning hours. This is illustrated in the plots of several consecutive polar cap passes during Orbits 1809-1811 (Figure 15), during which several spikes occurred on the dawn side but the evening side showed little disturbance. However, evening side spikes do sometimes occur while no disturbance is present on the dawn side, for example on Orbit 2269 (Figure 16).

Notice also that features changed radically in periods like 100 minutes (between passes) and either did not persist long enough to drift in longitude to the dusk side or could not due to being on incomplete L shells or open field lines.

DISCUSSION OF RESULTS

Relation of Ionization to Actual Particle Fluxes

In order to compare the ionization data with the results of other experiments and the predictions of theory, it is necessary to calculate the relative importance of ionization contributed by particles of particular species and energy. First, let us check to be certain that the dominate response of the chamber is not due to large fluxes of non-penetrating electrons, such as aurora. From the electron response calibrations of Anderson et al. [1967], it is seen that use of the approximation $R = 300 E^5$ for $E \leq 0.8$ Mev yields a reasonable fit to the upper limit of actual ion chamber response to non-penetrating electrons. It is therefore immediately clear that the ion chamber is responding to electrons with energies greater than 0.5-1 Mev when the electron differential energy spectrum falls off as $E^{-\delta}$ with δ less than about 4. This will normally be the case in the outer zone, where values of δ of 2-4 are reported by most observers [Frank, 1965; McDiarmid and Burrows, 1965]. Occasional values of δ up to 7 or 8 are sometimes reported during auroral, "island", or "spike" events. However, although ionization from such fluxes would result primarily from the lower energy electrons, total effect would be small.

Recent rocket measurements by Westerlund [1968], Evans [1968], and others show that the majority of the auroral energy flux consists of omnidirectional fluxes of $10^{-9} - 10^{10} \text{ cm}^{-2} \text{ sec}^{-1}$ of electrons strongly peaked near 10 kev. The response to this flux by the POGO ion chamber would be only 10^2 to 10^3 ion pairs $\text{sec}^{-1} \text{ cm}^{-3}$ (STP air), hardly over background levels due to cosmic rays over the polar cap. Response

to the largest 40 kev electron "spikes" reported by McDiarmid and Burrows [1965] would be somewhat greater, on the order of 10^4 ion pairs/cm³ sec for fluxes of 2×10^9 cm⁻² sec⁻¹ of 40 kev electrons. Such response is significant, but still small compared to the ionization exceeding 10^6 ion pairs/cm³ sec which have been observed in large "spikes" by POGO.

The low energy cut-off for protons is quite sharp at 10 Mev, resulting in total insensitivity to low energy protons. Response to X-rays generated in the ionosphere will not exceed rates generated by the same particle fluxes directly bombarding the chamber and can only result in broadening the observed spike. Such effects are not seen.

For a more exact calculation of the response of the ion chamber to any assumed electron spectrum, we represent the electron response function $R(E)$ as follows:

$$R(E) \equiv \frac{I(E)}{4\pi j(E)} = \begin{array}{ll} 80 & E_{\beta} > 1.35 \text{ Mev} \\ 130 & .8 \leq E_{\beta} \leq 1.35 \text{ Mev} \\ 10^3 \times E^{8.5} & .35 \leq E_{\beta} \leq .8 \text{ Mev} \\ E^{3.1} & .01 \leq E_{\beta} \leq .35 \text{ Mev} \end{array}$$

Integrating this response over an arbitrary electron flux spectrum of the form $j(E) = AE^{-\delta}$

$$I = A \int_0^{\infty} E^{-\delta} R(E) dE = A \left[\int_{.01}^{.35} E^{3.1-\delta} dE + 10^3 \int_{.35}^{.8} E^{8.5-\delta} dE + 130 \int_{.8}^{1.35} E^{-\delta} dE + 80 \int_{1.35}^{\infty} E^{-\delta} dE \right]$$

$$= A \left[\frac{1}{4.1-\delta} (35^{4.1-\delta} - .01^{4.1-\delta}) + \frac{103}{9.5-\delta} (.8^{9.5-\delta} - .35^{9.5-\delta}) \right. \\ \left. + \frac{130}{1-\delta} (1.35^{1-\delta} - .8^{1-\delta}) + \frac{80}{1-\delta} ((\infty)^{1-\delta} - 1.35^{1-\delta}) \right]$$

$$(*) \quad I(\delta) = A \left[\frac{1}{a} (.35^a - .01^a) + \frac{103}{b} (.8^b - .35^b) + \frac{50}{1-\delta} 1.35^{1-\delta} - \frac{130}{1-\delta} \times .8^{1-\delta} \right]$$

for $\delta > 1$; $a \equiv 4.1 - \delta$, $b \equiv 9.5 - \delta$, A = normalization constant

= omni-flux at 1 Mev

Applying equation (*) for average outer zone electron spectrum $\delta = 3 \Rightarrow a = 1.1$,

$b = 6.5$

$$I(\delta = 3) = A \left[\frac{1}{1.1} (.35^{1.1} - .01^{1.1}) + \frac{103}{6.5} (.8^{6.5} - .35^{6.5}) \right. \\ \left. + \frac{130}{2} \times .8^{-2} - \frac{50}{2} \times 1.35^{-2} \right]$$

$$I(\delta = 3) = A \left[.27 + 35 + 93 \right] \approx 130 A$$

For this case, the majority contribution is from electrons with

$.8 \lesssim E_\beta \lesssim 1.35$ Mev. Electrons with $350 \text{ kev} \lesssim E_\beta \lesssim 800 \text{ kev}$ cause 27 percent

of the measured ionization, and electrons with $E \lesssim 350 \text{ kev}$ contribute

only a fraction of a percent.

Applying equation (*) for $\delta = 4 \Rightarrow a = 0.1$, $b = 5.5$

$$I(\delta = 4) = A \left[10(.35^{.1} - .01^{.1}) + \frac{103}{5.5} (.8^{5.5} - .35^{5.5}) + \frac{130}{3} \times .8^{-3} \right. \\ \left. - \frac{50}{3} \times 1.35^{-3} \right]$$

$$= A \left[2.7 + 53 + 85 - 6.76 \right]$$

$$I(\delta = 4) \approx 130A$$

For this case, the majority contribution is still from particles of ~ 1 Mev. Contribution from electrons of $350 \text{ kev} \lesssim E_{\beta} \lesssim 800 \text{ kev}$ has increased to 40 percent, and electrons with $E \lesssim 350 \text{ kev}$ still contribute less than 3 percent of total ionization.

Applying equation (*) for $\delta = 7$ (steepest spectrum quoted by McDiarmid and Burrows for high lat. spikes)

$$\Rightarrow a = -2.9, b = 2.5$$

$$I(\delta = 7) = A \left[\frac{1}{2.9} (.01^{-2.9} - .35^{-2.9}) + \frac{103}{2.5} (.82.5 - .35^{2.5}) + \frac{130}{6} \times .8^{-6} - \frac{50}{6} \times 1.35^{-6} \right]$$

$$= A (3 \times 10^9 + 200 + 87 - 1.4)$$

$$I(\delta = 7) = A \times 3 \times 10^9$$

In this case, the only significant contribution is from particles $E < 350 \text{ kev}$ and comes predominantly from those with the lowest energies ($E \approx 10 - 50 \text{ kev}$). The magnitude of the coefficient of A is strongly dependent upon the lower energy cut-off of the assumed particle or response functions.

As observed earlier, normalization of the value A to match observed maximum fluxes at 10 kev or 40 kev results in values of $I \sim 10^2 - 10^4$. This indicates that the larger spikes (in terms of peak ionization) observed by POGO do not have spectra of exponent much greater than 4, and are a higher energy phenomena than the 40 kev spikes observed by McDiarmid and Burrows.

Development of Spikes

The development of these "spikes" appears to follow two distinct patterns:

- 1) Loss of surrounding radiation: Many spikes are observed as a relative enhancement in ionization over a small range of latitude at low altitudes (high B values). High altitude passes through the same latitudes on the same orbit show no spikes. It would appear in these cases that the particles responsible for the spike are simply mirroring at lower altitudes than particles on neighboring field lines. Such an effect could be caused by a redistribution of pitch angles. (If the ionization were due to non-penetrating electrons, a local increase in average energy of the electrons would appear as an ionization spike, even if fluxes and pitch angles remained unchanged.) These spikes would, therefore, appear to be due to particles from the population already present in the outer zone, which have been subjected to some localized disturbance.
- 2) Injection of new particles: Occasionally spikes appear which represent an absolute increase in ionization over that present at earlier times at the same latitude at any altitude. These spikes tend to be rather sharp (confined to a narrow band in latitude, often less than one degree) and occur at all altitudes. Several such spikes may occur together, at the boundary of trapping or just outside in the polar region. When present inside the boundary of trapping, they tend to appear in both

hemispheres and may appear to persist for two or three orbits, gradually growing and merging with the existing outer zone. However, their fine structure (especially when several are present) changes in periods of only minutes, making positive identification of a spike seen on one orbit as the identical structure seen in about the same position on the preceding orbit somewhat difficult and uncertain. It would appear that these spikes are due to "new" particles which are populating previously empty L shells at the boundary of trapping. (Perhaps this "boundary" is moving.)

In some cases it is possible to rule out protons as the dominate species. The POGO ion chamber does not respond to protons with energies less than 10 Mev, corresponding to a gyro-radius of about 10 km at low altitude near the boundary of trapping. Type II spikes whose width is only 10 - 50 km are not uncommon. Thus, the particles responsible for these features would appear to be relativistic electrons, which were not present in the particular L shell before the spike formed.

Trapping

The average location of the observed limit of trapping, taken to be the point at which the ionization level falls to ~ 10 times the cosmic ray background observed over the polar caps, was at an invariant latitude of $68\frac{1}{2}^\circ$, corresponding to $L = 7.5$ in McIlwain's B,L coordinate system. Data used to calculate this average were taken from the same orbits on which definite spikes were observed to occur, and cover the period from October 1965 to April 1966.

- 1) The distribution of spikes was plotted to show distribution of occurrence in invariant latitude versus local time (Figure 13). A similar polar plot is presented in Figure 14, where the radial quantity is now changed to "normalized" invariant latitude of each spike, defined as $\Lambda(\text{spike}) - \Lambda(\text{observed boundary of trapping on same orbit})$. This plot therefore corrects for changes in the location of the boundary of trapping and should produce a better ordering of any related phenomena.
- 1.1) Both plots reveal a fairly uniform distribution in local time for spikes appearing inside the boundary of trapping. These spikes range in total amplitude from 10^4 to $>10^6$ ion pairs/sec cm^3 (STP air) in excess of ionization levels interpolated from adjacent latitudes. In particular, they are greater than the ionization we have calculated to result from the maximum values observed for lower energy (10-40 kev) electron fluxes, such as aurora or McDiarmid's spikes. Therefore, they must represent fluxes of relativistic electrons (or possibly protons >10 Mev) which, whether or not they are co-occurring with such phenomena, exhibit much harder energy spectra. The question of where they got their energy cannot be easily explained in terms of any electrostatic acceleration mechanism.

In several cases, spikes in this group seem to recur during successive passes through the same L value in both

hemispheres and at both poles. In such cases, the same spike may appear to persist for periods up to ~300 minutes, gradually increasing in peak amplitude while moving to lower latitude and merging with the primary outer zone ionization. Such occurrences are emphasized because of the picture they present of an L shell suddenly (in less than 100 minutes) populated by relativistic electrons injected from some unknown source (the tail ?), which then move radially inward as a coherent group. Such behavior is the notable exception, rather than the rule.

Most spikes are generally smaller in size, and either appear once and cannot be detected on passes through the same L shell 10 to 40 minutes later, or else can be identified only on the conjugate pass.

- 1.2) Those spikes occurring at latitudes above the observed limit of trapping show a pronounced dawn-dusk asymmetry, dawn side occurrences exceeding evening events by more than two to one. Spikes in this region do not seem to recur on successive passes through the same L, or even on the near conjugate point pass 30-40 minutes later.

The peak amplitude of these spikes is generally smaller than those inside the boundary of trapping, seldom exceeding 10^5 . Spikes of relative amplitude as small as $1-2 \times 10^3$ show up clearly here, which would not be detectable over

the much higher background ionization levels inside the boundary of trapping. Such ionization levels could result from lower energy electrons such as McDiarmid's larger spikes or a really big aurora, either of which would show up on our ionization plots above the boundary of trapping. Therefore, the spikes we see outside the boundary of trapping must include those for electrons $\gtrsim 40$ kev reported by McDiarmid and Burrows. The fact that we do not see the strong day - night asymmetry which they reported is interpreted as showing 1) the spikes we see are mostly due to higher energy electrons and 2) the distribution of the higher energy electron spikes does not show the day - night asymmetry reported for 40 kev electrons. This is considered in more detail in paragraph 4.

- 2) The average location of the limit of trapping observed by POGO agrees well with the limits of stable trapping indicated in Figure 12 [from Roederer, 1967]. One is tempted to try to associate the region of pseudo-trapping indicated on the day side from $\sim 72^\circ$ to 80° with occurrence of transient fluxes which appear as spikes or broader enhancements in this region. This is treated in more detail in paragraph 4.
- 3) Let us consider the results to be expected following injection of a number of electrons into a region of space near, but inside

of, the boundary of stable trapping. Assume these electrons are injected instantaneously at t_0 within a small volume of space (say 10 km), with isotropic distribution of pitch angles and an energy distribution similar to outer zone electrons. The electrons would therefore initially distribute themselves along the original field line, narrowly confined in latitude and longitude and begin drifting eastward. Using Roederer's drift rates for electrons mirroring at low altitude (high latitude) we calculate the drift periods shown in Table II for electrons crossing the noon meridian at $8 R_E$ with $\cos e \approx 1$. At $t_0 + 800$ sec. the 700 kev electrons will have drifted 360° in longitude, while the 1.3 Mev particles have drifted 570° . Therefore, the electrons to which the POGO ion chamber predominantly responds in the outer zone have now spread out in longitude by 200° and will continue to distribute themselves in longitude on this particular "shell" at the rate of $1/4$ degree/sec. due to their differential drift rates. After about 30 minutes the electrons will be distributed in longitude to the extent that the POGO ion chamber would see an ionization "spike" in latitude when passing through this shell, of amplitude roughly independent of longitude. This "spike" would persist until the electrons diffused out of the spike or were masked by larger populations of ambient electrons.

Electron Energy	Drift Period
0.7 Mev	800 sec
0.8 Mev	700 sec
1.0 Mev	600 sec
1.3 Mev	500 sec

Table II. Drift periods vs. energy for electrons mirroring at low altitude, crossing noon meridian at $8 R_E$. Corresponding average dipole coordinates are $L \sim 7.5$, $\Lambda \sim 68\frac{1}{2}^\circ$. From Roederer, 1967.

Note that this spike would be observed independently of longitude only at low altitude/high latitude. For an observer near the equatorial plane, the spike would be observed near the longitude of injection only. Moving in longitude it would rapidly spread out in L due to L shell splitting, increasing in radial extent from 10 to $\sim 15,000$ km in moving (for example) from an equatorial injection point at $8 R_E$ on the noon meridian to the midnight, thereby diffusing the flux by a factor of 1500. However, if the electrons were originally injected at high latitude, say from the ionosphere, the spike would be observed at all longitudes at the equator as well as at high latitude. This suggests a simple test for point of injection of increased particle fluxes if sufficient low latitude satellite data is available.

In a real situation, the injection process would continue for a finite period of time. Assuming a roughly constant rate of injection, the amplitude and time required to achieve longitudinal symmetry of the resulting ionization spike would depend on the length of time over which the injection process continued. Brief injection periods would result in spikes which would not endure (the process of differential drift diffusion in longitude will reduce its flux/unit area by a factor

$\frac{t(\text{drift})}{t(\text{injection})}$ and would only be observed if the satellite passed through the particular longitude where the particles were located shortly after injection. This is in qualitative agreement with the behavior observed for spikes inside the boundary of trapping if injection is assumed to occur over a wide range of local times.

- 4) Let us now consider the companion problem of electrons injected into a region of space slightly outside the boundary of stable trapping. The results are most interesting if we consider the case of an injection at local time somewhat after midnight, before dawn. This is chosen because of prospective sources of particles for injection at this time from plasma instabilities associated with the post-midnight break-up phase of aurora and also from the electron "islands" observed near the neutral sheet in the magnetosphere tail.
 - 4.1) This region is also interesting because of the effect of the regions of pseudo-stable trapping derived by Roederer for electrons drifting eastward in this region. An electron which is originally on an open field line near the high latitude region of pseudo-stable trapping can drift eastward across the boundary onto closed field lines, in the exact inverse of the process of westward drifting particles initially trapped becoming lost in the

tail (Figure 18). Once having drifted into the region of pseudo-stable trapping, the electron will be temporarily trapped and will continue to drift eastward across the daytime hemisphere until it is lost once more into the tail on the evening side of the Earth. Therefore, neglecting losses and variations in drift velocity, we would expect to see the same particle fluxes at any longitude in the region of pseudo-stable trapping, with time variations similar to those on the adjacent open field lines between midnight and dawn.

- 4.2) Consider now two possible locations in latitude for injection of electrons. We will see that both sources result in a pitch angle distribution such that the eastward drifting electron fluxes entering the high latitude region of pseudo-trapping will all mirror at low altitude (i.e. - equatorial pitch angles will be small).

- 4.2.1) If the electrons are injected at high latitude, as by ionospheric plasma instabilities generated by the post-midnight breakup phase aurora, all except those with pitch angles near 90° are lost immediately out the open field lines. The closer to 90° the electron's pitch angle, the more time it will have to drift sufficiently eastward to enter the high latitude region of pseudo-stable trapping.

- 4.2.2) If the electrons are injected near the equator (from the tail), either they will be in the low latitude region of pseudo-stable trapping and all except those with small equatorial pitch angles (high latitude, low altitude mirror points) will be lost out the side of the magnetosphere as they drift eastward, or they will be on open field lines and those with small pitch angles will spend the most time near the boundary of trapping so as to drift sufficiently eastward to become pseudo-trapped.
- 4.2.3) One further point to note is the faster drift of electrons into the pseudo-trapped region with increasing energy. Drift perpendicular to the field line is proportional to E ($\propto V^2$) while motion along the line is proportional only to V^1 . The result of this effect will be a relative hardening of the pseudo-trapped particle spectrum relative to the untrapped population from which they derive.
- 4.3) At this point we have shown that injection of electrons near the boundary of trapping at local times between midnight and dawn would lead to equal occurrence of fluxes, spikes, etc. with longitude throughout the region of pseudo-trapping, with a relative hardening of fluxes relative to those on open field lines in the tail. This picture should be modified to consider the effect of losses of particles near their predominantly low altitude mirror points. This

effect should result in a monotonic decrease in flux with local time. McDiarmid and Burrows [1966] have calculated that the time constant for such losses may be shorter than a single drift period.

Comparison with "Islands"

The location of the spikes observed by POGO near the boundary of trapping leads to a strong suspicion that they are related to the frequent intense fluxes ("islands") of electrons reported in the magnetospheric tail [by Anderson, 1965].

Flux levels observed in these "islands" are orders of magnitude above the non-island fluxes, typically ranging from $10^4 - 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ of electrons with $E \gtrsim 40 \text{ kev}$. Their energy spectra are typically a power law of about 4, with reported variation from event to event over a range from 1 to 8 [Montgomery, 1968]. Using the calculations of ion chamber response presented earlier, such fluxes would appear to the POGO ion chamber as typically ($\delta = 4$) 100 ion pairs/sec cm^3 (STP air). The steepest spectra ($\delta = 8$) reported would result in negligible response, while the hardest ($\delta = 1-2$) could result in response of $10^4 - 10^8$ if applied to the larger "islands".

The electron "islands" have been found to occur mostly near to the neutral sheet, probably more often toward the dawn side of the tail. The field lines from this region would reach the earth's surface on the night side immediately outside the boundary of trapping. The "island" fluxes with very small pitch angles would therefore be expected to appear at high latitude on the night side, beginning near the boundary of trapping

and decreasing in frequency with increasing latitude over the polar cap. Their frequency of occurrence would also tend to increase toward dawn.

The preceding pattern might well be modified by perturbations to the particles' path between the tail and the top of the ionosphere, particularly as described in the earlier discussion of drift motion into the pseudo-trapped regions of the magnetosphere. Additional modifications might result from diffusion onto closed field lines in the outer belt, energization, or other violation of the magnetic invariants of the particles' motion. Such effects might well alter the flux, spectrum, and spatial distribution of "islands" reaching the high latitude ionosphere from the values expected from simple propagation from the tail along smooth, undisturbed magnetic field lines. It is considered probable that many, if not all, of the spikes in the POGO ion chamber data are in fact due to a component of the electron "islands" found in the tail.

The temporal behavior of the ionization spikes cannot be determined from the POGO satellite data with sufficient detail for comparison with that of the electron islands. The K_p dependence of the occurrence of spikes agrees with that of the electron "islands". However, this is hardly conclusive, since just about everything in the magnetosphere can be shown to vary with K_p if it varies at all.

Comparison with Other Data

McDiarmid and Burrows [1965] have reported seeing sharp fluxes (spikes) of electrons with detectors on the Alouette I satellite, in polar orbit near the noon-midnight plane. They report these spikes occur

mostly on the night side (36 cases out of 38) on field lines that should be open. Fluxes up to $10^9 \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$ with $E \gtrsim 40 \text{ kev}$ were observed at an altitude of 1,000 km. 70% of the spikes had widths of less than 2° (latitudinal extent). The spectral distribution was fitted to a power law at 40 kev and 250 kev, with indicated exponents of 4 to 7. This is steeper than the normal range for outer zone electrons of 2-4. The experimenters identify these spikes with the electron "islands" in the tail. The POGO ion chamber response to these fluxes was calculated earlier to be up to $\sim 10^4$ ion pairs/sec cm^3 (STP air), and would be very similar to the spikes which we actually saw. The major points of disagreement are in the maximum amplitude and local time. Since the range of energies to which the two experiments responded are not the same, it is quite conceivable that the extrapolation to 1 Mev on the basis of a two point spectrum fit at 40-250 kev would account for the order of magnitude difference in peak polar cap fluxes. In particular, the expected energy dependence of drift into pseudo-trapped regions would bias occurrence of the higher energy fluxes to which we are sensitive, which initially occurred in the night hemisphere, toward observation in the dawn hemisphere. In view of this, we do not believe that the local time distribution of spikes observed by the two experiments is actually in conflict with what would be expected if both experiments were detecting fluxes associated with the magnetotail.

Lanzerrotti et al. [1967] detected drifting "bunches" of Mev electrons at $6.6 R_E$ at the ATS satellite. The drift period and decay rate of these

particles is noted to agree with the expected diffusion of longitudinally narrow spikes due to longitudinal drift. They are believed to be identical to the nonpersistent ionization spikes observed by POGO on field lines inside the boundary of trapping.

Other observations pertinent to the behavior of the POGO ionization spikes are those of Rosen [1965] on Explorer 6, Craven [1966] on Injun 3, sounding rocket flights by Mozer and Bruston [1966], and O'Brien [1964] on Injun 3. Rosen reported observation of "bunched" electrons just outside the boundary of trapping at intermediate latitudes. If the spike features are associated with the fluxes in the tail, spikes should also be observed in this intermediate region of the same field lines. Rosen's reported "bunches" of up to $10^5 \text{ cm}^{-2} \text{ sec}^{-1} \text{ Mev}$ electrons would appear to be the expected spikes.

Craven's Injun 3 observations showing inward diffusion of 1.6 Mev electrons at the rate of $2 R_E/\text{day}$ at $L = 6$ are similar to the apparent inward motion of persistent spikes seen by POGO.

The observations by Mozer of separate electron groups with energies over 400 kev, which varied independently of the 40 kev auroral fluxes he was measuring, and the Injun 3 observations of O'Brien that Mev electrons remained unperturbed during precipitation of large electron fluxes with $E \gtrsim 40 \text{ kev}$ further confirm that the higher energy electrons respond differently to the disturbances affecting high latitude particles.

SUMMARY AND CONCLUSIONS

- 1) The POGO spacecraft was launched into a low altitude polar orbit and returned ionization chamber data during the period October 14, 1965 to April 1, 1966. This data has been edited and compiled in the form of ionization rate versus time and position, with typical resolution of seconds in time and fractional degrees in orbital position. It is recorded in chronological order on magnetic tape and computer print-outs. It has also been machine plotted in the form of graphs showing ionization rate and spacecraft altitude as a function of invariant latitude. Each graph displays one half orbit, pole to pole, of data.
- 2) A most significant feature of these plots is the frequent occurrence of ionization spikes at high latitudes in both hemispheres, near the boundary of trapping. These spikes are typically less than 1-2 degrees of latitude wide, with amplitudes ranging from 10^3 to $>10^6$ ion pairs/sec cm^3 (STP air) which at times exceed the maximum values observed in the outer radiation belts.
- 3) The distribution of spikes occurring inside the observed boundary of trapping (which was found at an average invariant latitude of $68\frac{1}{2}$ degrees) showed no dependence on local time. These spikes were normally seen on only a single pass through the boundary of trapping and did not recur except occasionally near the conjugate point. However, on several occasions they seemed to populate an entire L shell; appearing on all passes through the boundary of trapping for periods up to ~300 minutes and tending to move to lower latitudes and merge with the existing outer belt ionization.

While some of these spikes are thought to be due to local pitch angle redistribution or other local perturbations along a field line, others, particularly the larger and persistent ones, are thought to be due to injection of large numbers of relativistic electrons onto closed field lines inside the boundary of trapping. They are identified with the drifting "groups" of Mev electrons observed at $6.6 R_E$ in the equatorial plane by Lanzerotti.

- 4) The distribution of spikes occurring outside the boundary of trapping showed a strong dawn-dusk asymmetry, with occurrences in the dawn hemisphere outnumbering spikes in the evening hemisphere by more than two to one. These spikes were generally smaller in amplitude than those observed inside the boundary of trapping, seldom exceeding 10^5 ion pairs/sec cm^3 (STP air). They did not appear to persist from one pass to the next, as was often observed to happen for spikes inside the boundary of trapping.
- 5) The drift motion of energetic electrons on open field lines near the boundary of trapping was studied in the magnetosphere model of Mead, which modifies the usual dipole model by addition of the magnetopause and tail current sheets. L shell splitting in this model, as calculated by Roederer, is shown to result in drift of such particles into a region of pseudo-trapping. The probability of drifting into this pseudo-trapped region was shown to increase

for higher energy particles. Particles becoming temporarily trapped in the post-midnight quadrant by this mechanism would then drift across the dayside hemisphere, confined to this region of pseudo-trapping which expands to higher latitudes, reaching a maximum extent of ~ 10 degrees above the boundary of stable trapping near local noon. They will appear at any given local time once, and are then lost into the evening side of the tail before completing a full 360° drift. The location of spikes observed by POGO outside the boundary of trapping is in agreement with the predictions of this mechanism.

- 6) Two particular sources of electrons for injection into the region of pseudo-trapping were considered, ionospheric plasma instabilities associated with the post-midnight break-up phase of aurora and the electron "island" fluxes discovered in the tail by Anderson. (It is noted that these two sources could be one and the same.) It is concluded that the spikes observed by POGO are in fact associated with a component of the electron "islands" observed in the tail, which become temporarily trapped and drift into the morning magnetosphere. The energy spectrum of these spikes is, however, substantially harder than that of the "islands" or of the spikes reported by McDiarmid and Burrows.

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FIGURE CAPTIONS

- Figure 1. Sketch of a north-south cross-section of the magnetosphere (from Bame et al, 1966). The amount of field connection shown across the neutral sheet is open to question.
- Figure 2. Sketch of theOGO-C spacecraft, showing location of the ion chamber.
- Figure 3. Cross-sectional drawing of the Neher type ion chamber and electrometer, as flown on Mariners 2 and 4. The POGO instrument is similar. The quartz collector and fiber, shielding can, cup, and spider mount on the header fed-through pins. The spherical shell is made of non-magnetic stainless steel 0.025 cm thick (0.2 g/cm^2) and is brazed or welded to the neck onto which the header is clamped.
- Figure 4. Measured ionization rate produced by unit omnidirectional flux of monoenergetic electrons vs. electron energy. Electrons with $E \geq 1 \text{ Mev}$ fully penetrate to the sensitive volume of the chamber. Results at lower energies have an estimated uncertainty of a factor of 2. (from Anderson et al, 1967).
- Figure 5. Calculated ionization rate produced by unit omnidirectional flux of incident protons vs. proton energy. The rate equals the average specific ionization, and the estimated uncertainty is $\pm 5\%$. (from Anderson et al, 1967).
- Figure 6. This is an example of a category 3 segment; it shows a "normal" outer zone profile with no indication of a spike. Notice also the effect of digitization of data values. If

a small spike were present between $\Lambda = 45^\circ$ to 53° on this pass, it probably would not be resolved. Such segments are classified as category 3 (no spike) in this study, resulting in a probable slight underestimate of the actual number of category 1 and 2 passes recorded.

Figure 7. Example of a category 2 segment - possible spike present at $\Lambda = 66^\circ$.

Figure 8. Example of a category 5 segment - multiple spikes present. Note spike at $\Lambda = 67^\circ$, an example of a category 1 feature. This would qualify as a definite spike, but is not sufficiently large relative to normal ionization values at $\Lambda = 67^\circ$ to be classified as a large spike. The feature at $\Lambda = 77^\circ$, although smaller in absolute size, does classify as a large (category 4) spike as defined for this study.

Figure 9. Example of a category 4 segment - large spike present. The peak value of I exceeds levels recorded at this L value on previous passes.

Figure 10. Occurrence of spikes vs. K_p - All data segments were grouped according to concurrent 3 hour K_p value. Percentage of segments classified in categories 1, 2, and 3 were calculated for each group and are plotted vs. K_p group.

Figure 11. Occurrence of large and multiple spikes vs. K_p - The same procedure was followed as for Figure 5, for segments classified in categories 4 and 5.

Figure 12a. Location of the two psuedo-trapping regions in the magnetosphere. Particles mirroring inside these regions are unable to complete a 180° drift around the earth. Those injected into the (left side) high latitude region will be lost into the tail; those injected into the (right side) low latitude region will abandon the magnetosphere through the boundary, on the day side (from Roederer, 1967).

Figure 12b. Relationship between geomagnetic latitude of the intersection of a field line with the earth's surface and the radial distance to its equatorial point, for the noon, midnight, and dawn/dusk meridians.

Figure 13. The invariant latitude (Λ) of each spike observed is plotted vs. local time. Category 4 (large) spikes are indicated by a small circle. It should be noted that the scarcity of events within about 2 hours of local noon and midnight merely represents our lack of data at these times and must not be interpreted as a local time asymmetry.

Figure 14. Same as Figure 13, except that radial quantity has been "normalized" to the observed boundary of trapping on each particular orbit. Positive values are degrees of latitude outside the boundary, negative values are degrees inside.

Figures 15 a, b, d, d, e, f. Plots of ionization vs. invariant latitude for six consecutive polar passes, during orbits 1809-1811. Note that occurrence of spikes and enhancements is

-- primarily on the dawn side of each polar cap, with such less activity on the evening side. Local time and longitude of data points is indicated along the top of each plot.

Figure 16. Plot of polar pass during orbit 2269. Similar to Figure 15, except at this time spikes are occurring in the evening side at $\Lambda = 68^\circ$ and 69° , while the dawn side is undisturbed.

Figure 17. Sketch of equatorial cross-section of the magnetosphere, showing location of various particle domains (from Anderson, 1965).

Figure 18. Polar plot of Invariant Latitude vs. Local Time showing location of pseudo-trapping region for particles mirroring at low altitude. Outer dark line is the average observed boundary of trapping for the POGO ion chamber. Inner dark line shows the approximate location calculated by Roederer for high latitude limit of pseudo-trapping (limit of closed field lines), with shadow line indicating the probable effective limit for higher energy electrons. Drift path in local time (longitude) of a particle crossing midnight meridian at $\Lambda = 70^\circ$ is shown as dashed line. Originally located at the very edge of closed field lines, the longitudinal drift motion of the particle carries it across the day hemisphere well inside the region of pseudo-trapping. The location in the post-midnight quadrant where electrons

originally on open field lines could drift into the
region of pseudo-trapping is indicated by arrows.

PLASMA SHEET ORIENTATION

FIGURE 1

OGO-C EXPERIMENT LOCATIONS

Fig. 2

Fig 3

Figure 4

Figure 5

POGO I OCCURRENCE OF SPIKES vs K_p

POGO I OCCURRENCE OF LARGE OR MULTIPLE SPIKES vs K_p

x N HEMISPHERE
 • S HEMISPHERE
 ⊗ OR ⊙ LARGE SPIKE

POGO I IONIZATION SPIKES — Δ vs LOCAL TIME

$\Delta_{\text{(SPIKE)}} - \Delta_{\text{(Boundary of trapping)}}$ VS. LOCAL TIME

Figure 14

DAY
53

POGO I

ORBIT 1809

IONIZATION

DAY 87	POGO I ORBIT 2269	→
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LONG.	L.T.
360°	2:58
350°	2:09
207°	16:33
196°	15:47
195°	15:35

FIGURE 47

00:00
FIGURE 1C