An Unusual Charging Event on ISEE 1

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Electrostatic cleanliness requirements on ISEE 1 were expected to prevent negative charging in sunlight. This has largely been true, but on three occasions, ISEE 1 has been observed to charge to significant negative potentials in sunlight. Data from the two electric field experiments and from the plasma composition experiment on ISEE 1 show that the spacecraft charged to close to -70 V in sunlight at about 0700 UT on March 17, 1978. Data from the electron spectrometer experiment show that there was a potential barrier of some -10 to -20 V about the spacecraft during this event. The potential barrier was effective in turning back emitted photoelectrons to the spacecraft. Potential barriers can be formed by differential charging on the spacecraft or by the presence of excess space charge in the plasma. The shape of the barrier suggests that it is due to the former, even though electrostatic cleanliness specifications imposed on ISEE were intended to eliminate differential charging. Modeling of this event showed that the barrier could not be produced by the presence of space charge, but that it was most likely produced by differential charging of the solar arrays.

INTRODUCTION

The International Sun Earth Explorer (ISEE) project involves three spacecraft which were designed to study the magnetospheric plasma under the auspices of the International Magnetospheric Study program. ISEE 1 and ISEE 2 were launched on October 22, 1977, into almost identical orbits but with a variable separation distance in order to be able to separate temporal and spatial variations of the environment. Their apogee was at 23 earth radii, and their period was approximately 57 h. ISEE 3 was launched into a "halo orbit" about the libration point at about 240 earth radii towards the sun from the earth [*Ogilvie et al*. 1978a; *Knott et al.* 1979].

Satellite charging, a major concern for scientific and engineering reasons, is a consequence of the balance of currents from the ambient plasma and photoemission. In the plasma sheet, low plasma densities and electron temperatures (Te) of a few keV, result in a current balance to a spacecraft such that spacecraft potentials are a few volts positive. Typically, ISEE 1 was +10V to +20V in the near earth (5-8 Re) plasma sheet, and was >+30V in the lobes. When Te is high, it is possible for shadowed materials to charge negatively. The response of the spacecraft then depends on its construction, specifically on the presence of exposed non-conducting materials or of isolated conducting surfaces. The presence of such surfaces leads to differential charging and the creation of electrostatic potential barriers. These barriers can suppress the emission of photoelectrons and secondary electrons by turning such electrons back to the spacecraft so that they do not escape. Such spacecraft can charge to negative potentials in sunlight, unlike fully conducting satellites. ISEE 1 had a conductive path from shadowed to sunlit surfaces, but with a finite resistance. The establishment of a potential difference between sunlit and shadowed surfaces on ISEE 1 ultimately depends, therefore, on current (flux), and hence both density and temperature.

This difference in response has been verified for a number of spacecraft. Daylight charging of ATS-5 and ATS-6 was found to be dominated by differential charging [*Olsen and Purvis*, 1983], and *Mullen et al*. [1986] suggested that the formation of potential barriers could explain sunlight charging of SCATHA. These satellites experienced potentials of several kV (negative) in eclipse and several hundreds of volts negative in sunlight. Each of these had exposed insulating areas and differential charging has been experimentally inferred for all of them (*Katz and Mandell,* 1982; *Olsen and Purvis*, 1983). On the other hand, spacecraft with only grounded conducting exposed surfaces, such as ISEE and GEOS, have experienced much smaller potentials, e.g. +1 to +50 for ISEE in sunlight, and +1 to +10 for GEOS in sunlight (*Wrenn*, 1979; *Wrenn et al*., 1979; *Whipple*, 1981). The electrostatic specifications for ISEE required that no exposed components (with some exceptions) charge to potentials in excess of 1 v with respect to the spacecraft ground. Also, all components exposed to the plasma environment were to be "sufficiently conducting", and be connected to the spacecraft ground through low impedance paths.

In spite of these electrostatic cleanliness requirements, and general success in controlling negative charging, there have been indications of significant charging events on ISEE 1, with the spacecraft reaching a negative potential on the order of -100 volts in sunlight. These indications initially came from ion data obtained by the plasma composition experiment which showed that low energy (thermal) ions had been accelerated to kinetic energies on the order of 100 eV before they were detected by the instrument (E. Shelley, private communication, 1982). It is important to understand such charging events, if they are indeed real, in order to be able to evaluate the effectiveness of the electrostatic cleanliness specifications. For example, the charging of electrostatically "dirty" spacecraft such as ATS-5, ATS-6, and SCATHA has been shown to be very dependent on differential charging effects (Olsen et al., 1981; Olsen and Purvis, 1983). The purpose of this paper is to examine in detail a sunlight charging event on ISEE 1 and to determine if differential charging occurred in spite of the electrostatic cleanliness requirements.
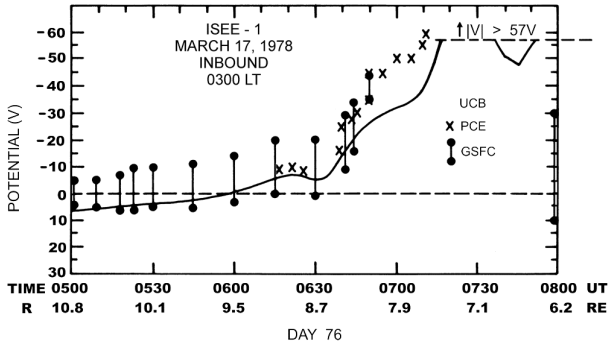
Figure 1. ISEE 1 satellite potentials inferred from the UCB electric field experiment, GSFC electric field experiment, and the Lockheed Plasma composition experiment, March 17, 1978, inbound.

INSTRUMENTS

This study utilized data from two electric field experiments, three particle spectrometers, the plasma compostion experiment, and the plasma wave experiment. The pertinent characteristics of each instrument are as follows.

The spherical double probe electric field experiment on ISEE 1, provided by The University of California (UCB), measures the potential difference between two probes, which are 4 cm radius spheres at the ends of wire booms separated by 73.5 m in the spin plane of the spacecraft [Mozer et al, 1978a,b]. The antenna wires are shielded from the ambient plasma for 35 m by a conductor which can be grounded to the satellite, or biased to the potential of the spherical probe. For the events studied here, the antenna shields were grounded to the satellite. Besides the electric field measurement, the experiment monitors the potential difference between each of the probes and spacecraft. The potential of the spheres with respect to the plasma is adjusted to be near zero by introducing bias currents to the sphere based on current/voltage sweeps which are made during a quarter-second interval every 128 sec (e.g., the antenna are briefly operated as Langmuir probes). The relationship between the floating potentials of the spacecraft and probes has been investigated extensively by Pedersen et al. [1984] and Lindquist [1983].

The GSFC electric field experiment uses a different approach, with long wire antenna, and a cylindrical geometry. The active probes in this experiment are the 36 m uninsulated tip sections of two wires independently deployed to lengths of 106.7 m. This gives an effective baseline between the two elements of 179 m [Heppner et al.,1978a,b]. A similar geometry was used for the SCATHA satellite antenna, which have been successfully used in following negative charging on that satellite [Mullen et al. 1986]. The antennas are floating with respect to the ambient plasma, in contrast to the UCB experiment. The floating potential is modulated by the spin of the spacecraft, and is most positive when the wire elements are perpendicular to the direction of the sun since this is the orientation where the photo-emission is a maximum. This experiment, therefore, differs from the UCB experiment in three important ways: (1) no bias current; (2) cylindrical geometry for the active elements; and (3) length.

The GSFC electron spectrometer provides electron distribution functions from 7 eV to 7 keV, from 6 identical electrostatic analyzers. The analyzers are arranged with two sets of three analyzers on opposite sides of the satellite, on the belly band, with each of the three detectors in one set paired with a detector on the other side, looking anti-parallel. The energy range is swept six times per spin, providing 36 sets of energy spectra, and covering most of phase space [Ogilvie et al., 1978b]. Details of the look directions are discussed in conjunction with data shown below. The solid angles are 8.5° x 11°.

The University of Iowa LEPEDEA, is a quadrispherical detector, divided into 7 segments to cover the polar angle, but only the 'radial' look direction is utilized in this work (Detector "4e"). This detector covers a 60 x 380 solid angle. During periods of low bit rate telemetry (i.e. for this work), the detector covers the 200 eV to 45 keV energy range in 32 steps [Frank et al., 1978].

The Lockheed plasma composition experiment combines a mass spectrometer with a retarding potential analyzer, and some of the functional elements of an electrostatic analyzer. The ions enter through a collimator and then go through a three-grid retarding potential analyzer (RPA). The retarding grid is programmable between 60 mV and 100 V in 32 steps with approximately equal logarithmic intervals. After passing through the third grid, the ions are accelerated through a potential difference of approximately -2950 V before they pass through a cylindrical electrostatic analyzer. Due to the pre-acceleration, the lowest energy step of the electrostatic analyzer passes all ions with external energies between zero energy (i.e., those cold ions which can reach the spacecraft) and approximately 100 eV. It is data from this lowest energy channel which will be used here. There is a modified Johnston electron multiplier prior to the mass analysis which is used for much of the analysis below. It is generally termed the H+ measurement. Following the mass analyzer, there are again Johnston multipliers. [Shelley et al. 1978].

Information on the high energy (20-100keV) electrons which are principally responsible for negative charging is obtained from the LEPEDEA, and the Medium Energy Particles Instrument (MEPI) [Williams et al, 1978]. The MEPI covers the 20-1200 keV energy range with 8 channels in low bit rate. The detectors provide an angular resolution of 100 x 450 at low bit rate including spin and scan platform. Energy resolution is - 5%, with a geometric factor of 10^{-2} cm^2 sr.

OBSERVATIONS - DAY 76 - INBOUND

Satellite Potential

ISEE 1 was observed to charge on both the inbound and outbound segments of its orbit on March 17, 1978 (Day 76). In this section, we present evidence from the two electric field experiments and from the plasma composition experiment which indicate that between 0600 and 0800 UT on March 17, 1978 (Day 76), the ISEE 1 spacecraft charged to at least -70 volts, and perhaps -100 V, in sunlight. At the time of maximum potential (0730 UT), the vehicle was near synchronous orbit, at 7.1 earth radii, and 0300 LT. In addition, we present data from a synchronous altitude spacecraft, ATS-5, on the same date but at about 0400 UT and at midnight local time, which show that ATS-5 charged to about -6kV in eclipse. These latter data indicate the plasma environment during this period was sufficiently hot to provide significant charging on a satellite in eclipse.
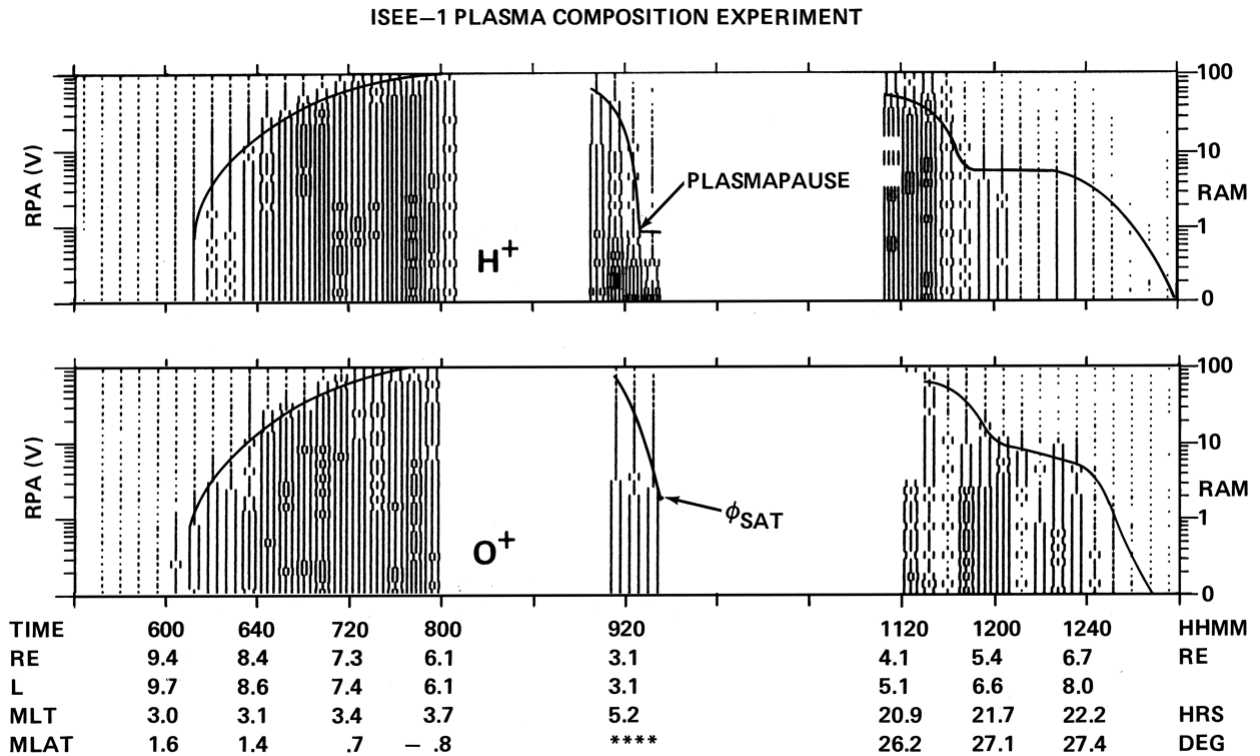
ISEE—1 PLASMA COMPOSITION EXPERIMENT

TIME	600	640	720	800	920	1120	1200	1240	HHMM
RE	9.4	8.4	7.3	6.1	3.1	4.1	5.4	6.7	RE
L	9.7	8.6	7.4	6.1	3.1	5.1	6.6	8.0	
MLT	3.0	3.1	3.4	3.7	5.2	20.9	21.7	22.2	HRS
MLAT	1.6	1.4	.7	— .8	****	26.2	27.1	27.4	DEG

Figure 2. RPA-time spectrogram for data from the Lockheed PCE, for the ram direction H+ and 0+.

Figure 1 shows the satellite potentials inferred from the PCE, UCB, and GSFC experiments. The PCE measurements of potential are derived from RPA curves, as described below. These data show that between 0610 and 0740 UT, the satellite potential drops from -0 to --60 V. These measurements have a substantial uncertainty, but the trend is clear. The UCB data are the "common mode" voltage, the potential difference between sphere #2 and the spacecraft. [See *Lindquist*, 1983; and *Mozer et al.*, 1978b]. This is nominally the spacecraft potential assuming the probe is near ambient plasma potential. The UCB data show that the spacecraft was near zero volts at 0600 UT and that it gradually charged to a more negative potential, going off-scale at -57 volts at about 0715 UT. The potential came back on scale briefly at 0745 UT. During the period from 0700 to 0800 UT the vehicle potential was close to or more negative than -57 volts. Since the sphere bias current is negative at this time (i.e., electrons are being pushed onto the sphere), the fact that the spacecraft is more negative than the sphere implies that the spacecraft and the sphere are responding differently to the environment. For example, there may be more secondary electrons emitted from the sphere, or there may be potential barrier effects around the spacecraft that are not around the sphere. The GSFC data are again the satellite-probe potential difference. The range for each GSFC measurement is the spin modulation of that experiment, as shown below. The three data sets are in agreement, demonstrating that the inferred charging is

not an artifact in one instrument. The data from each instrument are now considered in detail.

Figure 2 shows data from the plasma composition experiment (PCE) in RPA-time spectrograms for the "total" or "H+" channel (top), and for "O+" mass channel (bottom), from 0520-1300 UT. The potential of the spacecraft can be inferred from the retarding potential required to "cut off" the ion current in a particular ion channel (e.g., *Whipple et al.,* 1974). Over this time period the satellite charges, reaches - -100 V or greater at 0800 UT, then discharges as the satellite enters the plasmasphere (0920 UT). The satellite discharges completely as it passes through perigee, and is again 10's of volts negative as the satellite moves outward at local dusk (1120-1240 UT).

Figure 3 expands the PCE data from 0600-0800 UT on March 17. Ten minute segments of the data are used to construct spin phase-RPA spectrograms. The vertical axis is spin phase, with the center (0°) oriented towards ram ion measurements, and ±180° in the wake. The pitch angle corresponding to these measurements is plotted between the H+ and O+ panels, with the two traces showing the range of values at the beginning and end of the sampling period. The horizontal axis is RPA voltage, which sweeps from 0-100 V. The top panels, from 0610-0620 UT, show field-aligned plasmas, which have energies in excess of 10 eV. The isotropic background retards out at 1 or 2 V. In the 0640-0650 panels, second row, the field-aligned distributions are still visible, with significant fluxes up to at least 50 V. The isotropic background now fills in up to at least 10 V. It is this background

which is analyzed as accelerated plasma, revealing the satellite potential. The oxygen shows similar behavior. Note that these data are from the mass analyzer, so we can be reasonably certain of the mass identification for H+. The O+ data may be contaminated by a satellite generated heavy ion population (see appendix), but give the same result. From 0710-0720 UT, the ions

suggest a potential of 50-70 V, and in the last panels (0740-0750 UT), a potential near 100 V. There are faint hints that a charging peak is visible in the next ESA channel (centered near 200 V) after 0800 UT.

ISEE PCE DAY 76 OF 1978

Figure 3. Thermal plasma measurements from the Lockheed plasma composition experiment, as a function of spin phase and Retarding Potential Analyzer (RPA) voltage.

Individual RPA scans were examined during part of this period of time, and the spacecraft potential was estimated for scans when the experiment was most nearly looking at ions coming in the ram direction. Individual scans were obtained approximately every three minutes, although there were some gaps in the data. The results were shown in Figure 1. The data show that the potential of the spacecraft increased in the negative direction from near -5 V at about 0630 UT to a value more negative than -60 V after 0710 UT.

Figure 4. Common mode potential measurements from the UCB electric field experiment.

Fluctuations of 1-2 V with spin have also been observed for the SCATHA satellite in the plasma sheet, as recently noted by *Craven et al.* [1987]. The modulation of the ISEE 1 satellite potential, which can reach magnitudes of 5 to 10 V in the tail lobes [F. S.

Figure 4 shows expanded plots of the UCB data, for 12s intervals during the period of study. The top panel shows "normal" data for this experiment. The data shown are the common mode voltage, i.e., the potential between probe and satellite. Initially, the probe potential with respect to the satellite is -5 V, indicating a +5 V satellite potential, with some spin modulation.

Mozer, private communications, 1980], is due to assymetries in the exposed satellite conducting area. A major contribution to the effect is the area of the electric field antenna shields, which are grounded to the satellite at this time (they can also be biased). The effective area of these shields drops to zero when they are along the sun-satellite line. This effect was reduced later in the mission when the experiment operating modes were revised.

The satellite potential becomes negative (- -1 V) by 0600 UT, with a modulation of similar magnitude. At 0700 UT, the satellite potential is -30 t -35 V, with a 5 V fluctuation. The last clear potential measurements came at 0712 UT, where the satllite potential reaches -50 V. (The maximum telemetered voltage is 57 V, but the voltmeter response at this level is a little uncertain.)

As noted earlier, the relative response of the UCB probes implies they are responding to the plasma in a manner which is substantially different than the spacecraft body. The probes are being driven with a current which would normally force them to be negative with respect to the satellite, not positive. Interpreting the UCB (or GSFC data below) as a spacecraft potential measurement assumes we will find a model for the ISEE charging behavior which allows the long antenna data to be interpreted as we have.

Figure 5 shows data from the GSFC electric field experiment at similar resolution. This measurement is limited to ± 30 V, so a slightly different set of times was chosen. The figure shows the potential difference between one antenna element and the spacecraft. The potentials of the antennas in this experiment are floating with respect to the ambient plasma, in contrast to the UCB experiment. The floating potential of the active wire elements with respect to the local plasma is not directly measured in this experiment, but it is expected to be on the order of a few volts positive when the wires are perpendicular to the sun direction and near plasma potential or slightly negative when along the sun-satellite line. The two spherical probes in the UCB electric field experiment floated at approximately +5 V during this period of time, as determined from current/voltage sweeps when the bias current was zero. If the wire element is also floating at about +5 volts during this time, then the spacecraft potential has changed from near zero to about -25 V between 0600 and 0641 UT. These values are in reasonable agreement with the data from the UCB experiment, as summarized in Figure 1.

The data from the three experiments are essentially in agreement. The PCE data give slightly more negative values than the UCB antenna. This disagreement is probably largely due to the coarse temporal average for the particle data, and ambiguities in the potential measurement. The difference may also be partially explained by a non-zero potential on the UCB antenna - i.e. a negative potential with respect to the plasma. The charging behavior of ISEE 1 is anomalous enough to suggest the need for further corroboration. Support for our interpreting the ISEE data as indicative of negative charging can be gained by comparing these observations to measurements on a nearby satellite.

Figure 6 shows a spectrogram from the UCSD particle detector on Applied Technology Satellite 5 (ATS-5) between 0410 and 0510 on the same day. Data is only available during the time when

the spacecraft was entering and within the earth's shadow. This was a period when special operations of the ATS-5 ion engine neutralizer were being carried out to test the capability of this device to discharge the spacecraft [*Olsen* 1981]. The spacecraft entered eclipse at 0411 UT; the neutralizer was turned on at 0418 and off at 0433 UT. The neutralizer consisted of a heated filament which emitted thermal electrons. During the neutralizer operation, the spacecraft potential was held to about -2 kV. When it was turned off the potential went to about -6 kV. The ion spectrum during this period of time as measured by the UCSD detector is in good agreement with the ion spectrum measured by the LEPEDEA experiment on ISEE 1 at 0700 UT. Thus, it appears that the plasma near geosynchronous orbit during the morning of March 17, 1978, was sufficiently hot to charge "dirty" spacecraft such as ATS-5 to several kilovolts negative in shadow, and "clean" spacecraft such as ISEE 1 to approximately -100 V in sunlight.

Figure 5. Common mode potential measurements from the GSFC electric field experiment.
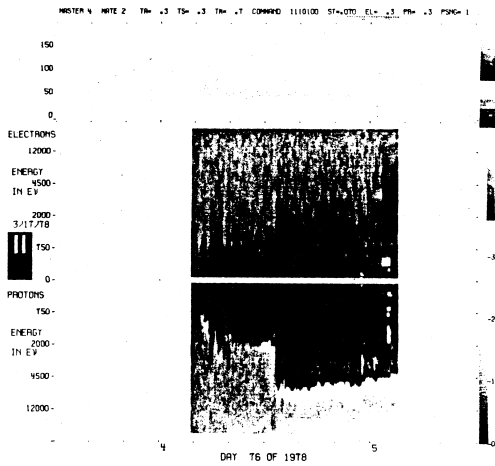

Figure 6. UCSD Plasma data from ATS-5, in eclipse.

Potential Barrier

For geosynchronous satellites, significant daylight charging is associated with differential charging on shadowed insulators and the presence of potential barriers. We therefore examined the electron data to determine if a barrier existed at this time. Figures 7
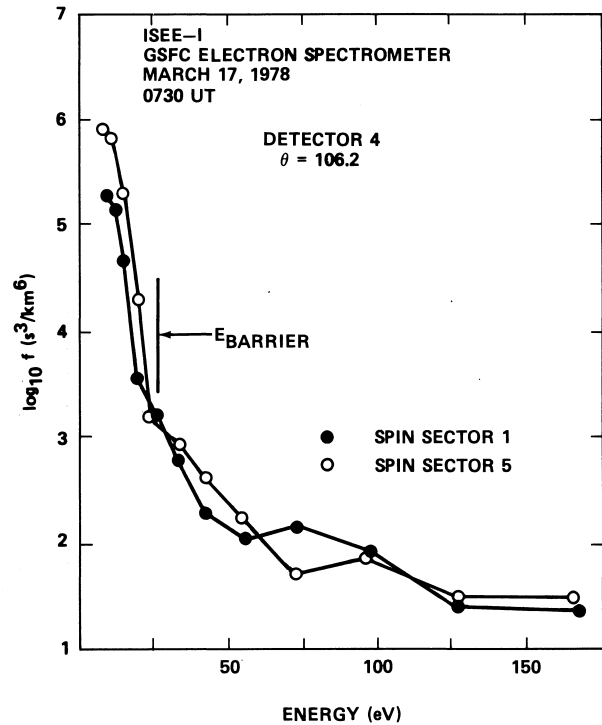

Figure 7. Electron distribution function from the GSFC experiment on ISEE 1, as a function of energy, detector 4.
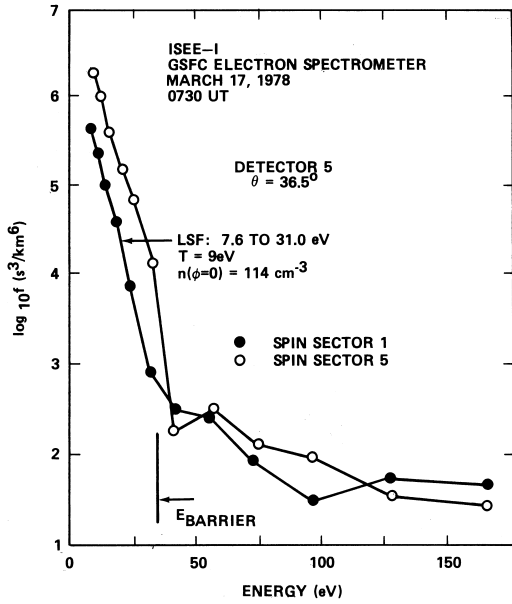
Figure 8. Electron distribution function (or phase space density) from the GSFC experiment on ISEE 1, detector 5.

Figure 9. Electron distribution function, as a function of polar angle from the GSFC experiment on the satellite.

and 8 show electron data from the GSFC Electron Spectrometer experiment. The electron distribution function on a logarithmic scale is shown against electron energy at 0730 UT for two detectors (see below for geometry, also *Ogilvie et al.* [1978]. The data in Figure 7 are from detector 4, which looks out at an angle of 1060 to the spin axis, i.e., nearly in the spin plane, while the data in figure 8 are from detector 5, which is mounted in the same location as detector 4, but pointing at an angle of 36.5° to the spin axis, or 53° from the spin plane, out along the solar arrays. At low energies, both Figures 7 and 8 show a steepening of the electron spectrum characteristic of photoelectrons and/or secondary electrons.

Analysis of the 10-20 eV electron distribution (spin averaged) displayed in Figure 7 indicates that these electrons are characterized by a density of 83 cm-3 and a temperature of 2.2 eV. These values are reasonable for photoelectrons emitted from typical spacecraft surfaces at the earth's distance from the sun. It is unlikely these are ambient electrons. The ISEE 1 plasma wave experiment and radio propagation experiment (*Gurnett et al.*, 1978; *Harvey et al.*, 1978), both indicate that the plasma density during this period of time was about 1 cm-3. The actual value of the photoelectron density would of course depend on the material and on the orientation of the emitting surface with respect to the solar direction. The fact that photoelectrons with energies as high as 20 eV are seen returning to the spacecraft indicates that there must be a significant electric field which turns back the emitted photoelectrons. In other words, there must be a potential barrier around the spacecraft. This behavior of the electron spectrum was seen at all orientations of the spacecraft during its spin, although the magnitude of the inferred photoelectron density was somewhat modulated by the spin.
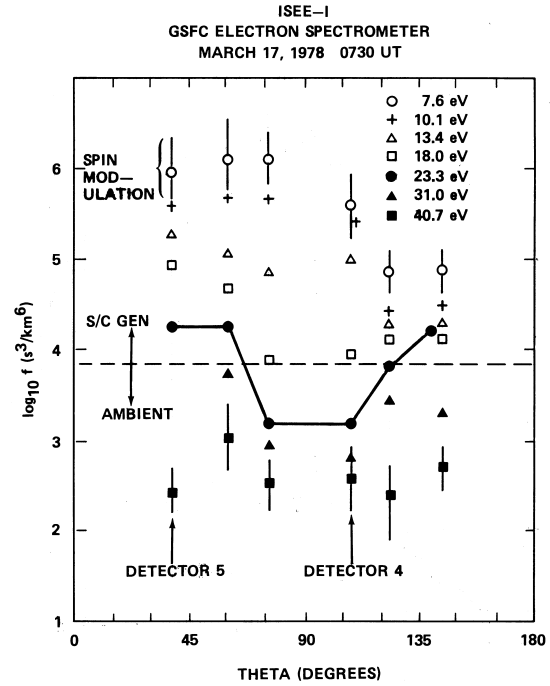
The behavior of the electron spectrum in Figure 8 is similar to that in Figure 7. The low energy part of the spectrum (7-30 eV) is fitted well by a Maxwellian distribution with a temperature of 9 eV and a density of about 114 cm-3 if these low energy electrons are photoelectrons coming from spacecraft. If these electrons were ambient plasma electrons reaching a negatively charged spacecraft at -50 V, they would have to have a density of 3×10^4 cm-3 in the undisturbed plasma. This is completely unreasonable for the plasma at this location near geosynchronous orbit in the earth's magnetosphere. We conclude, therefore, that there must still be a potential barrier around the spacecraft at 0700 UT in spite of the negative spacecraft potential. Secondly, the barrier is higher for detector 5 (about 35 V), than detector 4 (about 25 V). Hence, the detector which looks along the solar arrays sees a larger barrier.

The higher energy parts of the distributions in both Figures 7 and 8 give reasonable values for the plasma electron temperatures and densities for this location in the magnetosphere. Measurements of the electron spectrum at higher energies by this instrument and LEPEDEA show a significant increase of energetic (keV) electrons over this time period (not shown).

Figure 9 shows the angular distribution obtained by plotting distribution function values for the six detectors as a function of the polar angle (theta) of the detectors, for a number of energy steps. The data are clearly ordered by this plot, with a drop in the values of the distribution function in the middle angle range. By comparison with the plots versus energy, distribution function values over 5×10^3 s³/km⁶ are indicative of spacecraft generated electrons, while values below this level are from the ambient plasma. These figures suggest a barrier height of 18 eV for radial look directions at 0730 UT, with a higher barrier of 30 eV at low angles (along the spin axis). As described below, such angular variations are indicative of differential charging on the solar arrays.

The cause for this unusual event must lie partially in a plasma environment which differs from that normally encountered by ISEE. The electrons responsible for charging the satellite are observed by the LEPEDEA and MEPI, as shown in Figure 10. The spectrum at lower energies (up to 40 keV) is fairly typical of the inner plasma sheet. The keV electrons can be characterized with a Maxwellian of density 0.2 cm^{-3}, and temperature of 8 keV. The plasma below 1 keV in energy can be characterized with a density of 0.25 to 0.5 cm^{-3}, and temperature of 314 eV, (LEPEDEA and GSFC spectrometer). These values are not unusual for the plasma sheet. At higher energies (the MEPI data) the environment is more unusual. The fluxes of high energy electrons are higher than typically found in this region (D. J. Williams, private communication, 1986). The spectrum is roughly proportional to E^{-4}, and gives a flux of 10^7 10^8 electrons (el)/cm^{2}s, or 1-10 pA/cm^2. The charging begins as the energetic flux (100-300 keV) increases to 4×10^{3}el/cm^2•s•sr•keV at 0550 UT. There is a sharp increase to ~10^5 el/cm^2 at 0745 UT. This high energy flux is important, because lower energy electrons tend to self-balance. That is, they generate secondary electron fluxes which cancel the effect of the ambient current. This concept has been explored previously by *Olsen*, [1983], *Laframboise et al* [1982], *Laframboise and Kamitsuma* [1983] and others. Although the physical processes are yet to be determined (see modeling below), it appears that this enhanced flux of high energy electrons is the feature which makes this day one of the few which produce observations of negative charging.

OBSERVATIONS - DAY 76 -OUTBOUND

As the satellite entered the plasmasphere, it apparently discharged (Figure 2). The satellite is effectively discharged as it rises from perigee, and is positively charged (about 3 to 5 V) after it exits the plasmasphere (at 1100 UT). Fifty minutes later, the satellite again charges negatively. Figure 11 shows the potential found by the same trio of instruments as before. The UCB experiment suggest that the satellite potential was 0 to -30 V from 1150 to 1300 UT.
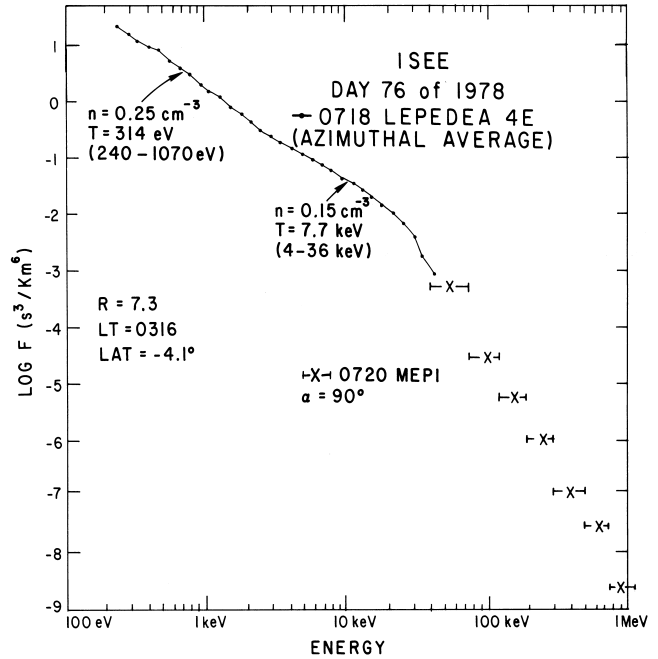

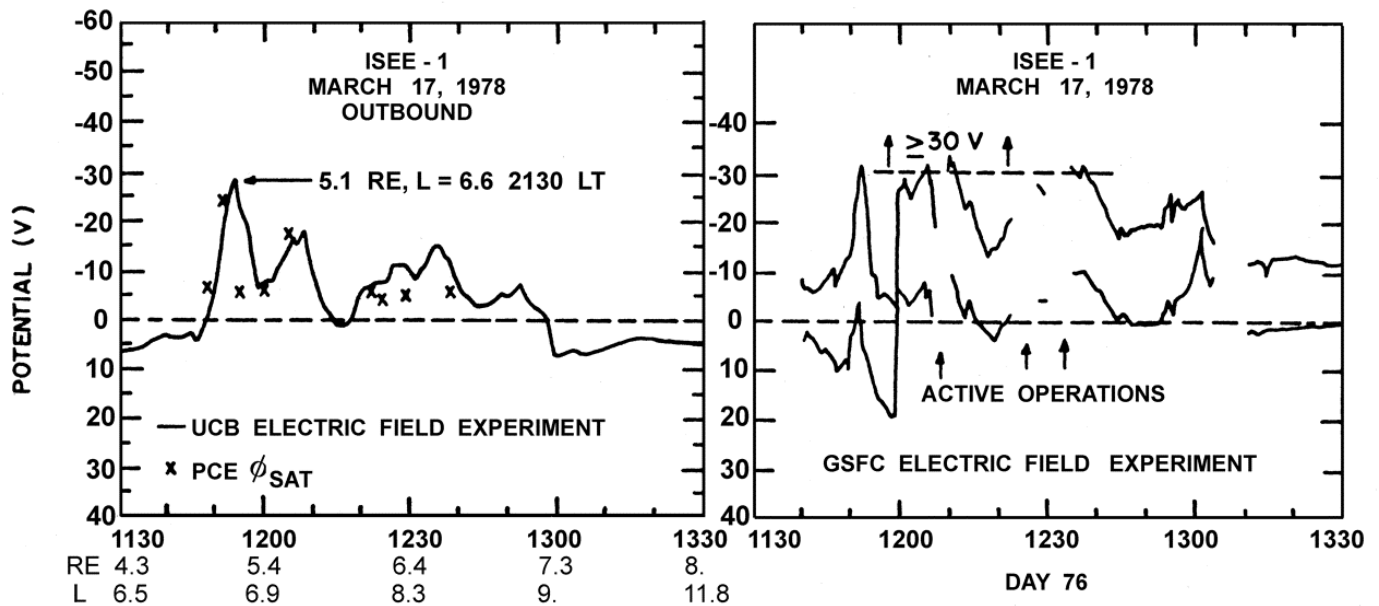Figure 10. Electron distribution functions from the LEPEDEA and MEPI.

Figure 11. Satellite potential measurements, March 17, 1978, outbound.

The Lockheed PCE supports the UCB data, while the GSFC experiment provides a more puzzling response. The maximum and minimum potentials for the GSFC experiment are plotted, reflecting the spin variation of the probe potential. It shows the same trend as the UCB experiment, with the exception of the discontinuity at 1158:45 UT. At this time, the GSFC probe potential jumps by about 30 V. This change occurs within 1 or 2 sample periods. This change is suggestive of a discharge of some sort. Aside from these changes in level, the GSFC data follow the UCB data. The gaps in the data are for periods when the active sounder is active [*Harvey et al.,* 1978].

These data represent a second charging event, and hence demonstrate the inbound charging event was not completely unique. Manual and computer searches of the UCB data set revealed one other charging event in the first three years of ISEE 1 data. The satellite charged to a few volts negative on April 19, 1978 (Day 109), from 1910 to 1920 UT, again near geosynchronous orbit, near local midnight. Both searches would have missed short intervals of low level charging, but it appears that these three times represent all the cases where there was negative charging of a few volts or more, lasting for more than a few minutes.

MODELING

The existence of negative charging on the supposedly "electrostatically clean" ISEE spacecraft is puzzling, given the nominal dependence of daylight satellite charging on differential charging. Also, the existence of a negative potential barrier when the spacecraft is either uncharged or at a negative potential requires a mechanism for its formation. There are two possibilities for a mechanism: one is that there is differential charging of the spacecraft surfaces. This can lead to a potential distribution which has a potential barrier more negative than the spacecraft body if there were some isolated surface such as a dielectric also at a more negative potential than the main body. The second possibility is that there is sufficient negative space charge in the vicinity of the spacecraft, produced by the emitted photoelectrons and by the ambient plasma, that a negative potential barrier is formed [*Guernsey and Fu*, 1970; *Fu,* 1971].

The situation here on ISEE 1 is somewhat similar to that on ATS-6 where photoelectrons and secondary electrons were observed to be reflected from a potential barrier about the spacecraft when the spacecraft was charged to a negative potential [*Whipple,* 1976a]. In the case of ATS-6, it was shown that the observed potential barriers were too large to be attributed to the effects of space charge [*Whipple*, 1976b]. It was inferred that the barriers must be caused by differential charging. This was later confirmed by detailed calculations [*Olsen et al.,* 1981].

It originally appeared unlikely that differential charging could be the mechanism responsible for the creation of the potential barrier around the ISEE spacecraft. The stringent cleanliness specifications that were imposed should have prevented potential differences of more than 1 V between portions of the spacecraft surfaces. A potential barrier of tens of volts is too large to be attributed to differential charging if the cleanliness specifications were effective in keeping differential potentials to less than 1 V.

Because the magnitude of the barriers observed on ISEE 1 were substantially smaller than those observed on ATS-6 (the latter occasionally reached a kilovolt), it was felt that space charge effects might be responsible for the barrier. Also, it seemed that adding a high energy tail to the emitted photoelectron spectrum (as observed) might allow the development of potentials due to space charge of 10-20 V. We modified the treatment of the spherical photoelectron sheath, described by *Whipple* (1976b), to include such a high energy photoelectron tail and calculated the maximum potential barrier that could be formed for the plasma conditions during this event on ISEE. We found that the combination of observed ambient plasma characteristics, and emitted photoelectron characteristics could not be reconciled with a barrier of more than a few volts, even with enhanced photoelectron temperatures. It seems likely that such effects exist at other times, and might effect the low energy electron measurements, but they are not sufficient to cause the observed barrier on day 76. Also, the observed angular distribution for the barrier is inconsistent with a photosheath barrier. Such a barrier would peak in the sunward direction, but it was found that spin phase did not order the data very well, and in fact the barrier height was better ordered by the polar angle, as shown in Figure 9. As shown next, these data actually support the idea that the solar arrays are charged negatively with respect to the satellite.

Modeling of differential charging effects was conducted using the NASA Charging Analyzer Program (NASCAP) is a three-dimensional numerical code, which solves Laplace's equation over a 16 x 16 x 33 grid [*Katz and Mandell,* 1982]. A satellite model is created in this , with potentials specified on the surface materials. The inner grid (which contains the model) can be imbedded in coarser, larger grids, in order to determine the potentials away from the object. This code was successfully used to model the differential charging effects inferred on ATS-6 [*Olsen et al*., 1981]. A simple octagonal model was used for the ISEE satellite.

The satellite was broken into three sections, the top and bottom representing the solar arrays (coated with indium oxide), and the center portion, the belly band, which contained the instruments (fiberglass with conducting paint). The three model sections could be separately biased with respect to one another and the ambient plasma. Figure 12 shows the results from a NASCAP run with -50 V on the belly band (satellite mainframe), and -140V on the solar array surfaces. The potential contours show the saddle point, or local minimum in potential between the belly band and the distant plasma. The effect of this potential distribution on electron detectors in the belly band is illustrated in Figures 13 and 14. The NASCAP model includes a detector feature which computes particle trajectories from the detector outwards, to determine if they escape, or are returned to the satellite. The detector angles in the model are the same as those for the GSFC experiment on ISEE.
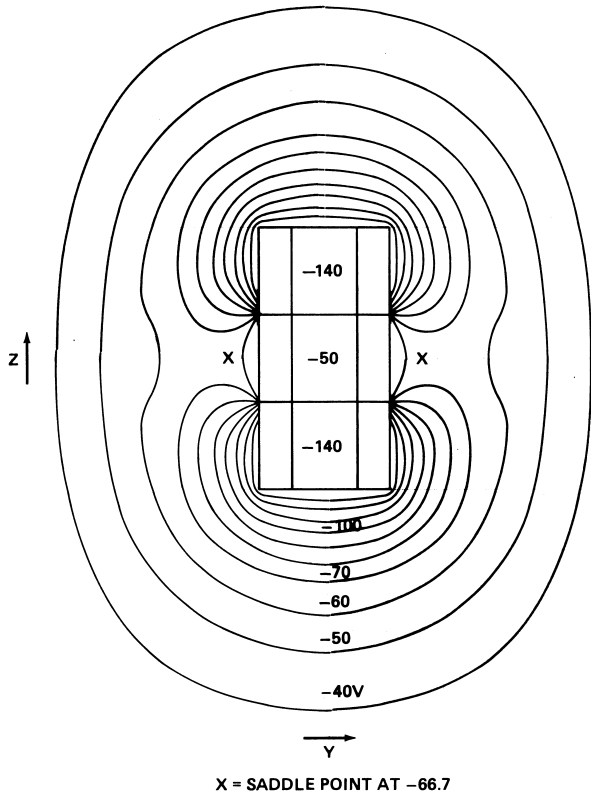
ISEE/NASCAP POTENTIAL CONTOURS

X = SADDLE POINT AT −66.7

Figure 12. NASCAP/ISEE potential contours.

ELECTRON TRAJECTORIES PROJECTED ONTO XY PLANE
DETECTOR 4

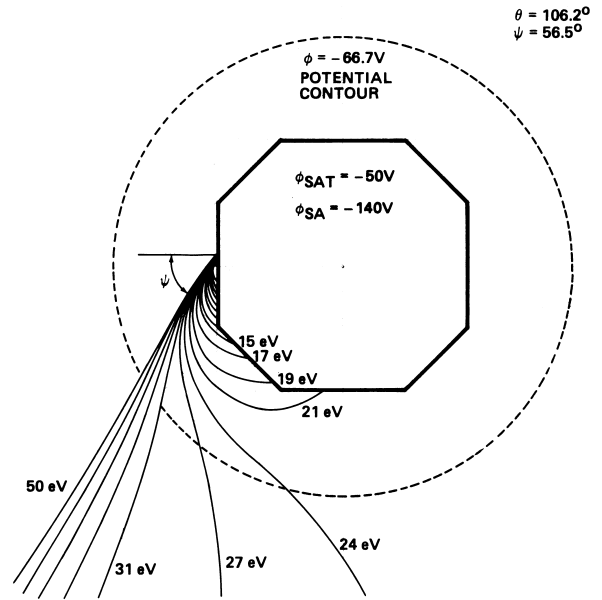
Figure 13. NASCAP/ISEE particle trajectories.

For detector 4, this means the model detector is looking at an angle of 33.5° from the local tangent, or 56.5° from the normal. This is the angle Ψ. The angle with respect to the satellite axis for detector 4 is 106°. This is as close to a radial look direction as the GSFC spectrometer provides. Detector 5 is also pointed 56.5° from the

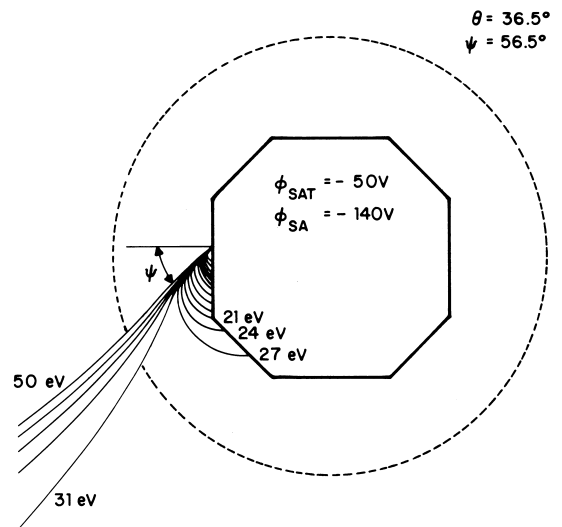## ELECTRON TRAJECTORIES PROJECTED ONTO XY PLANE
DETECTOR 5

Figure 14. NASCAP/ISEE particle trajectories, simulating detector 5.

normal, but is more nearly aligned along the spin axis, with θ = 36.5°. It can be seen that the effective barrier height increases as the detector look angles vary from the normal. For detector 4, 21 eV particles return to the surface, while for detector 5, trajectories up to 27 eV lead from the detector to the spacecraft. Thus, we infer that potentials on the solar arrays of ~100 V more negative than the spacecraft ground would influence electron trajectories in a manner consistent with GSFC electron data.

CONCLUSIONS

We have shown that on March 17, 1978, the ISEE 1 spacecraft charged to a negative potential on the order of -70 V in sunlight. Evidence for the charging was presented from the plasma composition experiment and from the two electric field experiments on the spacecraft. In addition, we showed that the ATS-5 spacecraft charged to a potential of about -6 kV in eclipse about three hours earlier on the same day but in what appeared to be a similar plasma environment.

We have shown from the electron spectrometer experiment on ISEE 1 that there appeared to be a potential barrier about the spacecraft during this event. The potential barrier was on the order of 10 -20 V negative with respect to the spacecraft body and was effective in returning emitted photoelectrons to the spacecraft.

It is likely that the potential barrier was produced by differential charging of the spacecraft surfaces. Space charge effects could not reproduce the observed barrier effects. From the modelling calculations we infer that the solar array panels were charged to a potential approximately 100 V more negative than the spacecraft ground during this event. Hence, it appears that the electrostatic cleanliness measures adopted for this satellite were not 100% effective. This interpretation of the ISEE charging process is consistent with our identification of the electric field data as a measure of spacecraft potential.

Our last conclusion is supported by several practical considerations. First, the indium oxide (IO) coating is extremely susceptible to abrasion, and such abrasion is very difficult to test. Once on orbit, it is likely that the surface will age, due to uv radiation, plasma impact, and atmospheric effects at perigee. First, the question of what represents a sufficient conductivity arises. The specification for the solar arrays was about 4 kilohm per square [*Gaddy and Bass*, 1978]. Laboratory test of thin IO coatings show that on a production basis, such goals are generally met, but can be as much as a factor of ten higher [*Schmidt,* 1981; *Levy et al.,* 1981). Conductivities of such levels should be sufficient to prevent arcing, and satellite damage, but not all charging. Exposure of indium tin oxide (ITO) coated solar cells to energetic electron beams in the labortory resulted in potentials of a few hundred volts, e.g., -400 V potential for 20 keV beam [*Schmidt*, 1981]. This value is consistent with our observations although it is difficult to draw a direct comparison between space and laboratory results. Laboratory tests of ITO coated second surface mirrors (SSM) showed susceptibility to contamination. Exposure of contaminated surfaces to hot electron environments resulted in degradation in conductivity. This effect was attributed to numerous micro cracks in the coating [*Levy et al.*, 1981]. *Reagan et al* [1983] have inferred radiation damage effects for satellite materials on orbit with the SCATHA data set. These data also suggest the possibility of deterioration of the ITO coating.

Conductive coatings were therefore successful in preventing frequent negative charging events, but not all negative charging. Applications requiring complete control of negative charging, or the elimination of positive charge, await the consistent use of more active charge control devices, such as a plasma emitter.

APPENIDX

One feature of the day 76 charging event which was unusual was the mass composition of the ions. Figure 15 shows mass scans at 0633 UT ($\Phi_{sat} \sim 0$ V) and 0721 UT ($\Phi_{sat} \sim -60$ V). These data are taken at zero volts retarding potential, and the scatter at each mass step is the result of variations with spin. The H+ data (step 54) show a substantial spin variation, because the ambient H+ is primarily field-aligned at this time. The peculiar feature in these data is the instrument response at low mass steps, or high atomic mass units. A broad peak is evident at both times, suggesting masses from 30 to 100 amu. The normal instrument response for O+ (or O+ and N+) is sketched on the right side of the peaks, and it is apparent that the high mass features are not the normal O+ population of the magnetosphere. These instrument responses may either be due to sputtered ions (such as silicon, mass 28), or hydrocarbons, and other refuse outgassing from the satellite, ionized at some distance from the satellite. Such heavy ions are not observed at any other time, to our knowledge.

Observations on the ATS-6 and SCATHA satellites, however, have occasionally indicated the existence of ions at energies below the satellite potential. It seems likely that these were also satellite generated ions, and hence this effect can be found on more than one satellite. As a practical matter, this means that on negatively charged satellites, that the ion charging peak may be contaminated by satellite generated ions, resulting in slight under estimates in the magnitude of the satellite potential.
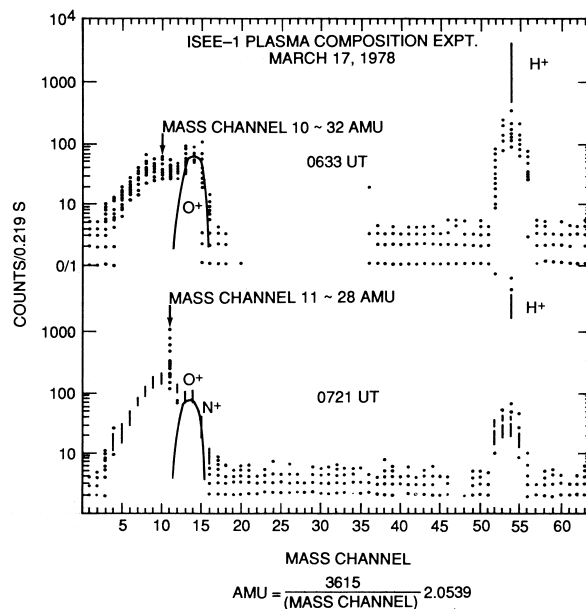

Figure 15. ISEE 1 PCE mass scan, showing anomalous heavy ion readings.

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