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Final Report

for

APPLICATIONS TECHNOLOGY SATELLITE 1 (ATS-1) SUPRATHERMAL ION DETECTOR EXPERIMENT (SID) DATA REDUCTION AND ANALYSIS

(December 6, 1966 - March 30, 1970)

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ABSTRACT

The Rice University Suprathermal Ion Detector Experiment (SID) on the ATS-1 began operation on December 10, 1966 and sent back useful data through February 16, 1967 when degradation of the Channeltron Electron Multiplier caused a significant loss of sensitivity to incident charged particles. During the more than 2 months of nearly continuous operation the SID returned data on low energy (< 50 eV) plasma flows during magnetically disturbed times which has in turn contributed to our knowledge of the magnetospheric electric field. A fortuitous crossing of the magnetopause boundary at 6.6 R_E has enabled a detailed study of low energy plasma flow at the boundary. Very low frequency plasma waves have been detected on a few occasions during magnetically disturbed times. Lastly, during magnetospheric and polar substorms the tail plasma sheet is found to penetrate to 6.6 R_E and is a highly recurrent feature of these phenomena.

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I. EXPERIMENT DESCRIPTION AND DATA REDUCTION

The Rice University Suprathermal Ion Detector (hereafter termed the SID) flown on the ATS-1 was a miniature retarding potential analyzer with a geometric factor of $4.5 \times 10^{-4} cm^2 ster$. The function of the SID was to obtain differential energy per unit charge spectra of positive ions in the range 0 to 50 eV with high angular resolution ($\approx 12°$). The SID was mounted perpendicular to the ATS-1 spin axis with the detector look axis lying in the equatorial plane. The SID completed an angular scan in the equatorial plane once every 0.64 sec. with each angular scan consisting of 29 separate accumulation intervals. Approximately 1.88 minutes were required for a complete energy scan of 22 steps (20 differential, 2 integral, see Table 1).

Particle detection was accomplished when charged particles of either sign were passed by the retarding potential analyzer then detected by a funnel-type Bendix Channeltron Electron Multiplier (hereafter referred to as the CEM, Figure 1) which is also sensitive to UV (see a review of CEM characteristics by Schmidt, 1969). Detection of very low energy ($\sim$0eV) ions was accomplished by biasing the front (funnel) end of the CEM at +3200 V. Thus, all positive ions passed by the retarding potential analyzer were accelerated into the CEM with about optimum emergy for detection. On the other hand, electrons with energies below 3200 eV were excluded from the CEM. There was no method of excluding UV from the CEM although this did not prove to be a serious problem.

Differential energy analysis was obtained from what is essentially an integral device (the retarding potential grid) by the following means. The retarding grid was biased at some predetermined voltage V_o by a voltage stepper (Figure 2). Also applied to the grid was a 200 Hz square wave with a peak to peak amplitude, ΔV, equal to the width of the differential energy channel. Synchronized with the square wave signal was an "up-down" counter which counted "up" the number of pulses arriving from the CEM during the 2.5 msec downward excursion of the square wave when ions with energy above $q(V_o - \frac{1}{2}\Delta V)$ reached the CEM. The counter then counted "down" i.e. subtracted during the upward part or the square wave cycle when ions of energy greater than $q(V_o - \frac{1}{2}\Delta V)$ reached the CEM. The result contained in the counter was the number of positive ions entering the SID in the energy range ΔV centered at V_o during a 2.5 msec period. To avoid complications the "up" count was started at 8 rather than 0 while the down count could not proceed past 0. Statistically it is entirely possible to have more "down" counts than "up" i.e.

$$j(E> q[V + \tfrac{1}{2}\Delta V]) > j(E> q[V - \tfrac{1}{2}\Delta V) \quad .$$

Thus even if all particles have energies outside the 0 to 50 eV differential range there will be some counts in the differential energy channels. The number of counts per accumulation interval will have a normal (Gaussian) distribution about a mean count of 8 rather than 0 because of the 8-count bias. The standard deviation of the differential count distribution is proportional to the magnitude of the background counting rate (as measured by the integral channels) while the mean of the distribution becomes larger (>0) when ions are detected with energies in the 0 to 50 eV range. For instance, during substorms when integral channel counting rates become quite large ($\gtrsim$50/accumulation interval) the differential counts will have a very broad distribution centered at 8 counts, indicating the absence of low energy ions during these events. Single isolated instances of large counting rates during a single 2.5 msec accumulation interval often occur in these circumstances but as discussed above they are due to statistical fluctuations so long as the mean does not depart significantly from 8.

Information regarding plasma flow direction was obtained directly by using the ATS-1 "see sun" timing pulse. This located the sun direction on each rotation of the satellite with an error of $\simeq 3°$. Some directional inaccuracy resulted as well from the 5 msec SID accumulation interval during which the satellite rotated $\simeq 3°$. Because nearly all plasma flows we found to be more than one angular channel wide errors resulting from the above inaccuracies may usually be ignored.

II. Scientific Objectives

The initial scientific objectives of the SID experiment were two-fold:

a) Test for existence of large scale magnetospheric convection.

b) Provide information on low frequency hydromagnetic waves by direct observation of the associated particle motions.

In addition to the above objectives several unexpected results were obtained and have considerably widened the scope of the experiment:

c) Observation of particle populations in the magnetopause-magnetosheath region during times of severe magnetospheric disturbance.

d) Observation of low-energy (~keV) plasma sheet particles at the synchronous orbit during polar magnetic substorms.

III. Summary of Experimental Results

A. Magnetospheric Convection

Bulk flows of low energy plasma during periods of high magnetic activity ($K_p \geqslant 5$) were detected on several occasions [Freeman, 1968, 1969a; Young, 1969]. A summary of these events is given in Figure 3. Estimates of the temperature and other parameters are given, the uncertainty in measurements arising from the rapid temporal variations. Figure 3 shows that the plasma flow directions were in general agreement with the convection pattern suggested by Axford and Hines [1961] and others, although the level of magnetic activity during these periods was too great to allow inference of quiet time flow patterns. Plasma flows during disturbed periods do contribute however to our knowledge of electric fields at such times. For instance, Freeman [1968] suggested that flows seen by the SID might be due to plasma lost from the bulge region of the plasmasphere during magnetically active periods. This conclusion has recently gained further experimental support [Carpenter, 1970].

Freeman [1969b] presented preliminary evidence of bulk plasma flow during times of magnetic quiet but the results of this study are not complete. The chief difficulties in making a long-term averaging study of SID integral channel data are the background corrections necessary to account for solar and geocorona UV, anisotropic fluxes of high energy particles, and the possibility of spacecraft potentials.

B. Low Frequency Hydromagnetic Waves

During periods of relative magnetic quiet the ATS-1 magnetometer often detected nearly monochromatic sinusoidal oscillations with peak amplitudes of 2 to 20γ and periods ranging from 50 to 300 sec. [Cummings et.al., 1969]. The oscillations were transverse to the main magnetic field at

ATS-1 and wave train durations from 10 to 400 min. were observed. Cummings et.al. proposed an MHD standing wave resonance (i.e., a standing Alfvén wave) model in which only the second harmonic of the wave was present. According to this theory a node occurs in the E vector of the wave at the equator and so no particle motion would be expected at ATS-1 in association with the waves. A search of the SID data has not shown any obvious bulk motion associated with the waves, however it must be noted that the angular and energy sampling schemes of the SID would make detection difficult as the sampling period in energy is nearly the same as the wave period. Radoski [1970] and Southwood [1970] have recently challenged the standing Alfvén wave interpretation of the ATS-1 observations but the implications for particle detectors in relation to the new interpretations is not yet clear.

Oscillations in SID particle fluxes have been detected on several occasions on the dayside of the magnetosphere under conditions of moderate geomagnetic disturbance (Figure 4). In this case there is a very strong correlation between the particles and the local magnetic field which appear to be modulations in the density of background particles above the energy range of the SID (electrons > 3200 eV or protons > 50 eV). The particle and field oscillations are similar in appearance to those expected from the drift mirror instability discussed by Lanzerotti et.al. [1969].

C. The Magnetopause

An unexpected dividend provided by the SID was a series of magnetopause boundary crossings during the magnetic storm of January 13 and 14, 1967 (see Figure 5 and Freeman et.al., 1968; Warren, 1969; Warren and Freeman, 1969). On this occasion solar wind pressure became sufficient to compress the sunward magnetospheric boundary in as far as 6.6 R_E. Bulk flows of relatively cold ions (see Table 2) were observed moving sunward for roughly an hour before the boundary crossings. The crossings themselves occurred intermittently for an hour during which time magnetosheath plasma (Table 2) was observed on either side of the magnetic field reversal region delineating the boundary. Warren [1969] deduced a kinematic viscosity from the data in general agreement with that found by Axford and Hines to be necessary for driving magnetospheric convective motions. Although the event indicated very strong coupling between the shocked magnetosheath plasma and plasma inside the magnetopause, the experiment was not able to give information on the exact nature of the coupling. Evidence was found for localized instabilities in the boundary which might provide some of the cross-boundary energy transport.

D. Magnetospheric Substorms

At the time the SID experiment was conceived it was generally held that auroral particles (~keV) originated on field lines which crossed the equatorial plane substantially beyond the 6.6 R_E orbit [Dessler and Juday, 1965]. Freeman and Maquire [1967] found however that plasma appeared at 6.6 R_E in the region of local midnight in association with magnetic "bay" disturbances at auroral zone stations located in the same local time sector as the ATS-1 field line (e.g. College, Figure 6). The plasma associated with substorms was found to be outside the differential range of the SID. Young [1970] has argued that the particles responsible for these fluxes are predominantly electrons between 3.2 and 50 keV. The SID substorm electrons have substantially different behavior patterns than do the energetic electrons (50 to 1,000 keV) detected by the University of Minnesota/ATS-1 electron spectrometer during substorms (e.g. Figure 6). The level of ground magnetic activity necessary for the appearance of the lower energy SID particles is quite small; moderate to large flux events are sometimes associated with as little as 50 to 100 γ of activity in the auroral zone. The general correlation between increasing geomagnetic activity and the occurrence of SID events near local midnight is shown in Figure 7.

Using data from the UCLA magnetometer on ATS-1 together with the electron spectrometer and the SID, Young [1970] concluded that at 6.6 R_E the tail plasma sheet always plays a role in polar magnetic substorms, even when the substorms are quite weak. Only when substorms are moderate to severe does the usual magnetospheric substorm in the sense of > 50 keV electron acceleration occur at 6.6 R_E (Figure 6).

By analyzing data from 7 weak to moderate substorms occurring on nights with little other magnetic disturbance (K_p= 2 to 4) Young estimated the mean electric field responsible for plasma convection to be 0.35 x 10^{-3} volts/meter. Using the method of whistler observations Carpenter [1969] estimated electric fields during substorms (K_p= 2 to 4) to have an average value of 0.2 to 0.3 x 10^{-3} volts/meter while Vasyliunas [1968] used a technique similar to Young's and inferred a field of 0.24 x 10^{-3} volts/meter for a single observation.

IV. Summary and Conclusions

Data from the SID experiment has shown that bulk motion of low energy plasma inside the magnetosphere occurs with velocities ~ 30 to 50 km/sec during periods of high geomagnetic disturbance with $K_p \geqslant 5$. These plasma flows occur predominantly in the noon to dusk quadrant magnetosphere and have led Freeman [1968] to suggest that they are the result of thermal plasma torn loose from the bulge region of the plasmasphere and convected sunward. The convection pattern suggested by the ATS-1 observations is consistent with that proposed by Axford and Hines and others.

Unexpectedly, the SID has proven useful in determining the gross characteristics of plasma flow at the magnetopause, showing it to be a region of laminar-like viscous flow of the sort proposed by Axford and Hines. This has considerable bearing on convection theories of the magnetosphere as it is clear from SID data that the streaming magnetosheath plasma has considerable effect inside the magnetosphere cavity.

Lastly the SID has been used to explore the role of plasma sheet particles in the substorm process. During substorms the tail plasma appears to be able to convect in to at least 6.6 R_E near the midnight meridian implying a strengthening of the convection electric field or a piling-up of flux tubes by "line-tying" or both. The implications of this results for substorm theory have not yet been explored.

The papers that discuss the intimate details of these results are attached and form the appendix of this report.

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Table 1

Energy Passbands for the SID,
Assuming no Spacecraft Potential

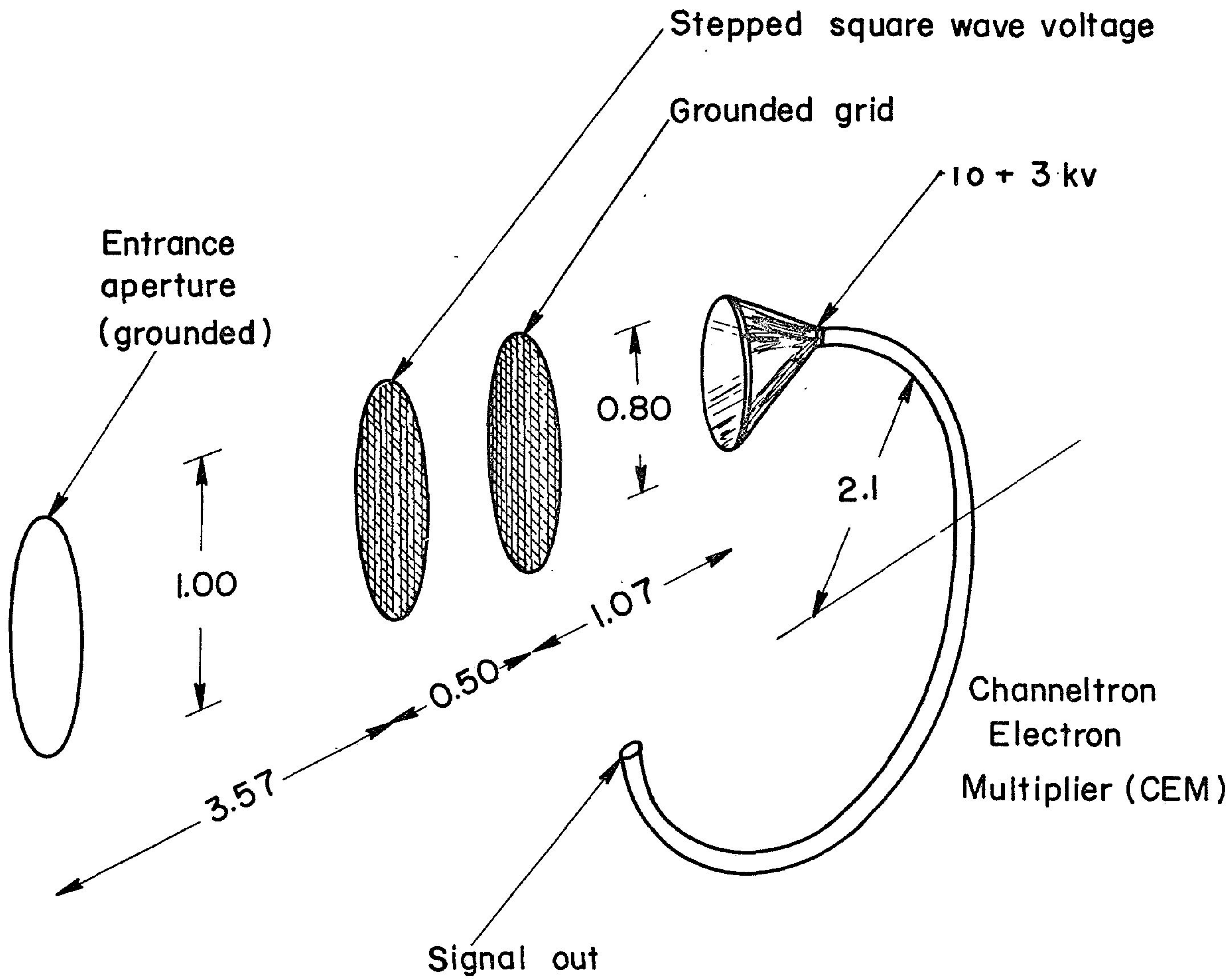
Step Number	Upper and Lower Limits (Energy per Unit Charge)		Width of Passband (eV)
21	-0.25	0.25	
1	0.25	0.75	
2	0.75	1.25	
3	1.25	1.75	
4	1.75	2.25	
5	2.25	2.75	0.50
6	2.75	2.75	
7	3.25	3.75	
8	3.75	4.25	
9	4.25	4.75	
10	4.50	5.50	
11	5.50	6.50	
12	6.50	7.50	
13	7.50	8.50	1.00
14	8.50	9.50	
15	0.50	10.50	
16	10.00	20.00	
17	20.00	30.00	
18	30.00	40.00	10.00
19	40.00	50.00	
20		> 50.00	
0		> 0.00	

Table 2

Characteristics of Plasma Flows Detected on January 13 and 14, 1967

[Warren, 1969]

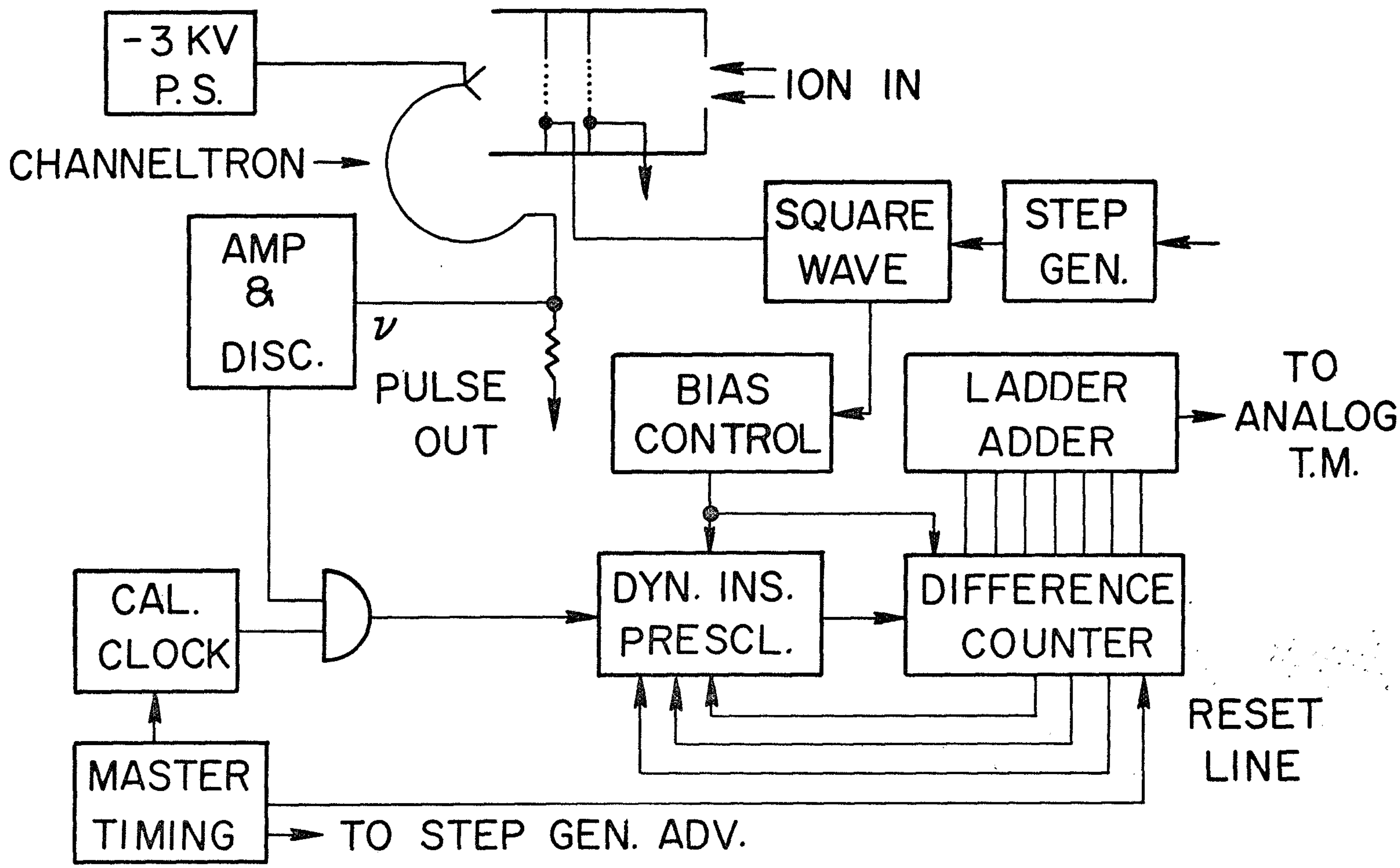
Description of Plasma	Mean Temperature	Mean Flow Velocity	Mean Number Density	Direction of Flow
Pre-magnetopause crossing	1700°K	21 km/sec	8.7 cm^{-3}	roughly sunward
During magnetopause crossing	1.9×10^{6} °K	90 km/sec	21 cm^{-3}	parallel to magnetopause boundary, away from the sun



(All dimensions in cm.)

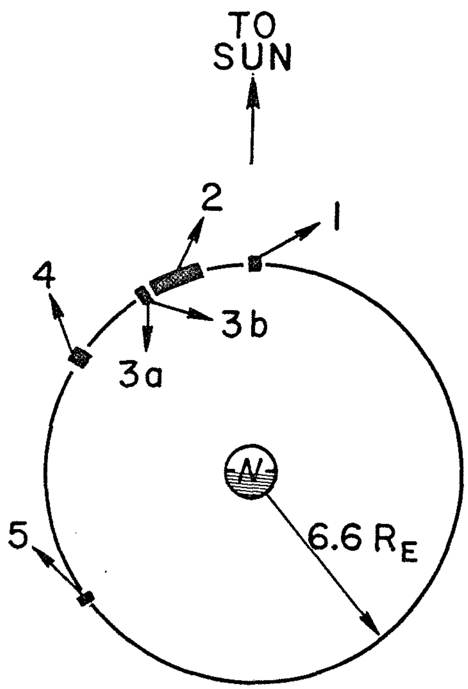
Schematic diagram of Suprathermal Ion Detector Assembly

Figure 1



Block diagram of Rice ATS-I Suprathermal Ion Detector Experiment

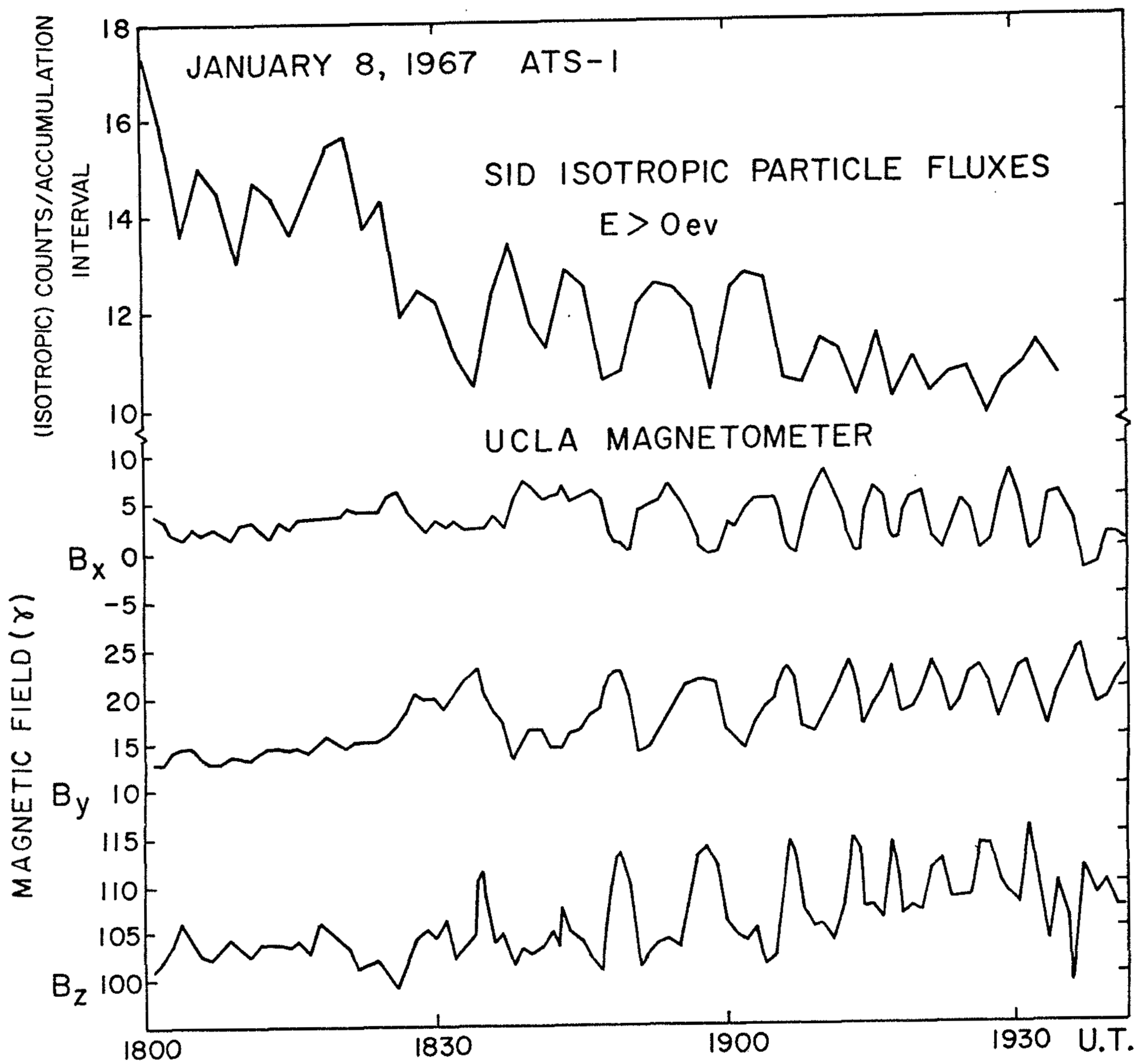
Figure 2



EVENT	DATE (1967)	K_p	TYPICAL ANGULAR DISTRIBUTION (FWHM IN DEGREES)	ESTIMATED PARAMETERS (ASSUMING IONS ARE PROTONS) T_p (°K)	$\bar{V}_p$ (km sec^{-1})	N (cm^{-3})
1	2/7	6+	24	$\sim 1.5 \times 10^3$	~30	~20
2	1/13	6−	24	1.7×10^3	21	9
3a	2/15	5-(ssc)	30	$\sim 5 \times 10^3$	~55	~10
3b	2/15	5-(ssc)	24	$\sim 5 \times 10^3$	~55	~5
4	1/8	6+	45	$\sim 10^4$	27	~10
5	2/16	5	24	$\sim 5 \times 10^3$	~55	~10

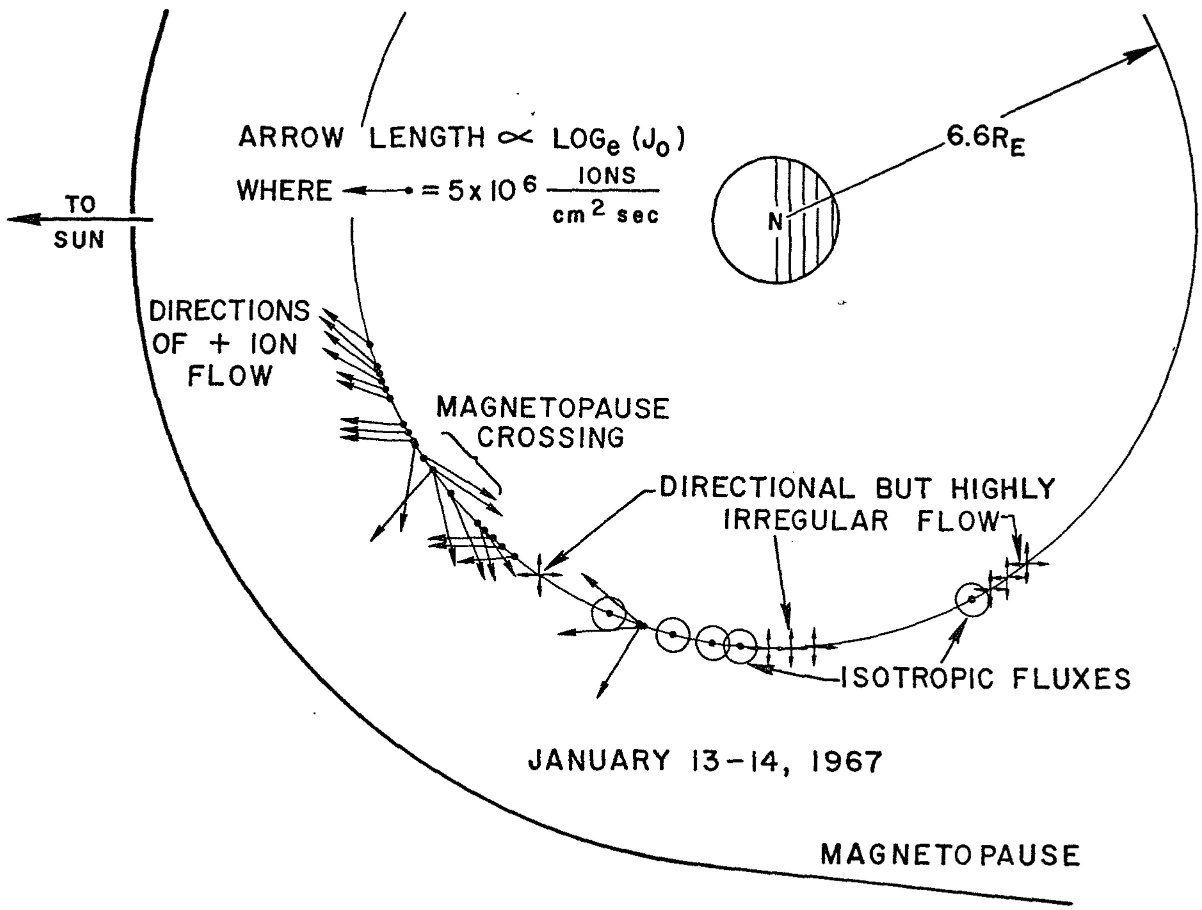
Summary of highly anisotropic fluxes with $E_p < 50$ ev detected by SID between Dec. 14, 1966 and Feb. 15, 1967 on ATS-1

Figure 3



Oscillations in SID particle fluxes and local magnetic field at ATS-1 on January 8, 1967

Figure 4



A partial view of the ATS-1 orbital pattern in the magnetospheric equatorial plane showing the ion flow directions in the quadrant from noon to dusk on 13 to 14 January 1967. The satellite crossed the noon meridian at 2200 U.T. on 13 January. The magnetospheric boundary (magnetopause) is shown in its undisturbed position; however, during this orbit it was actually pushed in to the vicinity of the ATS-1 orbit by heightened solar wind pressure. The section of the orbit labeled "magnetopause crossing" indicates where the satellite was at this time. The disruption in the normal ion flow pattern can be clearly seen. The quantity R_E represents earth radii; J_o is omnidirectional flux; and N is the North Pole.

Figure 5

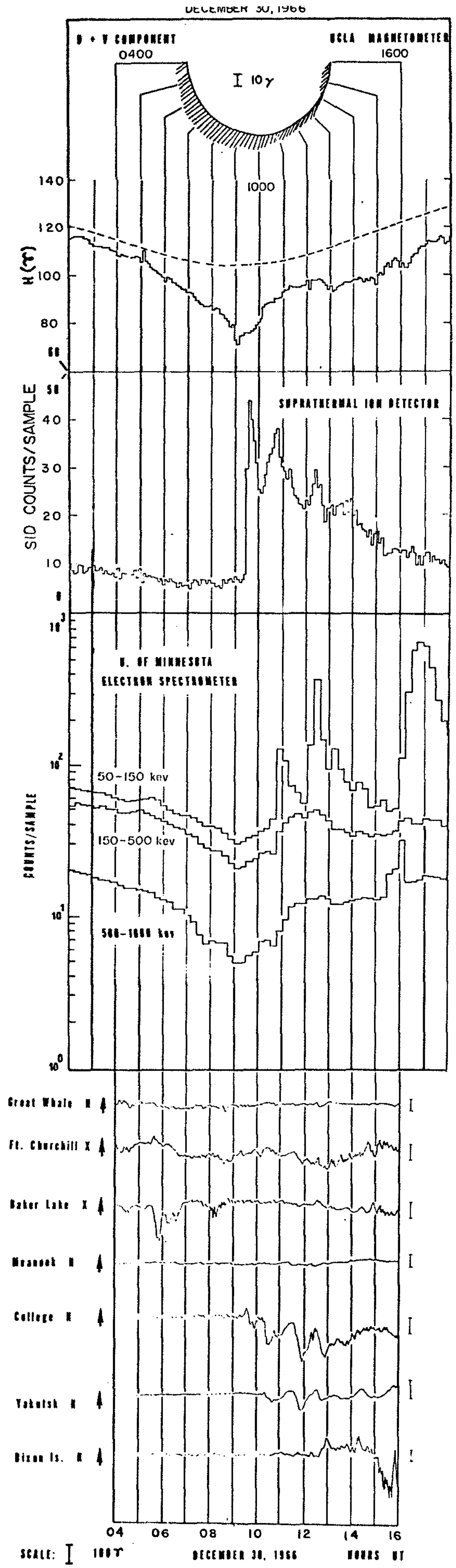

DECEMBER 30, 1966
D + V COMPONENT
UCLA MAGNETOMETER
0400
1600
1000
10γ
H(γ)
140
120
100
80
SUPRATHERMAL ION DETECTOR
SID COUNTS/SAMPLE
40
30
20
10
U. OF MINNESOTA
ELECTRON SPECTROMETER
COUNTS/SAMPLE
50-150 kev
150-500 kev
Great Whale H
Ft. Churchill X
Baker Lake X
College H
Yakutsk H
Dixon Is. H
04
06
08
10
12
14
16
SCALE:
DECEMBER 30, 1966
HOURS UT

Figure 6

DISTRIBUTION OF SID ENHANCEMENTS vs. ΔK_p

CHANGE IN K_p RELATIVE TO 3 HOUR INTERVAL PRECEDING ENHANCEMENT	NUMBER OF OCCURRENCES	$\Sigma \Delta a_p$ ALL OCCURRENCES
K_p INCREASE	23	+159
K_p DECREASE	7	−17
K_p SAME	2	0

DISTRIBUTION OF SID ENHANCEMENTS vs. ΣK_p

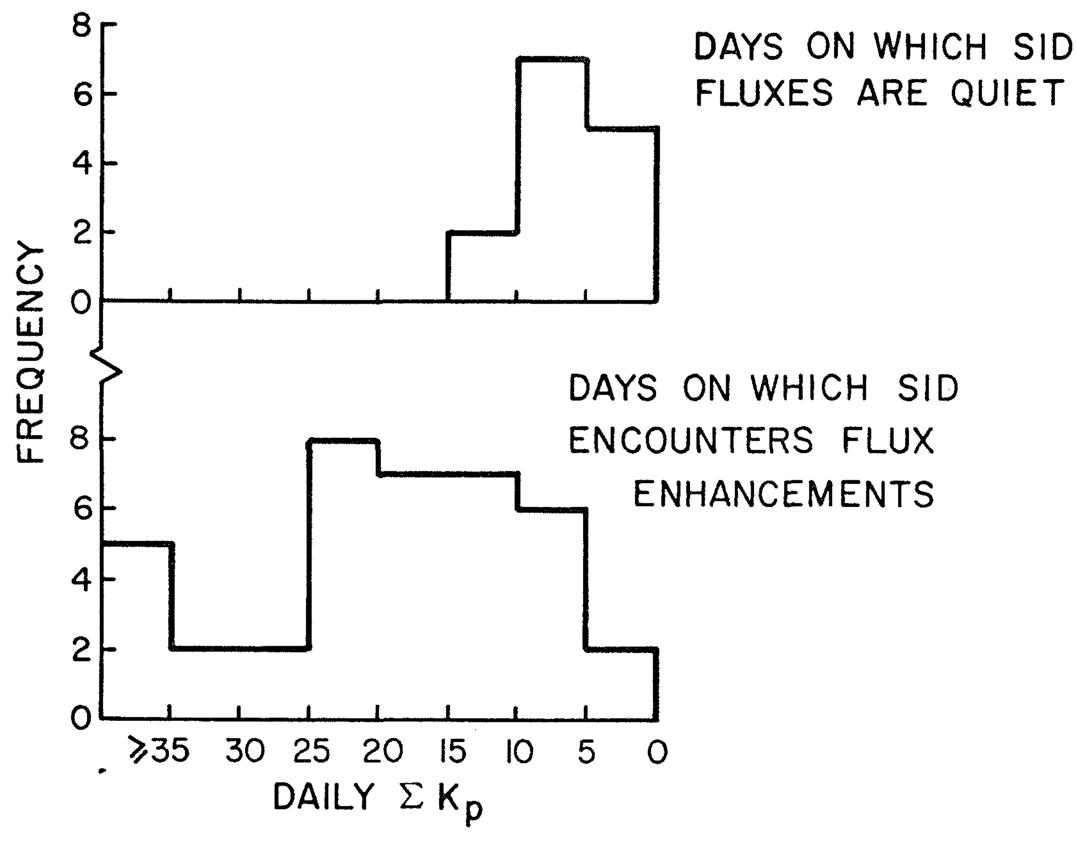


Figure 7

VII APPENDIX

Research Papers and Reports
Pertaining Directly to the ATS-1
SID Data