ROLE OF ENERGETIC PARTICLES IN CHARGING/DISCHARGING OF SPACECRAFT DIELECTRICS*

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SUMMARY

The role that energetic particles in the substorm plasma have on the charging and discharging of typical dielectric layers used on spacecraft has been investigated using spectra and pitch angle distributions measured in situ on the SCATHA spacecraft prior to and during a few kilovolt differential charging event in eclipse conditions on 28 March 1979. The particle spectra have been input to deposition codes that determine the dose rate as a function of depth in kapton and teflon layers used in the SSPM experiment on SCATHA. The calculated ambient dose rates of a few rads/sec throughout the bulk of the sample are sufficiently high that radiation damage levels can be reached on the time scale of 1 year. Surface dose is a factor of 100 higher. Bulk conductivity profiles have been obtained from the dose rates using empirical relationships available in the literature. The radiation-induced bulk conductivities calculated at the peak charging time are found to be smaller than the intrinsic dark conductivity range of solar-conditioned kapton but higher than the corresponding value for teflon. The radiation-induced surface conductivities in both materials are significantly higher than their intrinsic values. It is concluded that in this event the surface potentials of both materials were determined primarily by the current density carried by the electrons in the energy range < 30 keV and that radiation-induced bulk conductivity changes were not important for kapton but may be for teflon. It is further concluded that surface charging occurred when the spectrum hardened and a corresponding larger fraction of the charging current density was carried by higher energy electrons. The measured charging spectrum in this event is within a factor of 5 of the maximum allowable trapping limit according to experimental verifications of the Kennel-Petschek theory. It is proposed that the charging current density at this limit, in conjunction with material properties, will directly determine the maximum possible surface potential in eclipse conditions. Based on the measured potential across the SSPM kapton sample in this event, the maximum likely surface potential to be encountered in a substorm having similar spectral characteristics has been estimated.

INTRODUCTION

The purpose of this paper is to assess the role that the energetic portion of the substorm plasma has on the charging/discharging of spacecraft dielectric materials such as kapton and teflon. It is a well established fact that the most severe charging of spacecraft operating at high altitudes occurs in the magnetic midnight-to-dawn time sector where substorms are highly prevalent and

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where spacecraft at times can be eclipsed from solar illumination. At these times the electron plasma is characterized by a harder and more intense than normal spectrum, i.e., the number density of energetic electrons ($\gtrsim$ 1 keV) is increased over ambient conditions. The role that these energetic electrons play in dielectric surface charging through enhancement of bulk conductivities or to the generation of internal electrical discharges through charge buildup and subsequent dielectric breakdown are important issues that have not been adequately addressed for the actual substorm environment. A large body of data exists in the literature on this subject (see Ref. 1) but at electron irradiation levels that are typically several orders of magnitude higher than the substorm environment. Hence the results obtained in those cases are not directly applicable to the substorm case.

Recently Wall et al. (Ref. 2) performed an excellent parameterization of dielectric properties and electron interaction phenomena related to spacecraft charging. Frederickson (Ref. 3) and Summerfield (Ref. 4) have also reported recent work in this area. The measured plasma characteristics and the parametization of Wall et al. have been used in this paper to evaluate the radiation-induced conductivity in an actual eclipse charging event experienced on 28 March 1979 by the Satellite-Surface-Potential-Monitor (SSPM) on the SCATHA (P78-2) spacecraft as reported by Mizera (Ref. 5). The electron and proton spectra before and during this charging event were measured on SCATHA with a variety of plasma instruments. These spectra have been input to computer deposition codes that determine the ionization rate and hence dose rate profiles in 127 micron (5 mil) thick samples of kapton and teflon that are used in the SSPM. The radiation-enhanced conductivity levels were then determined using available empirical relationships between dose rate and conductivity. These values have been compared to typical intrinsic dark conductivities for kapton and teflon as measured in the laboratory and, in the case of kapton, in orbit with the SSPM experiment.

From the measured electron spectra, the current densities have also been determined as a function of particle energy and evaluated in light of the measured charging potentials on the SSPM samples. It will be shown that the measured electron flux at the peak of this event was within a factor of 5 of the maximum trapping limit set by experimental verification (Ref. 6 and 7) of the Kennel-Petschek theory (Ref. 8). It is proposed that this self-limiting process will determine the maximum charging current density and hence, in conjunction with the material properties, the magnitude of the charging potential that a dielectric can experience in the space environment. The maximum potential to which the SSPM kapton sample would ever likely charge in eclipse conditions during a substorm having an electron population with similar spectral parameters but at an intensity determined by the measured Kennel-Petschek stable-trapping limit (Ref. 6) has been estimated. Knowledge of these limits and measurements of the spectral hardness parameter in the substorm environment can therefore be used to guide laboratory testing and computer modeling of the spacecraft charging phenomena.

EXPERIMENTAL DATA

The SCATHA (P78-2) spacecraft, which is in a near-equatorial 24-hour orbit having an apogee of 43,192 km and a perigee of 27,517 km, contains a variety of plasma diagnostic and engineering experiments to study the spacecraft charging phenomena. A complete description of the P78-2 mission is provided in Reference 9. At 1637 UT on 28 March 1979, after the SCATHA spacecraft had been in eclipse for some 19 minutes, the kapton, quartz fabric and teflon samples in the SSPM experiment experienced charging to -2100, -1000 and -2000 volts, respectively, below spacecraft ground (Ref. 5). The charging characteristics of the kapton sample located on the bellyband of the spinning spacecraft (~1 RPM period) are shown in the top panel of Figure 1. The behavior of the energetic electron environment before and during this charging event is shown in the lower panels of Figure 1. The electron data were obtained with the Lockheed SC-3 experiment which measures electrons in several energy channels between 47 and 4970 keV. The SC-3 experiment is described in detail in References 9 and 10. The higher energy electrons measured in this experiment provide excellent tracers of the geomagnetic field behavior before and during substorms.

The time interval marked "A" centered at 1510 UT in Figure 1 represents the ambient flux levels prior to the sequence of the occurrence of the substorm, eclipse and the charging of the samples. It should be noted that the spacecraft at this time was in the pre-magnetic-midnight time period (22 MLT) at a magnetic L-shell of 6.7 and below the magnetic equator by 18 degrees. At 1520 UT the energetic electrons at all energies began to decrease precipitously by almost three orders of magnitude prior to the substorm. The period marked "B" in Figure 1 centered at 1615 UT represents a depressed flux situation in which the corresponding plasma current density is inadequate to charge the spacecraft despite its entry into eclipse at 1618 UT as indicated. That is, the current density incident on the spacecraft at this time was sufficiently low that it could be adequately compensated by the current density being emitted from the spacecraft through backscattering and secondary emission and significant charging was not required to maintain overall current balance.

At 1600 UT the Boulder index lists the occurrence of a substorm according to ground-based magnetometer records but the flux increase indicating the onset of the substorm effect at the SCATHA satellite did not occur until 1630 UT. Note that at this time the spacecraft is on the magnetic shell L = 7.2 at 2340 MLT and had been in eclipse for 12 minutes. The occurrence of eclipse and the timing of the substorm is coincidental. As the energetic electron flux increased rapidly at all energies up to a few MeV, the kapton sample on the spacecraft bellyband began to charge above ambient at 1637 UT and reached a maximum value of -2100 volts with respect to the spacecraft body by 1641 UT, a charging period of 4 minutes. The period marked "C" in Figure 1 represents the plasma conditions at this peak time of the charging event. The plasma intensity stayed high during the remainder of the eclipse period. As the spacecraft returned to sunlit conditions at 1716 UT the surface voltage on the SSPM discharged to the ambient state. Note the temporary reduction of the energetic electrons at the umbral exit and the subsequent return to the maximum levels. Whether this is a temporal coincidence or the result of the redistribution of the entire plasma environment around the spacecraft at the time of solar illumination is not known.

PARTICLE SPECTRA

The electron and proton spectra during the three periods identified in Figure 1 were measured over a broad energy range with a variety of instruments on SCATHA. For this study the lower and higher energy portions of the electron spectrum were obtained from the SC-2 experiment (courtesy of Dr. J. F. Fennell, The Aerospace Corporation) and from the Lockheed SC-3 experiment, respectively. Both experiments are located on the body of the spinning spacecraft. The pitch angle distributions measured with the SC-3 instrument at these times indicate a near-isotropic situation with the exception of a narrow but relatively empty loss cone. For treatment of the dielectric samples on the spinning portion of the spacecraft, spin-averaged flux intensities are the most relevant and have been used in this study. Figure 2 shows the resultant electron spectra obtained between 20 eV and 3000 keV, a dynamic range of 5 decades in energy and 11 decades in intensity. The ambient condition "A" exhibits a high intensity of low energy electrons. During the substorm precursor period "B" the lower energy fluxes decrease but the striking feature is the precipitous decrease of some 3 orders of magnitude in the flux at energies > 1 keV. At the time of sample charging, "C", the lower energy portion of the spectrum is decreased over an order of magnitude as a result of the negative barrier potential on the spacecraft body and dielectrics during this time. The energetic portion of the spectrum (> 5 keV) becomes more intense than that under ambient conditions. Thus, the electron plasma can be characterized as hotter than normal.

The proton spectra at the three corresponding times are also shown in Figure 2. The lower and higher energy portions were obtained from the Lockheed SC-8 experiment (courtesy of Dr. S. K. Kaye) and the SC-2 experiment (courtesy of Dr. J. Fennell, The Aerospace Corporation), respectively. The protons also exhibit a marked decrease during the substorm precursor period "B". It should be noted that overall proton flux is one to two orders of magnitude less than the electron flux at energies < 10 keV.

DOSE RATES

The electron and proton spectra shown in Figure 2 were input to two deposition programs available at Lockheed. The ion-pair production rate due to electron deposition in a simulated SSPM sample consisting of a 127 micron (5 mil) layer of kapton $(C_{22}\ H_{10}\ N_2\ O_4)_n$ followed by a 76 micron (3 mil) layer of silver epoxy and a 51 micron (2 mil) layer of copper, was obtained with a computer code called AURORA which solves the Fokker-Planck steady-state diffusion equation (Ref. 11). With this code the scattering and diffusion of electrons through the various layers are properly tracked and the energy loss rate (dose rate) and current density crossing each layer in the material are calculated. A similar calculation was performed for a teflon layer $(C\ F_2)_n$ of the same thickness. The ion-production rates in kapton corresponding to the three electron spectra are shown in Figure 3 based on the assumption that 30 eV of energy loss is required to create each ion-pair. The ionization rates are very high in the first 5 to 10 microns of the material near the surface. The bulk ionization throughout the remainder of the sample is relatively uniform and about 2 orders of magnitude lower than near the surface. The peak substorm flux, case "C", results in the highest ionization rates throughout the material.

The proton spectra were input to a code called PROTON (Ref. 12) which determined the ionization losses due to coulomb collisions in the kapton. The results of this code for the three cases are also shown in Figure 3. Except for the first few microns near the surface and in the pre-substorm case "B", the electron induced ionization dominates over the proton induced ionization by approximately two orders of magnitude and hence is potentially more important in altering the bulk conductivity properties of the material.

The dose rates corresponding to the calculated ionization rates are also shown in Figure 3. Near the surface the dose rates are in excess of 100 rads/sec. If period "A" is representative of ambient conditions over a year in the orbit, then this rate corresponds to an accumulated annual surface dose of over 3000 megarads. Such radiation levels are extremely damaging to dielectric materials such as teflon and hence the surface properties of these samples should be degraded after a year or so in orbit. The bulk material dose rate of a few rads/sec results in an annual dose of 63 megarads, a level that is also of some concern to the bulk properties of such materials as teflon.

BULK CONDUCTIVITIES

The dose rates shown in Figure 3 have been used with the formalism reported in References 2 and 13 to obtain the radiation-induced conductivities. Basically, the radiation-induced conductivity, σ_R, can be quantitatively related to the dose rate, $\dot{D}$, by two material dependent parameters, as follows:

$$\sigma_R = k \dot{D}^N \tag{1}$$

where k is called the coefficient of radiation-induced conductivity and N is a value that lies between 0.5 and 1.0. For this study N has been chosen to be 1.0 and hence represents the maximum possible conductivity value. The values of k for both teflon and kapton vary widely and hence we have used the range of values cited in Reference 2 in our calculations.

Figure 4 shows the radiation-induced conductivity profiles derived in this manner for the "B" and "C" time periods as a function of the kapton and teflon thickness. The electron and proton dose rates have been summed in obtaining Figure 4. The ambient "A" period was not plotted because it significantly overlapped the "C" data. The intrinsic dark conductivity ranges for both kapton and teflon are also shown against which the radiation-induced conductivity can be compared. An intrinsic bulk dark conductivity in a dielectric is a difficult parameter to define. Virgin kapton when exposed to solar illumination exhibits as much as a four order of magnitude increase in its bulk conductivity and even retains up to a three order of magnitude higher conductivity after being returned to the dark for several hours (Ref. 14). The actual bulk conductivity of 4.5×10^{-16} Siemen (S)-cm^{-1} measured on SCATHA with the SSPM kapton sample at the time of peak charging in this event (Ref. 5 and personal communication, P. F. Mizera, 1980) is shown as Item 1 in Figure 4. Also shown are the intrinsic bulk dark conductivities for kapton taken from References 15 (Item 2) and 14 (Item 3). For teflon, which has a much lower bulk dark conductivity than kapton, the intrinsic values were obtained from References 1 (Item 4) and 14 (Items 5 and 6). Adamo and Nanevicz (Ref. 14) report a value of 2.2 x 10^{-18} S-cm^{-1} for a 127 micron (5 mil) sample of FEP teflon at a surface potential of -1700 volts. Van Lint et al. (Ref. 1) gives a value of 3 x 10^{-18} S-cm^{-1} for a teflon sample exposed to a dose rate of 1 rad/sec at 25°C temperature.

The depressed fluxes during the "B" period clearly do not influence the intrinsic bulk dark conductivities of either kapton or teflon except within the first few microns of the surface. Even during the charging period "C", the radiation-induced conductivity in kapton is approximately one- to two-orders of magnitude smaller than the intrinsic bulk dark conductivity, except near the surface. The very high enhanced conductivity within the first few microns of the surface may, however, be important to surface leakage and surface discharge effects in dielectrics. Hence it can be reasonably concluded that in either the ambient or substorm environment the radiation-induced conductivity through the bulk of the kapton sample is significantly less than the intrinsic bulk dark conductivity. The case of teflon is less clear. At the time of peak charging the radiation-induced conductivity is comparable with the intrinsic dark conductivity but the uncertainties in both conductivity values are large. It is fair to conclude that radiation-induced conductivity in teflon is more important than in kapton and may have an effect on the surface charging potential depending upon the detailed history of the sample.

CHARGING CURRENTS

Since enhancement of the bulk conductivities of kapton and teflon does not appear to be the dominant factor in determining the magnitude of the surface charging potential in this event, another key parameter, the charging current density, has been examined. From Figure 2 it is evident that the dominant charging current is carried by the electrons. In Figure 5 the integral electron current density greater than energy E is shown as a function of E for the three periods during this event.

During the ambient period "A" the charging current density of ~50-60 picoamps/cm^2 is carried principally by electrons with energy $<$ 1 keV. At these energies the secondary emission coefficient of teflon is $>$ 1 (Ref. 2) and the surface can adequately balance the incident current without charging to any significant voltage, even in eclipse. During the depressed period "B" the current density is again carried by low energy electrons and because the magnitude is low, the dielectric surface can easily balance the incident current through secondary emission.

During the main portion of the substorm, the current density begins to be carried by higher energy electrons in the several kilovolt range. The relatively flat curve of current density vs. electron energy up to a few kilovolts is probably due to the fact that the entire spacecraft body at this time in eclipse is charged negatively to several kilovolts. The spacecraft therefore acts as a retarding potential barrier to incident electrons up to several kilovolts. At this time the kapton and teflon samples charged to -2000 volts with respect to this negatively charged spacecraft. At 2 keV energy the current density is ~40 picoamps/cm^2 and higher than the corresponding density in the ambient case "A" at this energy. At 2 keV the secondary emission coefficient of teflon is unity, that is, an electron is emitted from the surface for every incident electron (Ref. 2). Thus, the incident current is effectively self-balanced by secondary emission from the surface up to an energy of 2 keV in the incident spectrum.

As the incident electron energy increases above 2 keV the secondary emission coefficient drops below unity and charging will have to occur. With the onset of surface charging, a current will be conducted through the sample to the spacecraft. The magnitude of this steady-state conduction current, i, will be equal to $\sigma V/d$ where σ is the bulk conductivity, V is the charging potential and d is the sample thickness. The bulk conductivity is a fairly strong function of the electric field above a few kilovolts (Ref. 2) as well as a function of other environmental factors such as temperature, solar illumination and particle radiation.

The steady-state surface charging potential with respect to the spacecraft will be determined by the position along the "C" curve in Figure 5 where the current density incident on the surface is just equal to the sum of the secondary emission and backscattered current leaving the surface and the conduction current through the sample. For teflon, the conduction current should be approximately equal to the integral current density given in Figure 5 greater than an energy of V + 2 keV. Below this potential the current density is balanced by secondary emission. The magnitude of V can be determined approximately from

$$V = \frac{d}{\sigma} i_{v+2\ \mathrm{keV}} \tag{2}$$

Thus, the magnitude of the surface potential is directly related to the shape of the incident electron spectrum. As the spectrum becomes harder in the crucial 2 to 30 keV region, the surface potential must become more negative to retard the incident current density to the point where it just equals the bulk conduction current plus the secondary emission. There is a compensating feature in that as V increases linearly, the bulk conductivity increases faster than linear at potentials above 2000 volts (Ref. 2). The surface potential will therefore not need to rise linearly with increasing current density in order to satisfy Equation 2.

Of interest is the maximum potential to which a dielectric surface can charge in eclipse conditions. Dielectric breakdown of the material may well be the practical limit but the magnitude of the available charging current is the fundamental limit. It is proposed that there is a natural self-limit to this charging current in the magnetospheric substorm. According to the Kennel-Petschek theory (Ref. 8) the trapped electron flux on a magnetic field line can increase to a limit at which instabilities set in. Whistler waves which grow as a result of the instability interact with the trapped electrons resulting in the alteration of their pitch angle motion such that precipitation into the atmospheric loss cone occurs. Baker et al. (Ref. 6) established this limit for the geosynchronous orbit (L = 6.6) at a flux of 5×10^7 electrons/cm^2-sec-sr^{-1} for energies > 30 keV. In case "C" on 28 March 1979 the integral flux > 30 keV is $\sim 1 \times 10^7$ electrons/cm^2-sec-sr^{-1}. Hence, the substorm conditions on this day were probably within a factor of 5 of the maximum possible current density. If we assume a substorm condition having this maximum intensity and the same spectral characteristics as period "C", the limiting curve shown in Figure 5 is obtained. This curve will not be highly valid at energies below ~2 keV but should be more valid above that energy. Thus, for modeling and laboratory testing purposes charging current densities of 20 to 100 picoamps/cm^2 at energies near 10 keV would represent the range to be expected in the substorm environment.

The SSPM kapton sample charged to a differential potential of -2100 volts in the 28 March 1979 substorm. In the most intense substorm set by the trapping limit and under similar eclipse conditions, the sample would charge to -10,500 volts according to Equation (2), i.e. five times the value in case "C" on the assumption that the conductivity did not change with the impressed electric field. In fact, however, the conductivity of kapton at room temperature would increase by a factor of 30 between a potential of -2100 and -10,500 volts (Ref. 2). The actual surface potential would therefore be significantly less than -10,500 volts because of the increased conductivity and the fact that the integral electron current density to be conducted at -10,500 volts is less than at -2100 volts by approximately a factor of 2. In the case of teflon, the radiation-induced conductivity may be quite important. As the storm intensity increases, the teflon bulk conductivity would also increase in a linear and compensating manner such that the final surface voltage in the limit would be significantly less than -10,500 volts. Therefore, energetic particles can play an important role in determining the surface charging potential of dielectric materials in the geomagnetic substorm environment.

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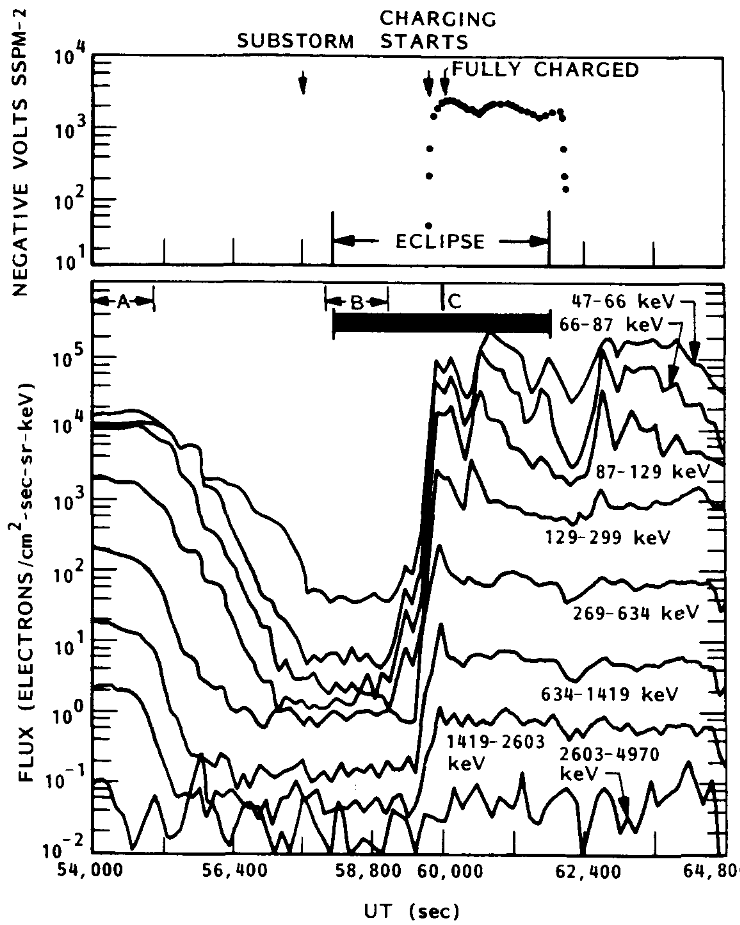

UT	15.00	15.67	16.33	16.67	17.33	18.00
LT	21.90	22.74	23.52	23.89	0.59	1.25
MLT	21.79	22.65	23.46	23.85	0.58	1.26
GLON	104.80	107.35	109.07	109.62	110.16	110.00
GLAT	-7.07	-7.61	-7.78	-7.75	-7.50	-7.03
MLAT	-18.30	-18.87	-19.05	-19.02	-18.76	-18.30
B/BO	2.09	2.21	2.23	2.23	2.27	2.34
L	6.63	6.90	7.14	7.26	7.51	7.76

Figure 1. Top Panel. Charging voltage characteristics of the SSPM-2 kapton sample on the SCATHA satellite during eclipse on 28 March 1979.
Bottom Panel. Characteristics of the energetic electron environment prior to, during and after the eclipse and charging event as measured with the Lockheed SC-3 experiment on SCATHA.

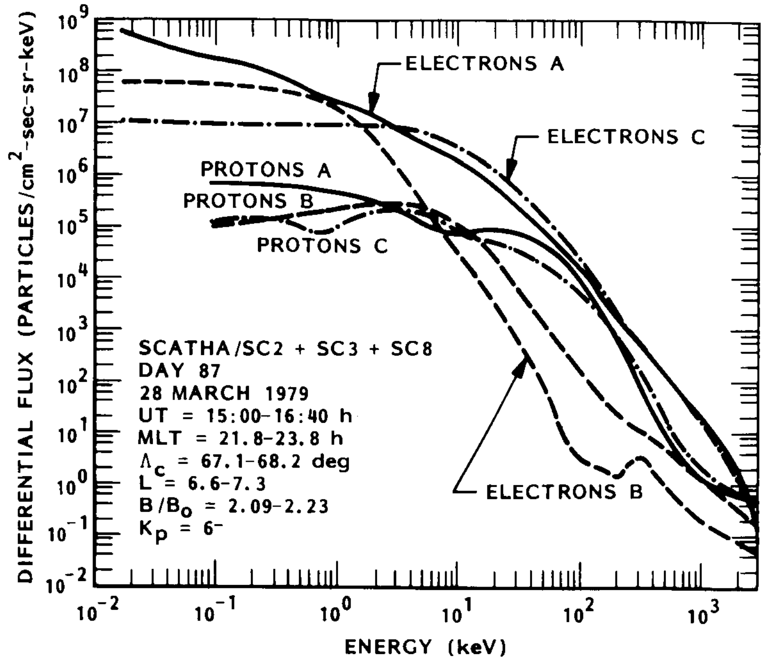

Figure 2. The electron and proton spectra measured on the SCATHA satellite during the three intervals indicated in Figure 1.

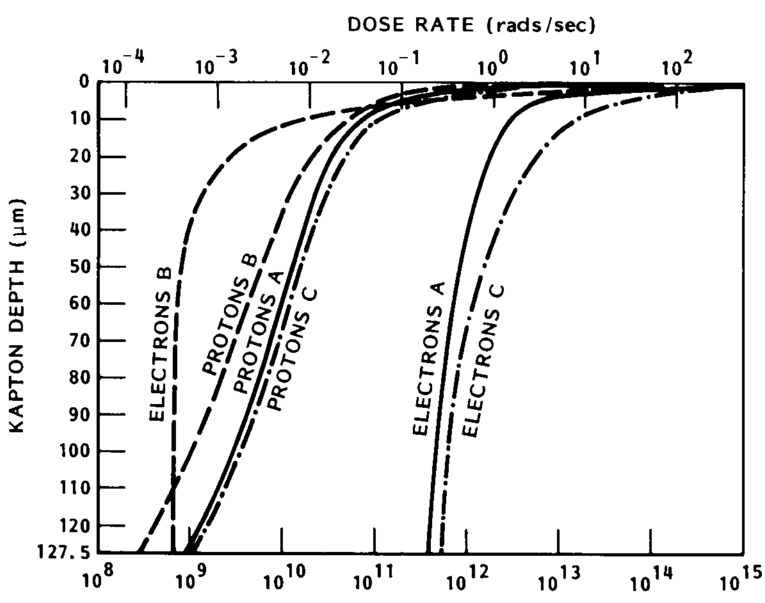

Figure 3. The ion production rate (bottom scale) and the dose rates (top scale) as a function of depth in the SSPM kapton sample resulting from the electron and proton spectra shown in Figure 2.

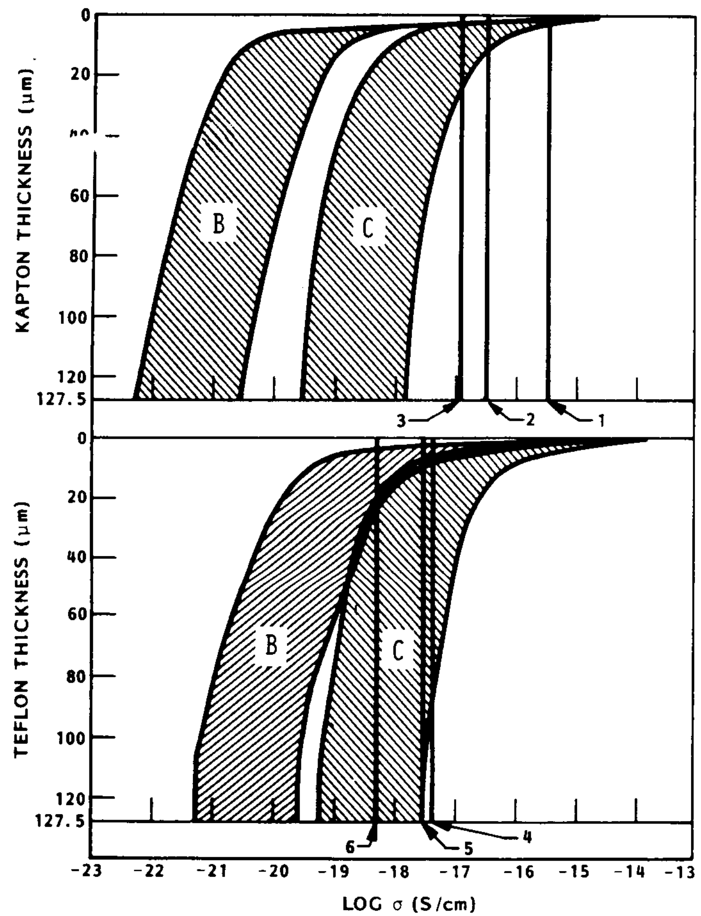

Figure 4. Radiation-induced conductivity as a function of kapton and teflon thickness corresponding to the combined electron and proton ionization created at the two time periods shown. Also shown as vertical lines are several different values of the intrinsic dark bulk conductivity of kapton and teflon cited in the text.

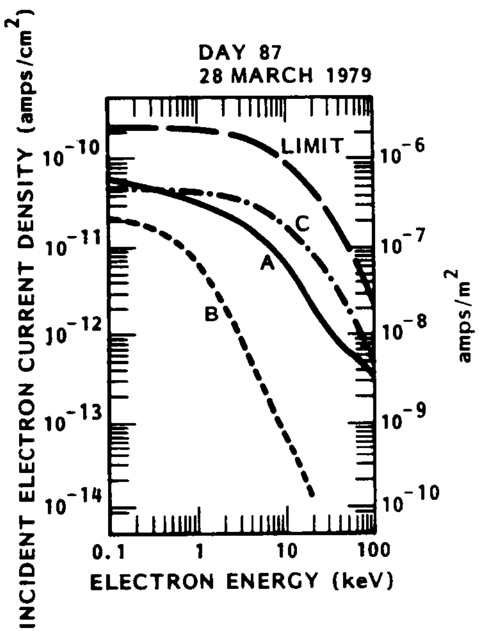

Figure 5. Integral electron current density greater than energy E as a function of E for the three spectra cited in the text. Also shown is the expected maximum limit to the substorm charging current density based on experimental verification of the Kennel-Petschek theory.