Space Environment Interactions

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Spacecraft Interactions

- ***SPACECRAFT CHARGING***
- ***PLASMA INTERACTIONS***
- ***RADIATION INTERACTIONS***
  - ***Particles***
  - ***UV/EUV***

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Spacecraft Surface Charging

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Things That Can Go Bump in the Night …

DSCS SPACECRAFT ARCING:

EMC: "SOLAR ARRAY CABLE SHOULD BE GROUNDED TO S/C"

DESIGNER: "BOLT COAXIAL CABLE SHIELD TO S/C GROUND"

MECH ENG: "DRILL HOLE INTO S/C CHASSIS, BOLT DOWN WIRE--USE LOCTITE SO IT DOESN'T COME LOOSE"

MORAL: DON'T ASSUME EVERYONE UNDERSTANDS YOUR REQUIREMENTS--ALWAYS, ALWAYS VERIFY!!

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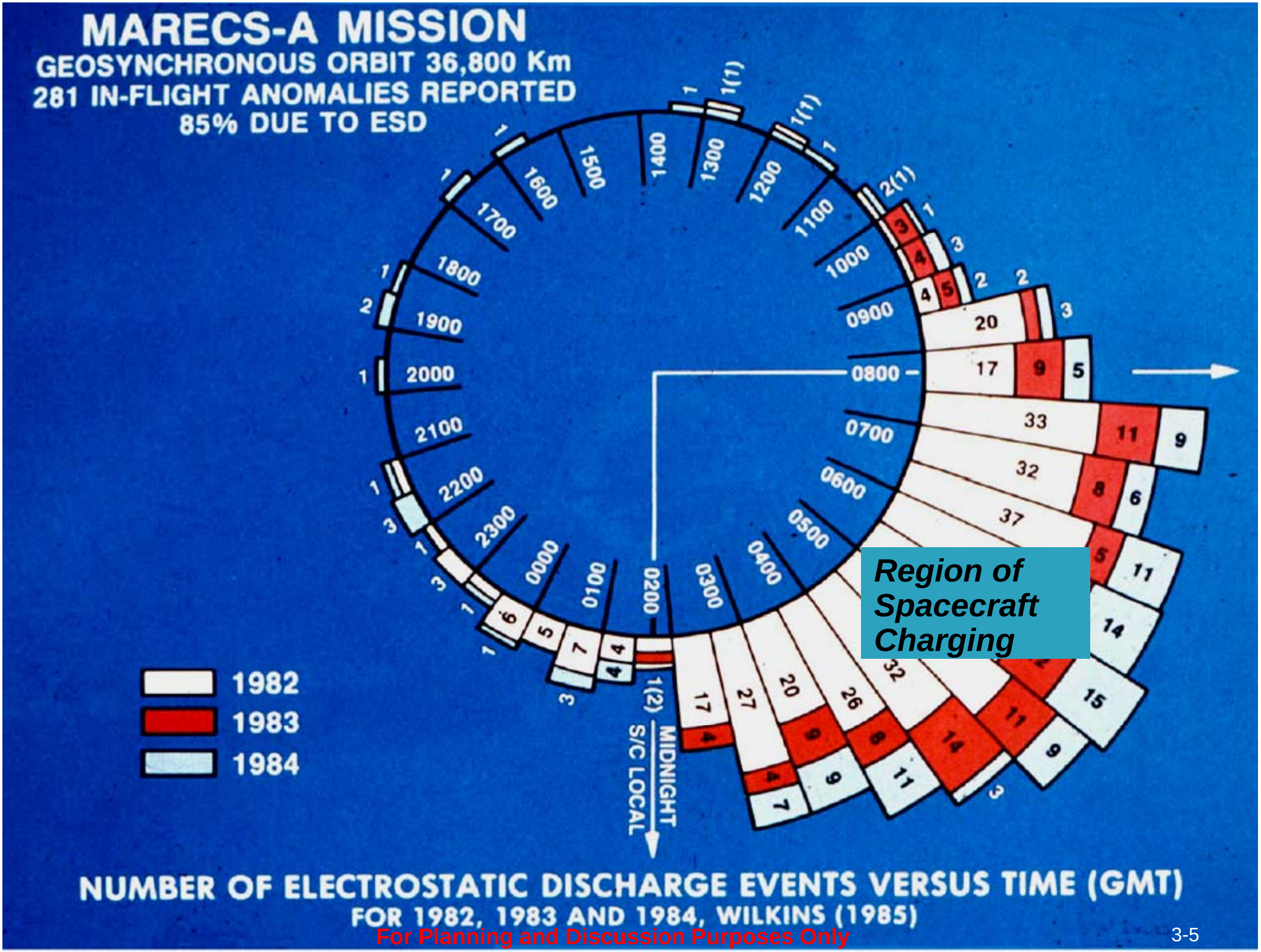

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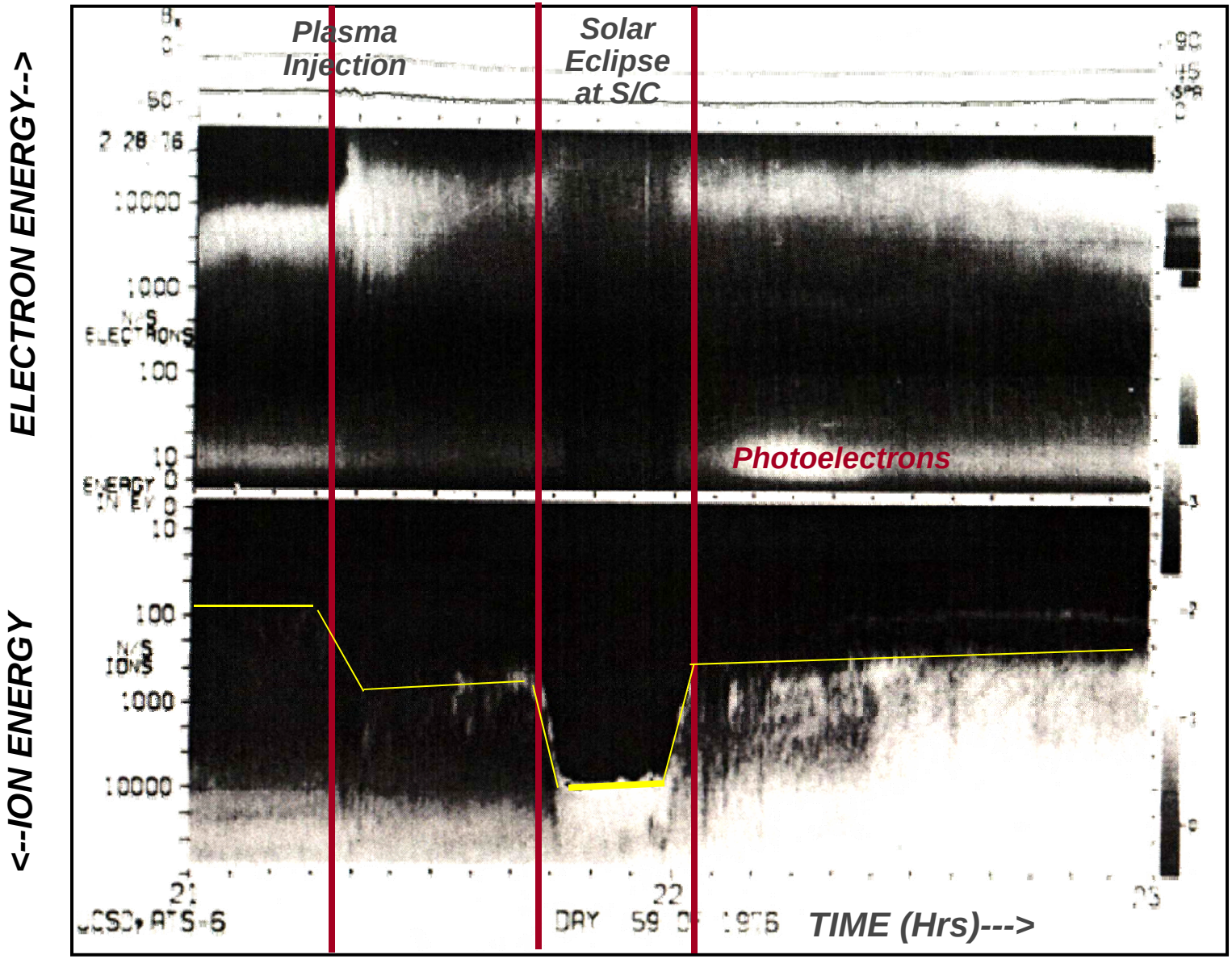
ATS-6 Spectrogram of Geosynchronous Charging



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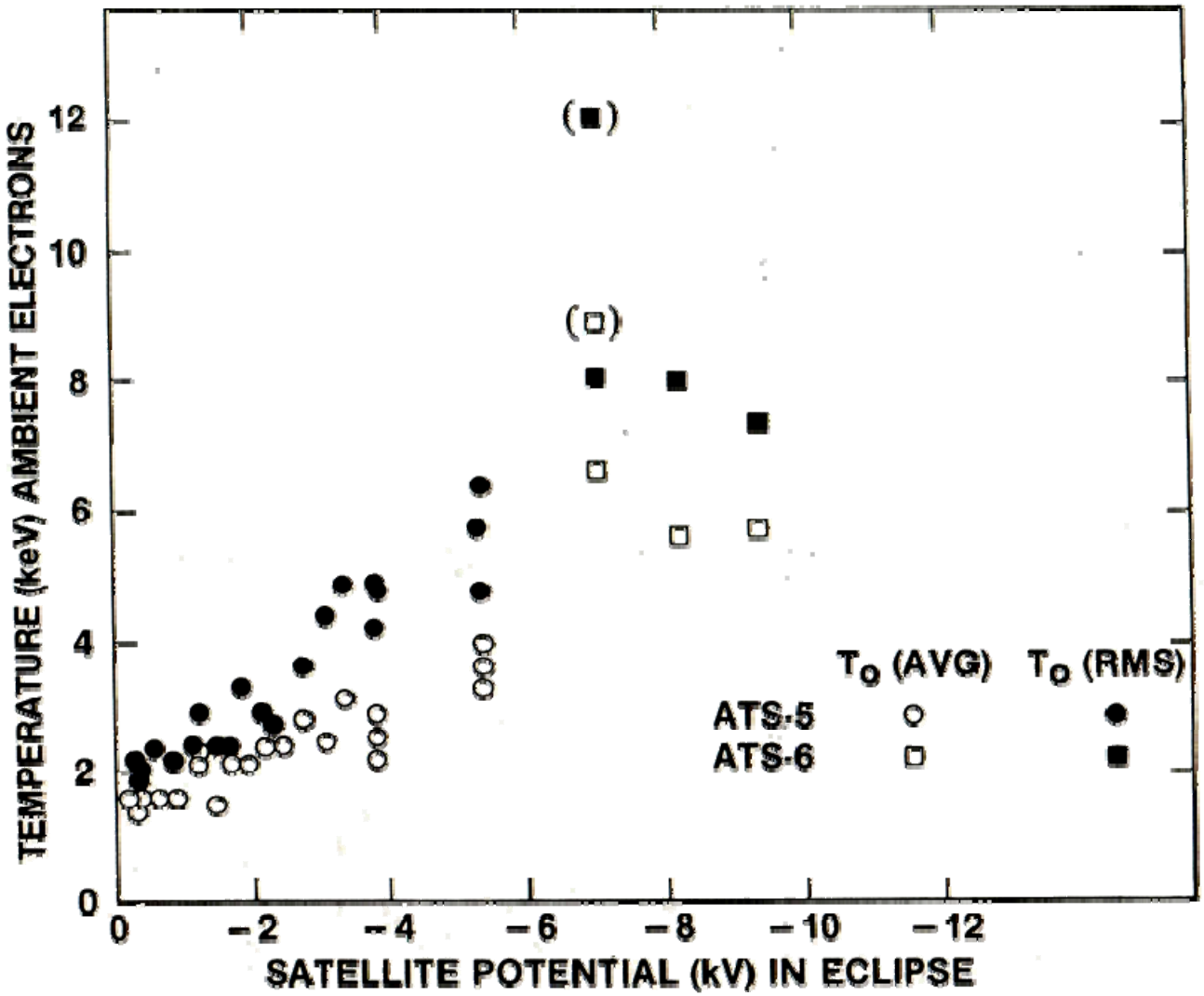
Spacecraft Charging Observations: Plasma Temperature vs Potential



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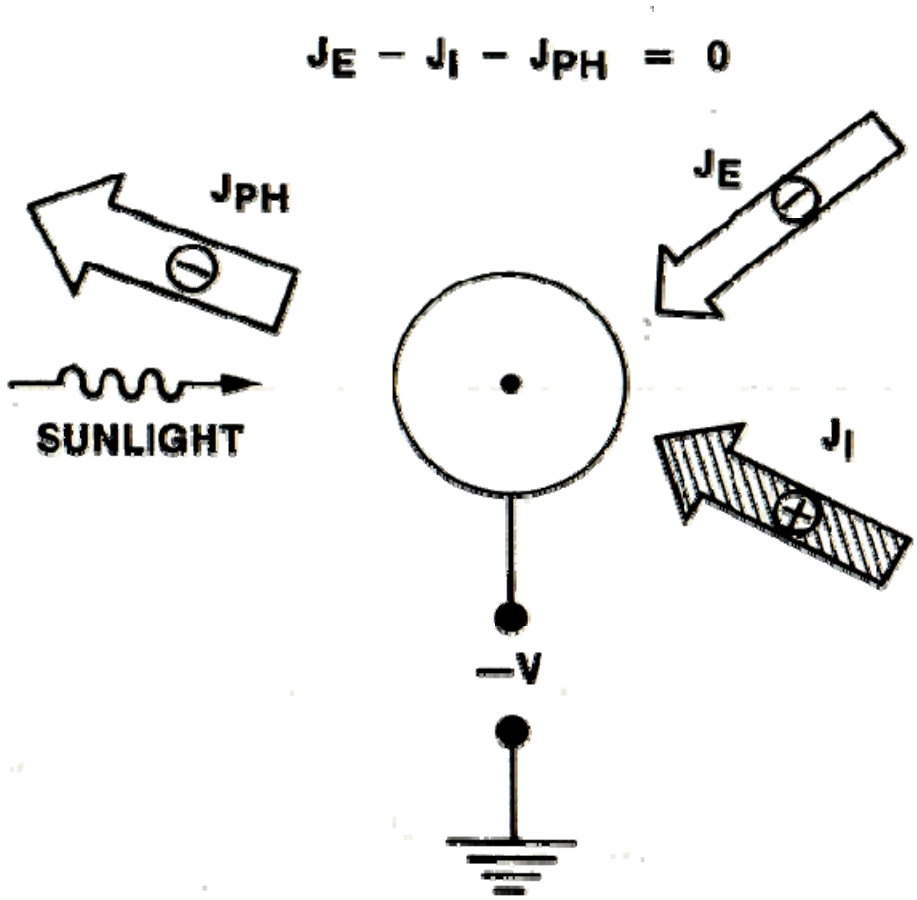
Theory of Spacecraft Charging: A Simple Picture …



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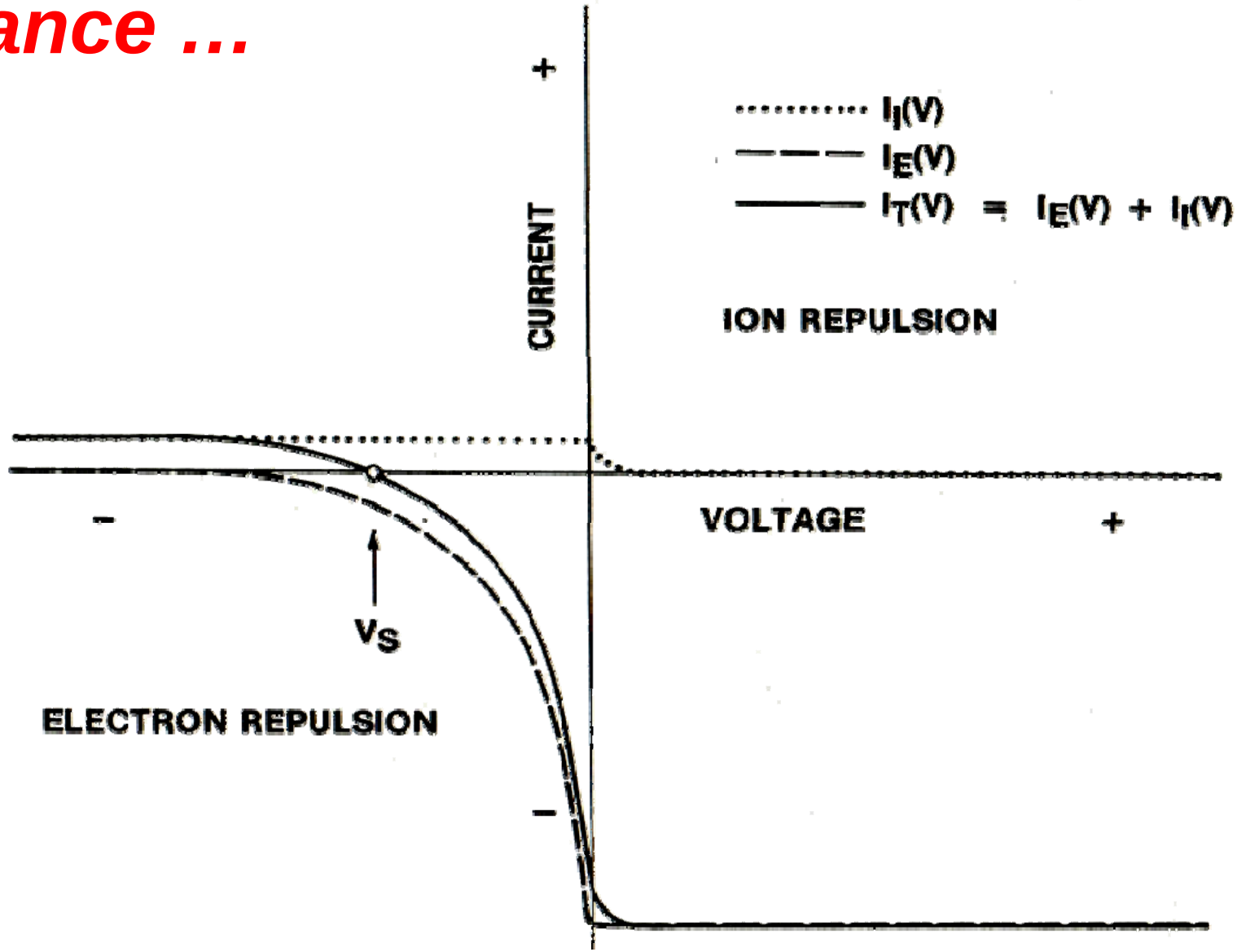
Theory of Spacecraft Charging: Current Balance …



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SPACECRAFT CHARGING THEORY

THE BASIC EQUATIONS:

- **CURRENT BALANCE:**

$$I_T(V) = I_e(V) - \left[I_I(V) + I_{Se}(V) + I_{SI}(V) + I_{BSe}(V) + I_{Pho}(V)\right]$$

- **POISSON'S EQUATION:**

$$\nabla^2 V = 4\pi q\left(n_s + n_e - n_I\right)$$

- **TIME-INDEPENDENT BOLTZMANN (VLASOV) EQUATION:**

$$\bar{v} \cdot \bar{\nabla} F_i - \frac{q_i}{m_i} \bar{\nabla} V(r) \cdot \bar{\nabla}_v F_i = 0$$

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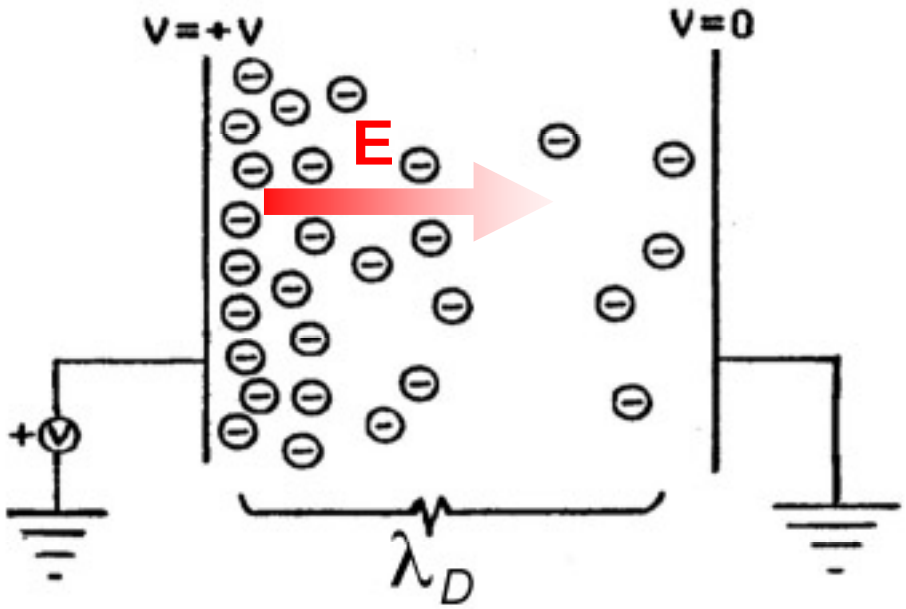
DEBYE LENGTH



Debye Length is a characteristic distance over which the plasma "shields" the electric field

SOLUTION TO POISSON'S EQUATION FOR SPHERICAL SYMMETRY:

$$V(r) = q\frac{e^{-r/\lambda_D}}{r}$$

WHERE: $$\lambda_D = \left(\frac{KT}{4\pi q^2 n_o}\right)^{1/2}$$ **THE DEBYE LENGTH**

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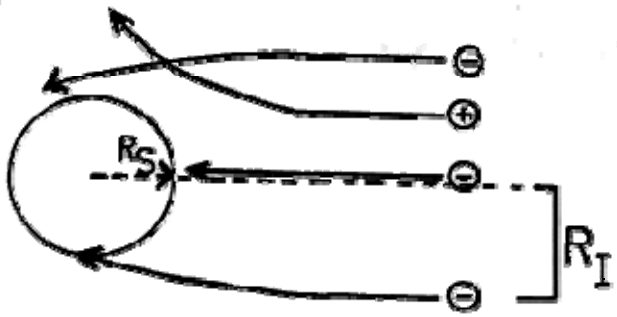
SPACECRAFT CHARGING

ORBIT LIMITED, MONO-ENERGETIC PARTICLE CURRENT COLLECTION



ASSUME:

- **ENERGY CONSERVATION:** $$\frac{mv_o^2}{2} = \frac{mv^2(R_s)}{2} + qV(R_s)$$
- **ANGULAR MOMENTUM:** $$mR_I v_o = mR_s v(R_s)$$

SOLVE FOR IMPACT PARAMETER: $$R_I = R_s\left(1 - \frac{2qV(R_s)}{mv_o^2}\right)^{1/2}$$

CURRENT DENSITY AT SPACECRAFT IS: $$J(V) = \frac{I}{4\pi R_s^2} = J_o\left(1 - \frac{2qV(R_s)}{mv_o^2}\right)$$

WHERE: $$J_o = \frac{I}{4\pi R_I^2}$$

THIS IS THE "THICK SHEATH, ORBIT-LIMITED" CURRENT SOLUTION

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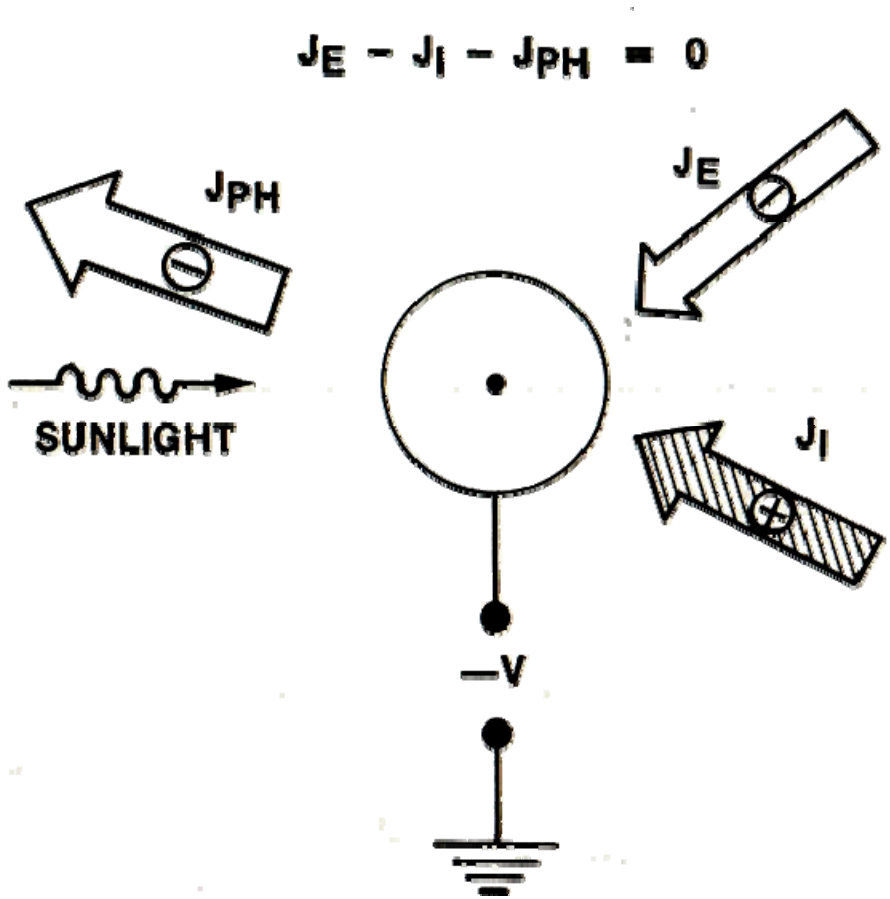
Theory of Spacecraft Charging: A Simple Picture …



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SPACECRAFT CHARGING

MAXWELL-BOLTZMANN DISTRIBUTIONS

ASSUME:

- **LIOUVILLE'S THEOREM:** $F(\bar{v}) = F'(\bar{v}')$
- **ENERGY CONSERVATION:** $\frac{mv_o^2}{2} = \frac{mv^2(R')}{2} + qV(R')$

THESE IMPLY: $F_i'(\bar{v}') = e^{\pm qV/KT_i} F_i(\bar{v}')$

SIGN IS: + FOR ELECTRONS, - FOR IONS

AND: $(\bar{v}')^2 \geq \max\left(0, \pm\frac{2qV}{m_i}\right)$

INTEGRATING THE PHASE SPACE DENSITY TO GET CURRENT GIVES:

$$J_e = J_{eo} \cdot \begin{cases} e^{qV/KT_e} \\ 1 + \frac{qV}{KT_e} \end{cases} \qquad J_I = J_{Io} \cdot \begin{cases} e^{-qV/KT_I} \\ 1 - \frac{qV}{KT_I} \end{cases}$$

WHERE: $J_{io} = \frac{qn_i}{2}\left(\frac{2KT_i}{\pi m_i}\right)^{1/2}$

UPPER VALUE: REPELLED SPECIES
LOWER VALUE: ATTRACTED SPECIES

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Theory of Spacecraft Charging: A Simple Example

FOR A NEGATIVELY CHARGED SPACECRAFT:

$$J_T(V) = J_{Io}\left(1 - \frac{qV}{KT_I}\right) - J_{eo}\left(e^{qV/KT_e}\right)$$

TYPICALLY AT GEOSYNCHRONOUS ORBIT:

$$\frac{qV}{KT_I} \sim 0$$

FOR CURRENT BALANCE:

$$J_T(V) = 0$$

THIS IMPLIES:

$$V = \frac{-KT_e}{q}\ln\left(\frac{J_{eo}}{J_{Io}}\right)$$

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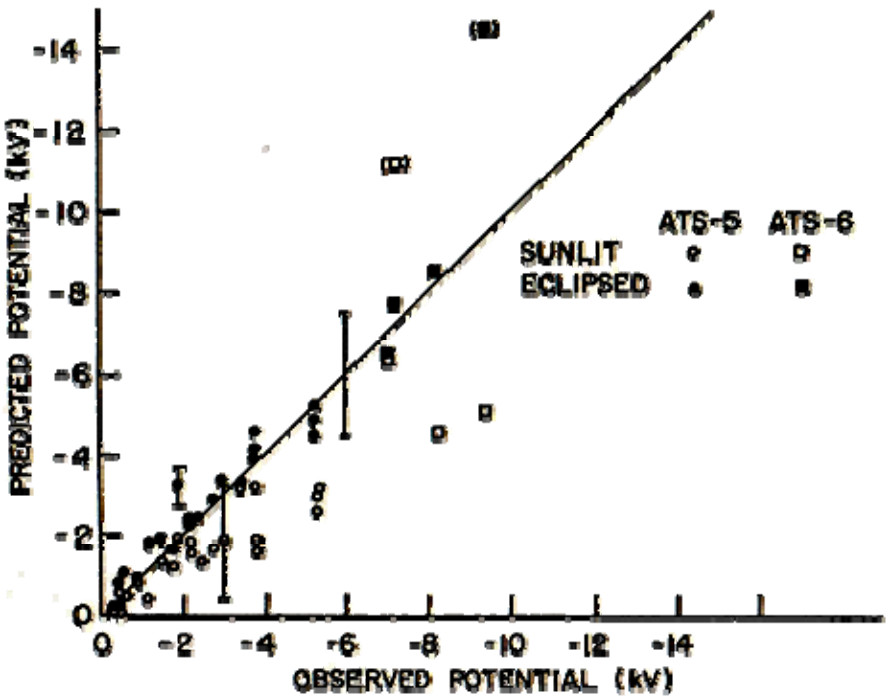
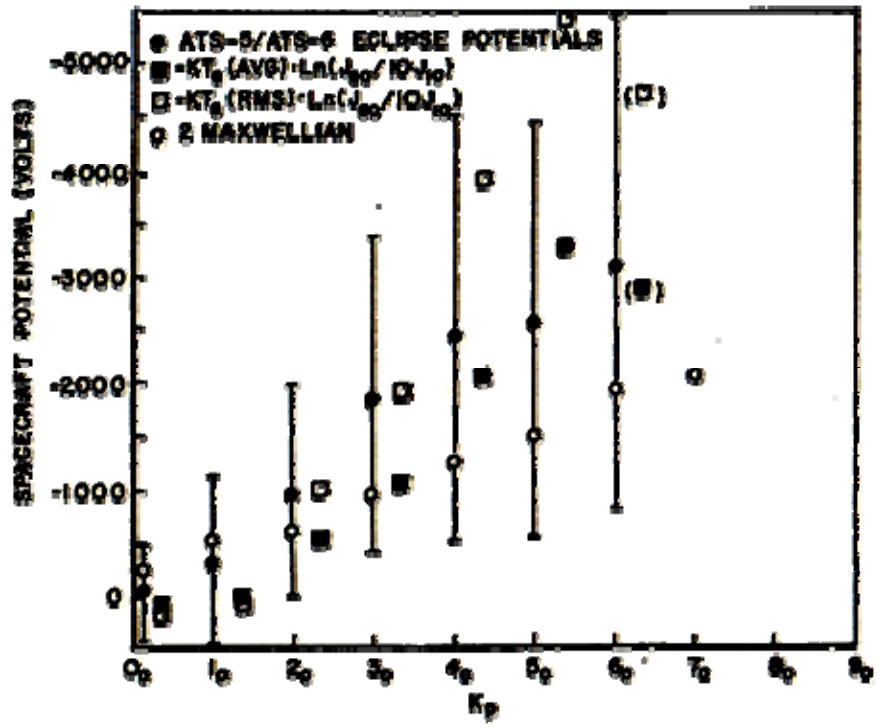
FIRST ORDER MODELS OF GEOSYNCHRONOUS CHARGING

ATS-5/ATS-6 ESTIMATED VERSUS OBSERVED ECLIPSE POTENTIALS



ATS-5/ATS-6 ESTIMATED ECLIPSE POTENTIALS VS Kp



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3-D SPACECRAFT CHARGING

OBJECTIVES

- TO IDENTIFY BASIC CONCEPTS
  - CURRENT BALANCE
  - SPACE CHARGE LIMITED
  - ORBIT LIMITED CURRENT COLLECTION
- TO IDENTIFY CAUSES OF 3-D CHARGING
- TO DEMONSTRATE 3-D CHARGING CALCULATIONS

SOURCES

- FLUX ASYMMETRIES
  - MAGNETIC FIELD
  - ELECTRIC FIELD
  - RAM/WAKE
- GEOMETRIC
  - SHADOWING
  - MATERIAL PROPERTIES
  - PHOTOELECTRONS
- SPACE CHARGE
  - POTENTIAL BARRIERS

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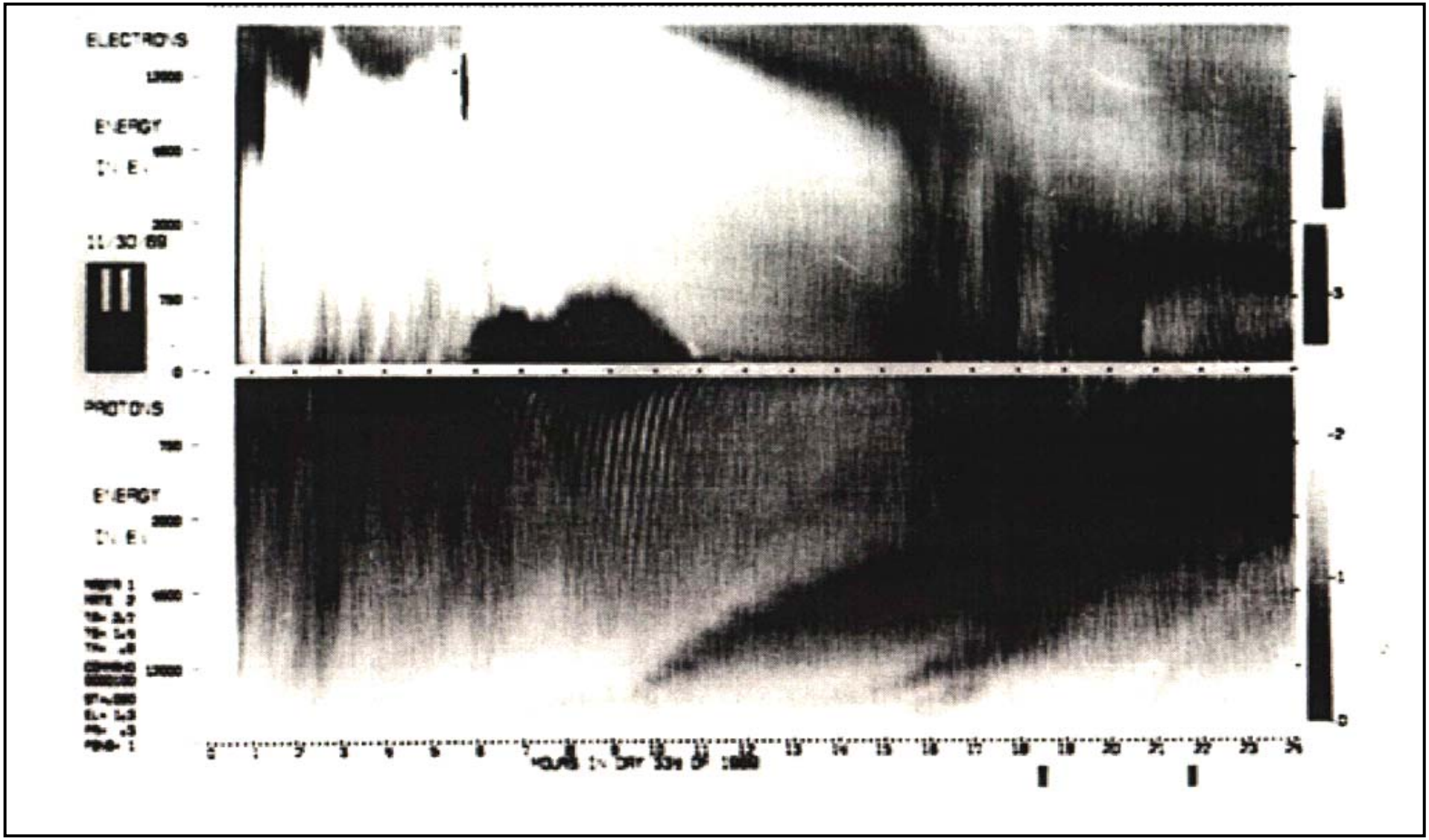
Differential Charging on ATS-5



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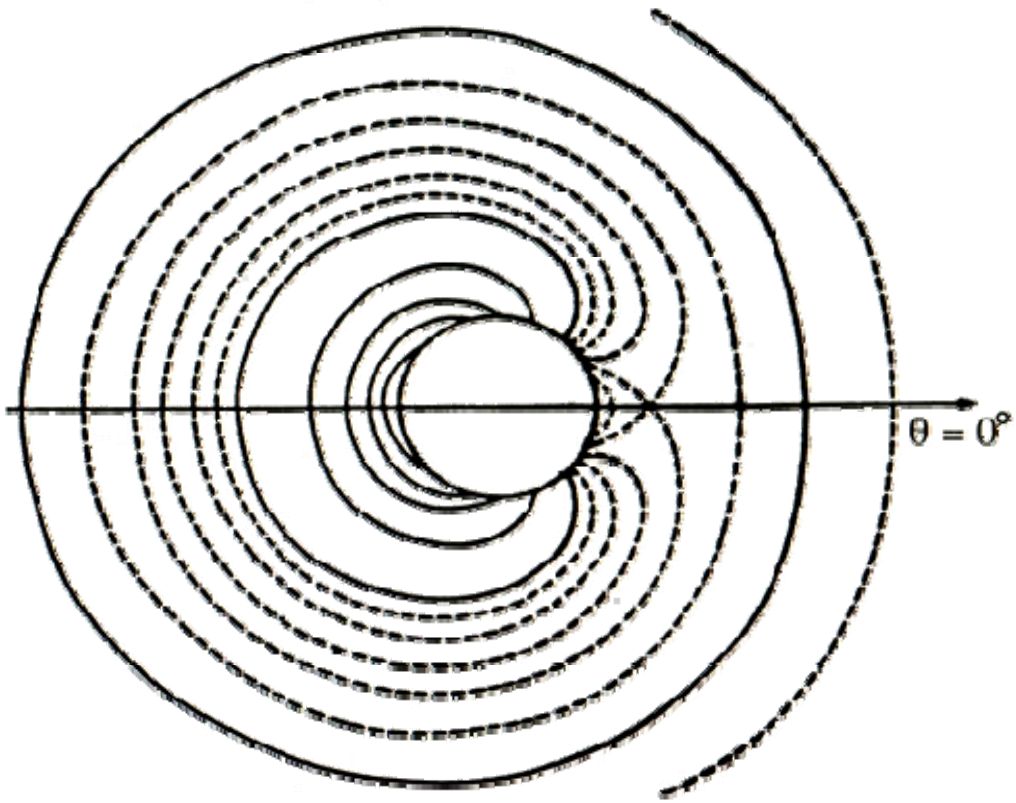
3-D MODELING OF SPACE CHARGE EFFECTS

EQUIPOTENTIAL CURVES FOR MONOPOLE-DIPOLE FIELD



$$eV = K\left(\frac{1}{R} - \frac{A\cos\theta}{R^2}\right)$$

SPACE CHARGE LIMITED PARTICLE TRAJECTORIES

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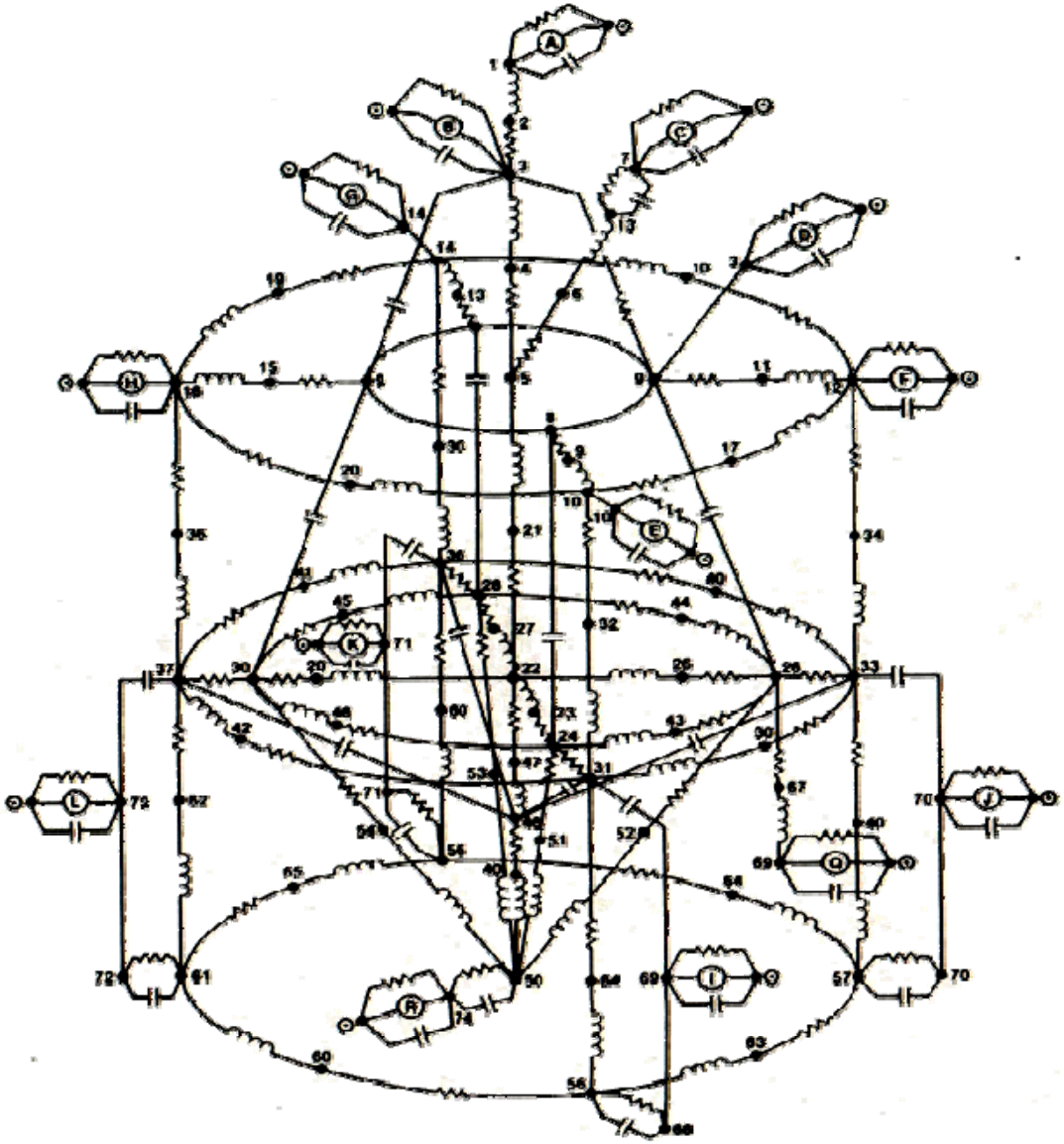
FINITE ELEMENT MODEL OF PIONEER-VENUS SPACECRAFT



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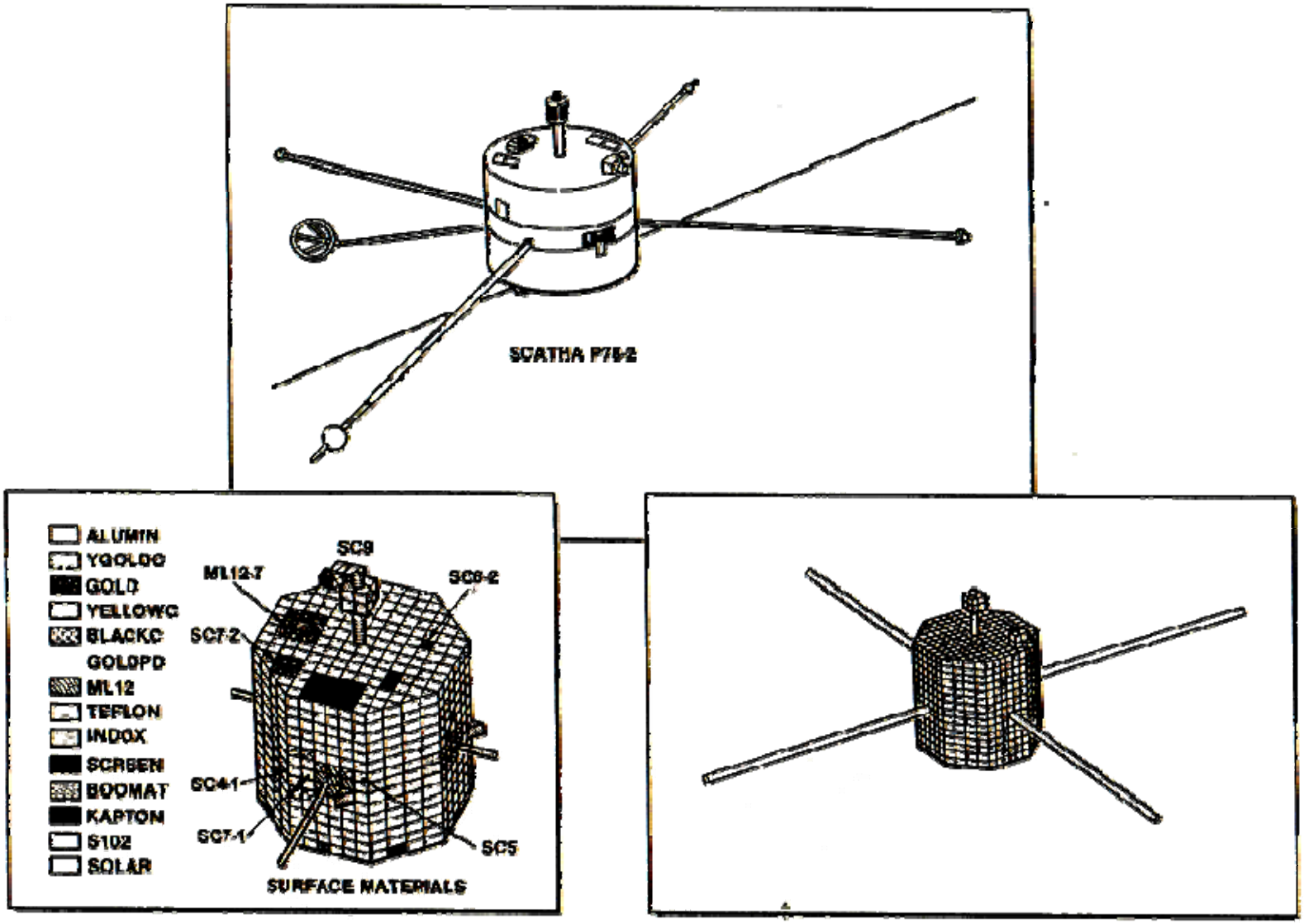
THE "NASCAP" SPACECRAFT CHARGING CODE



NASCAP MODELS

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Plasma Interactions

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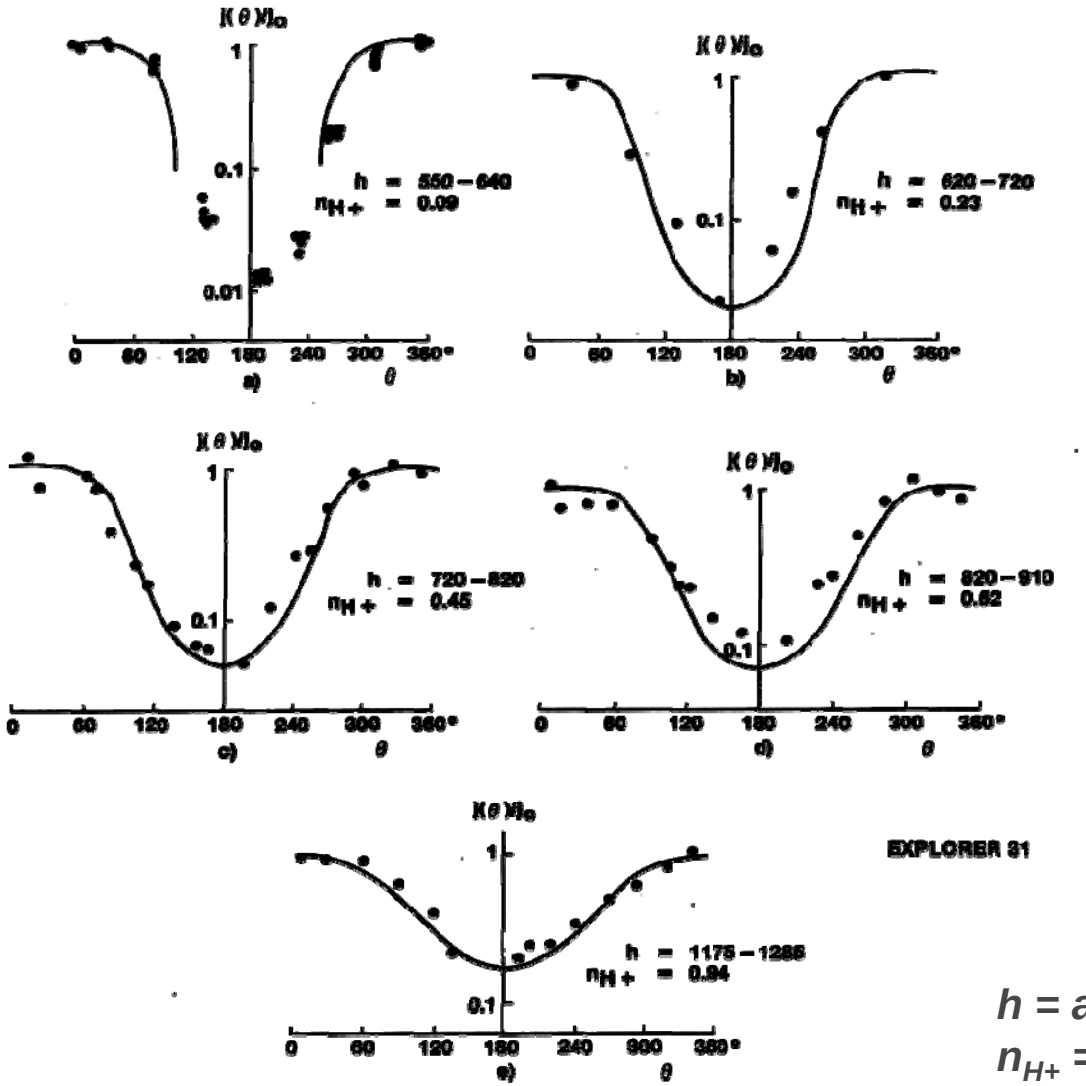
Normalized Electron Current Density vs Ram Angle and Altitude



h = altitude in Km

n_{H+} = % H^+

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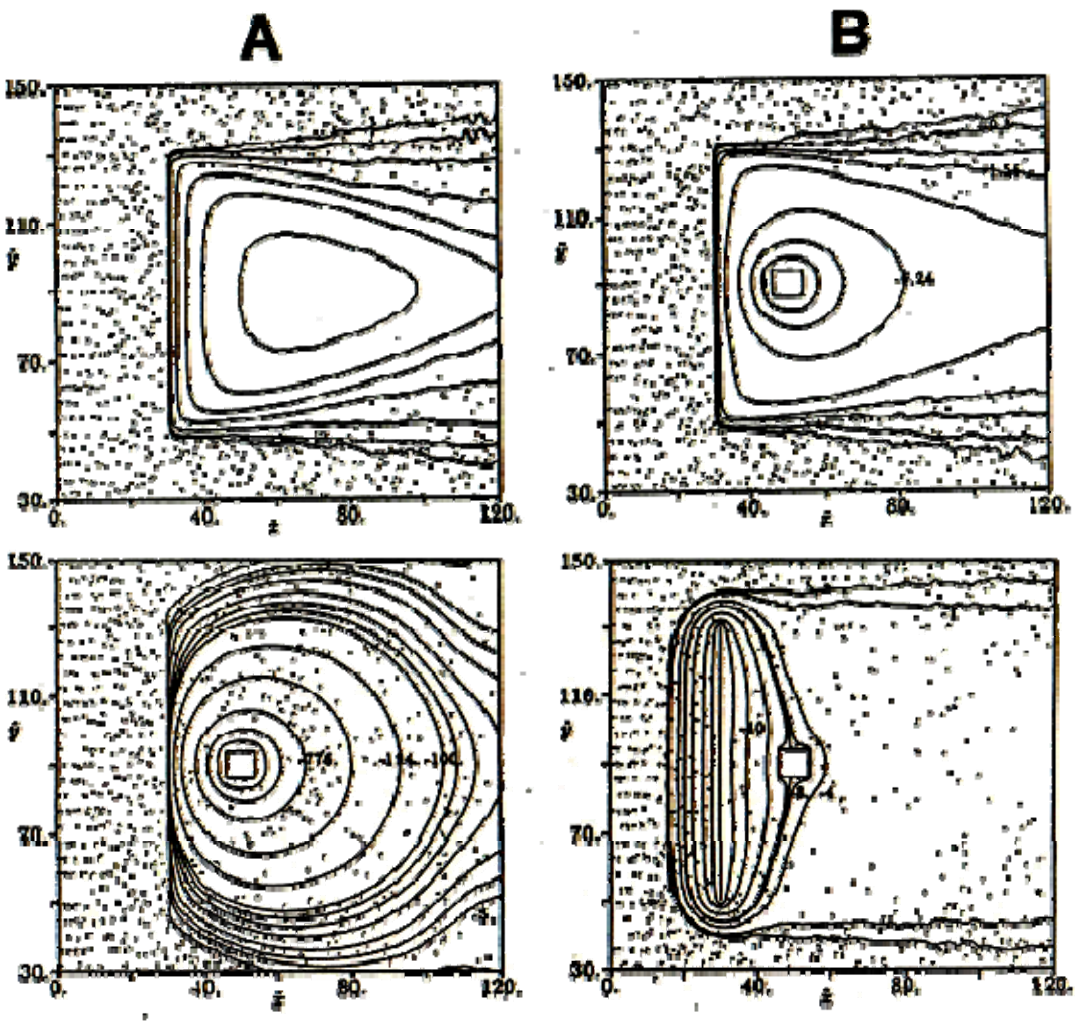
MULTIBODY CHARGING AT LOW ALTITUDES*



A. AMBIENT CHARGING

B. MULTIBODY CHARGING

C. AURORAL CHARGING

D. BIASED + AURORAL

*WANG, LEUNG, GARRETT, AND MURPHY (1994)

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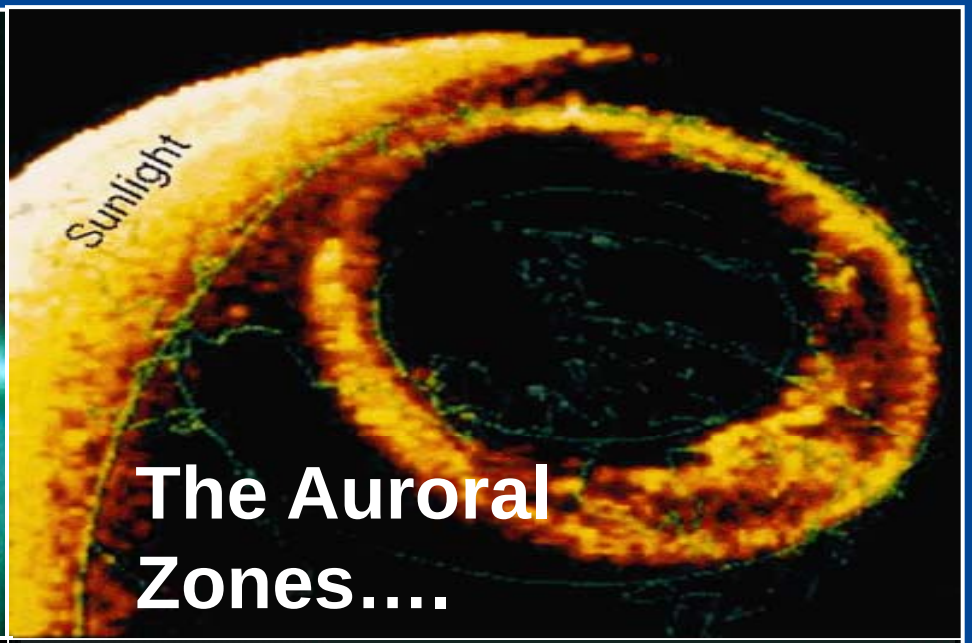
The Aurora Are Everywhere …



AURORAL CHARGING OVERVIEW

WHAT IS THE CONCERN?

- Auroral charging is a major concern for polar orbiting spacecraft at Earth
- Jupiter has pronounced auroral features:
  - A narrow auroral zone at high latitudes
  - A complex and variable environment over the poles
  - Aurora-like features associated with the main jovian moons and their magnetic flux tubes
- ***IF*** we understand the environment, ***THEN*** proper mitigation techniques should allow us to limit their effects…

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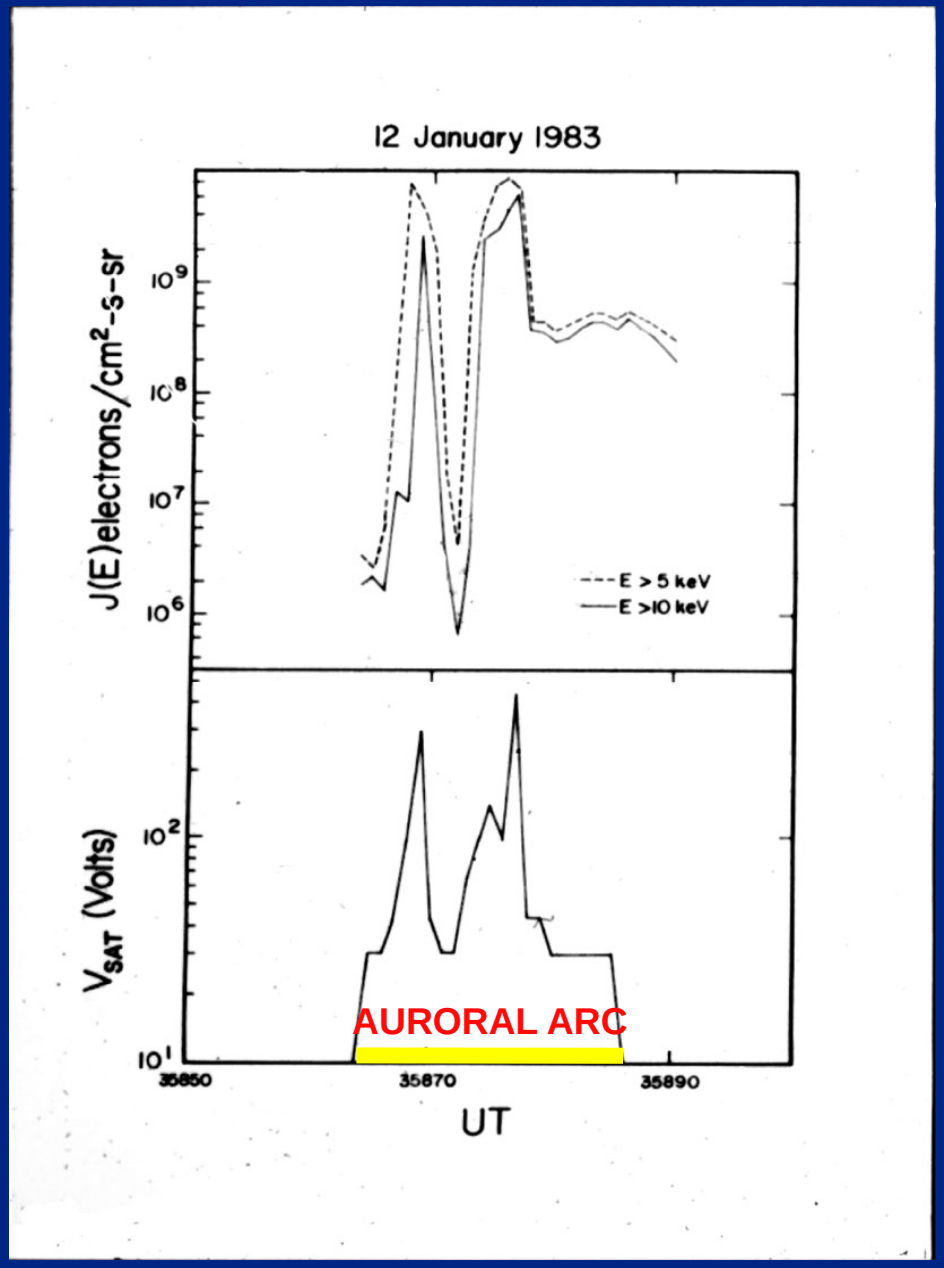
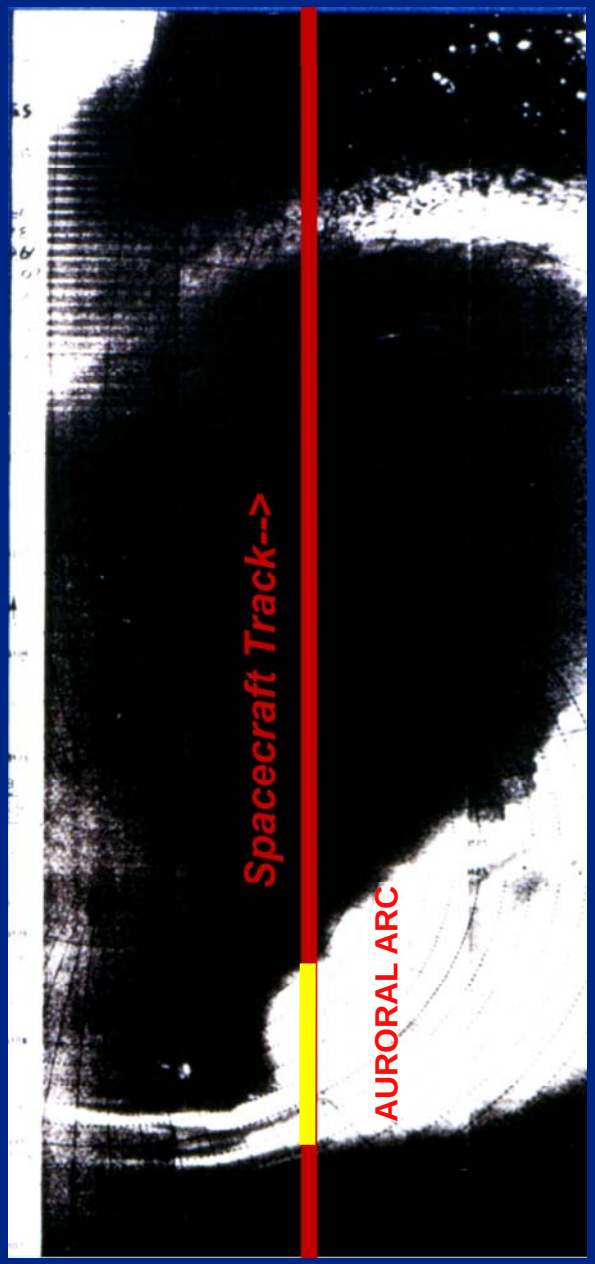
DMSP Low Altitude Spacecraft Charging





DMSP low altitude charging in Earth's auroral zone. Left side plots electron fluxes and spacecraft potentials along nadir track of spacecraft at 800 km (red-yellow line on right). Left hand data correspond to passage through auroral arc along yellow segment (right side). ***(Courtesy AFRL)***

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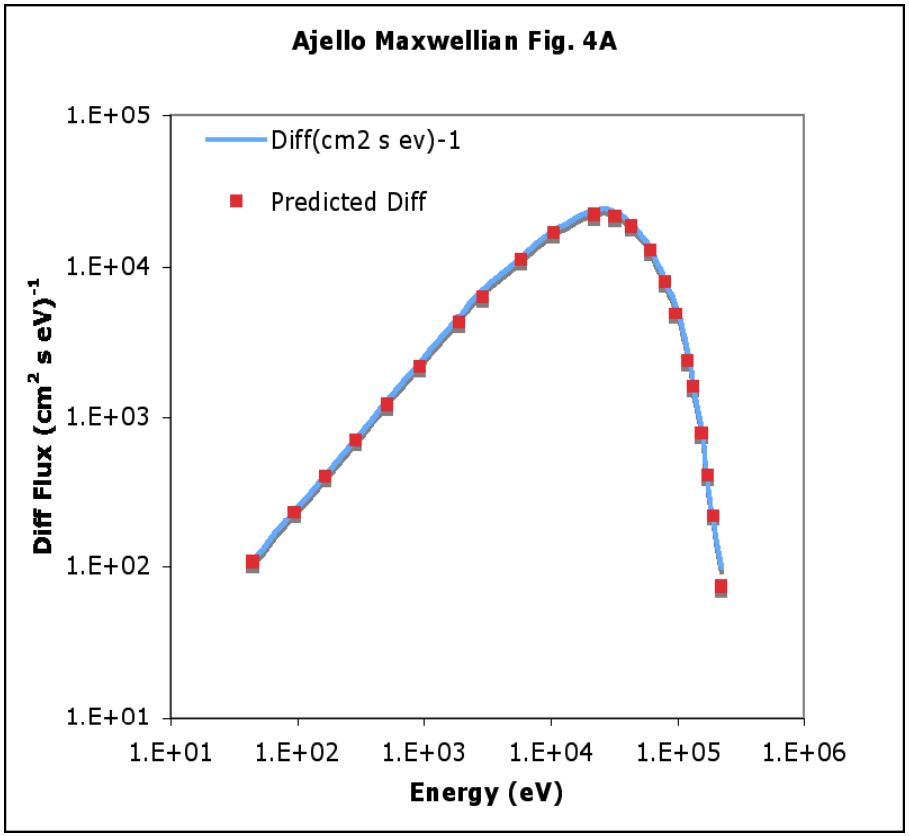
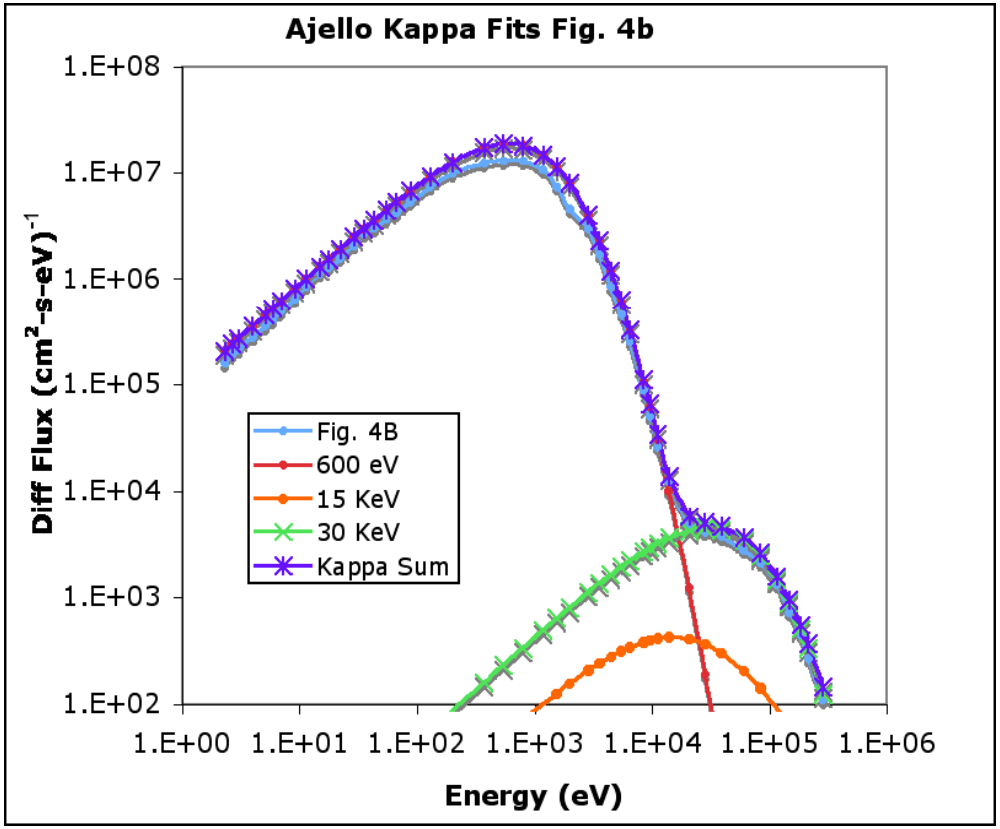
Jovian Auroral Zone Spectra





Ajello et al., "Spectroscopic Evidence for High-Altitude Aurora at Jupiter from Galileo Extreme Ultraviolet Spectrometer and Hopkins Ultraviolet Telescope Observations", Icarus, 152, pp. 151-171, 2001.

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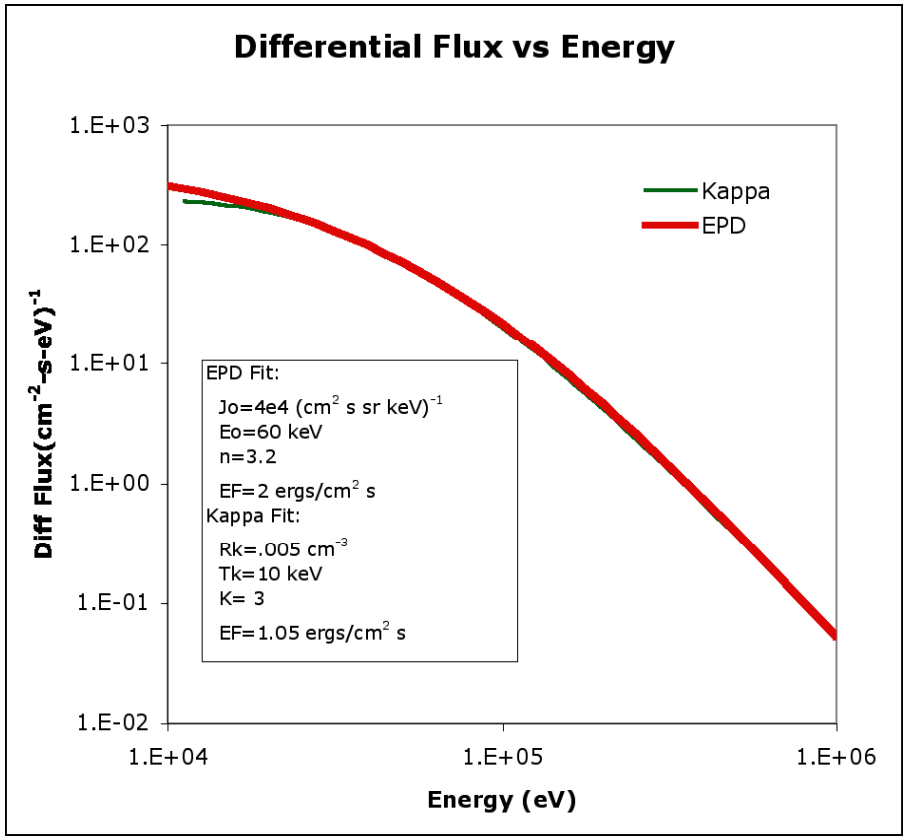
Jovian Diffuse Aurora



Observed EPD electron spectrum at 18.4 Rj*. As Energy Flux varies from ~1 to ~100 ergs/cm^2-s, we assumed a "Worst Case" of ~100 ergs/cm^2-s.

*Bhattacharya et al., "On the energy source for the diffuse Jovian auroral emissivity", Geophys. Res. Lttrs., 28, 2715-2754, 2001.

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INTERNAL ELECTROSTATIC CHARGING

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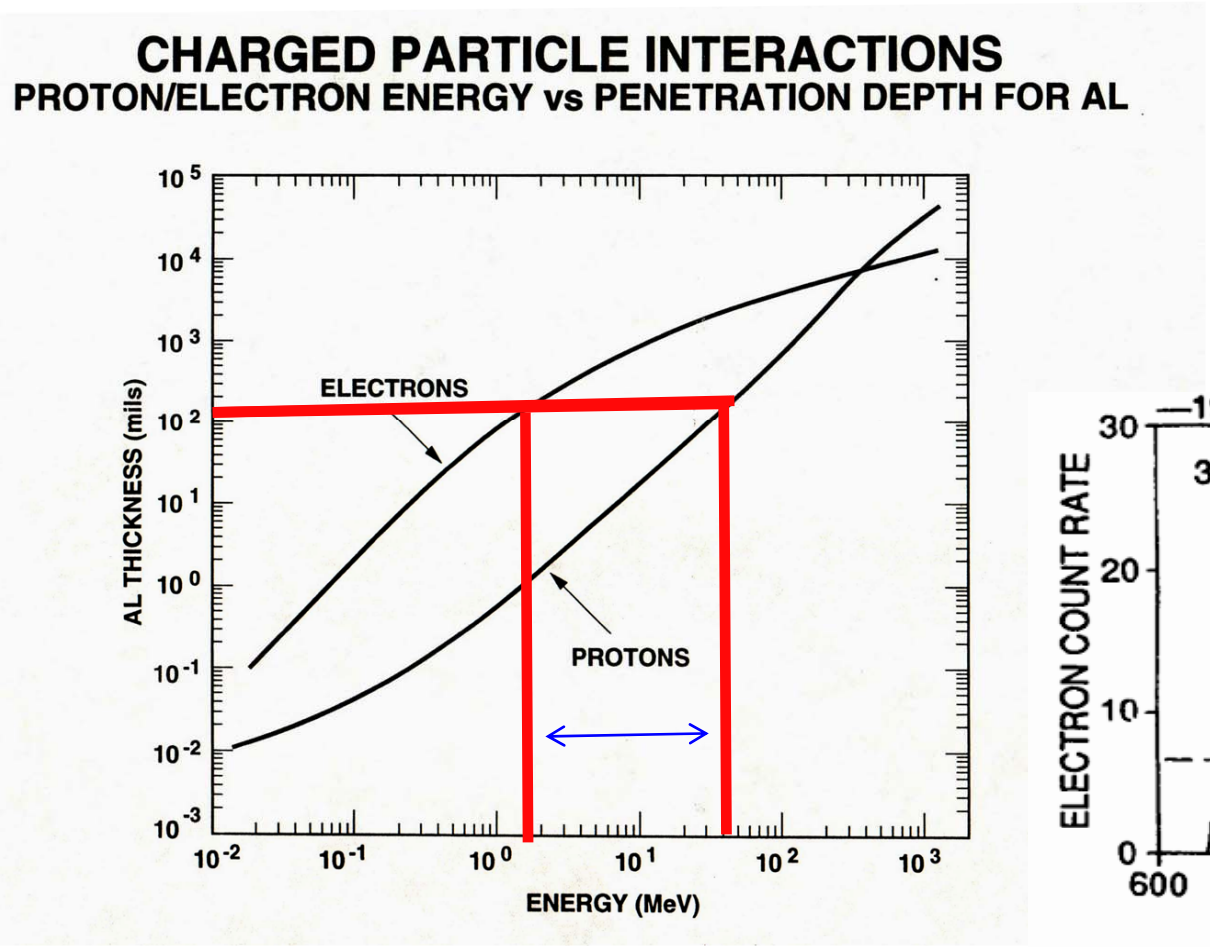
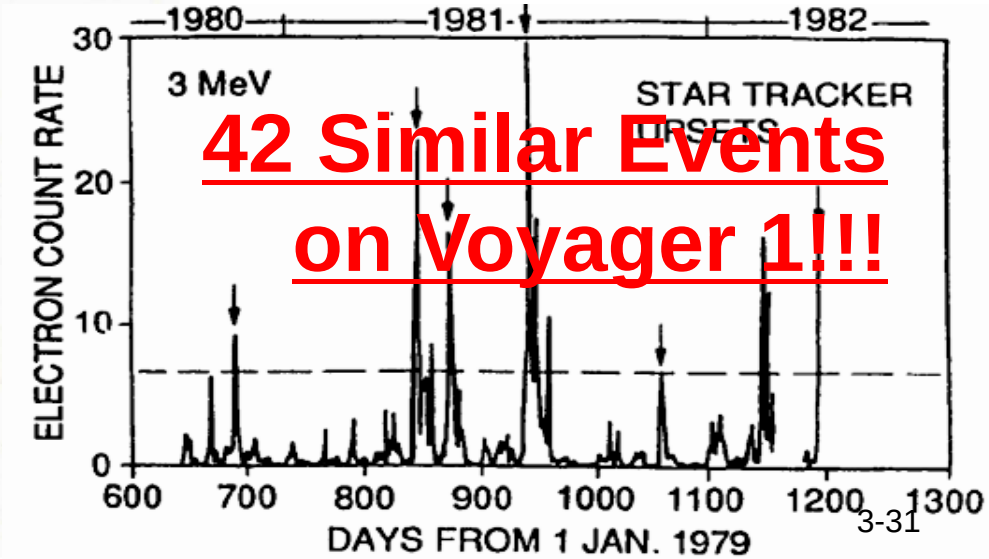
Internal Electrostatic Discharge—Satellite Killer …

DISCHARGE PATTERN





42 Similar Events on Voyager 1!!!

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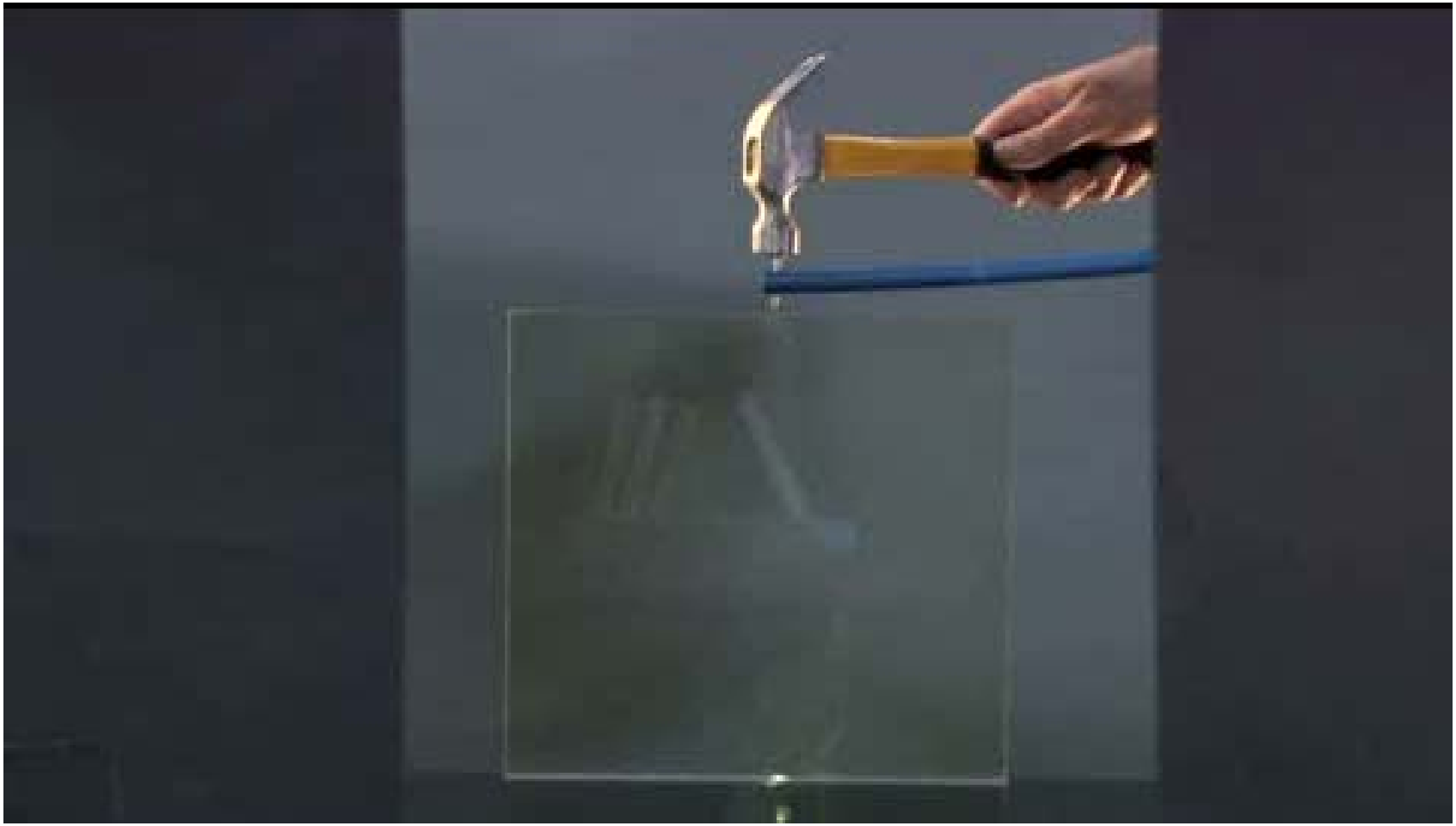
Internal Electrostatic Discharge—The Movie



VxB

THE ELECTRIC FIELD INDUCED BY A MAGNETIC FIELD

$E = 0.1\ (v \times B)$ V/m

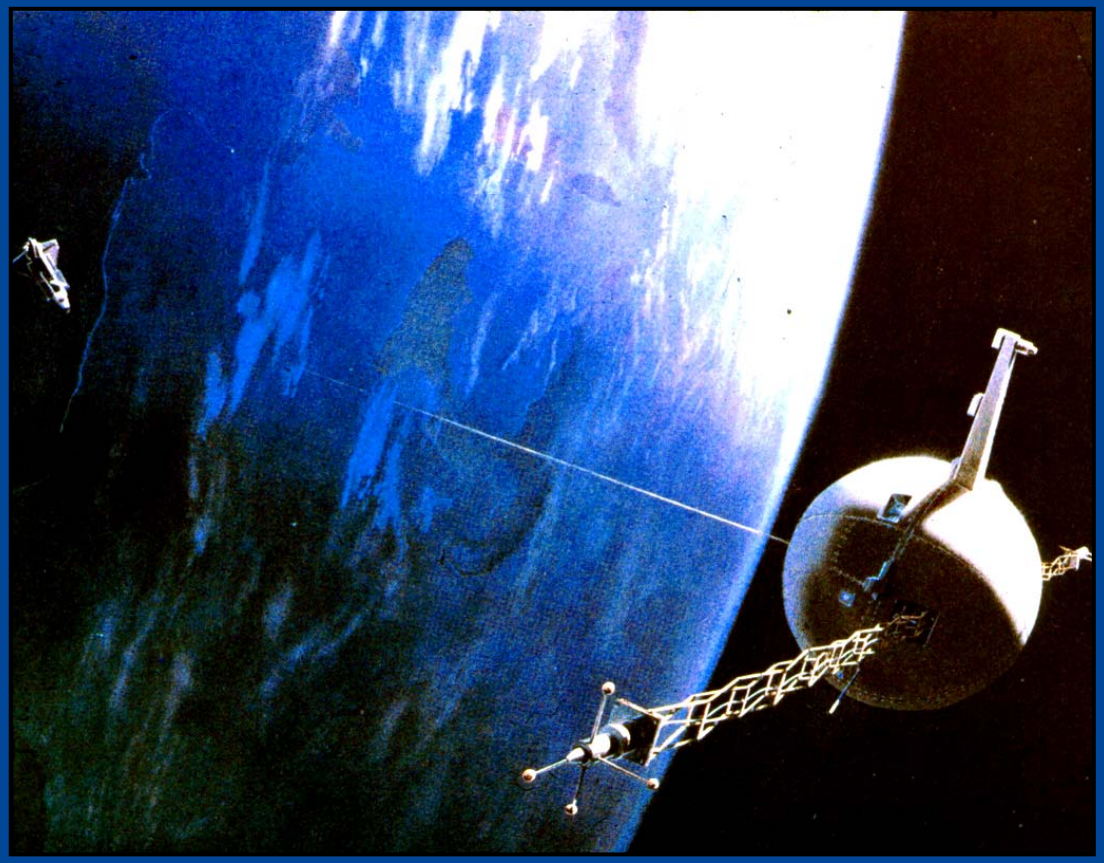
$v \sim 7.6$ Km/s

$B \sim 0.3$G

$E \sim 0.3$ V/m

SHUTTLE —

15m x 24m x 33m



At Jupiter, E ~ 20-30 V/m!!!

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Radiation Interactions

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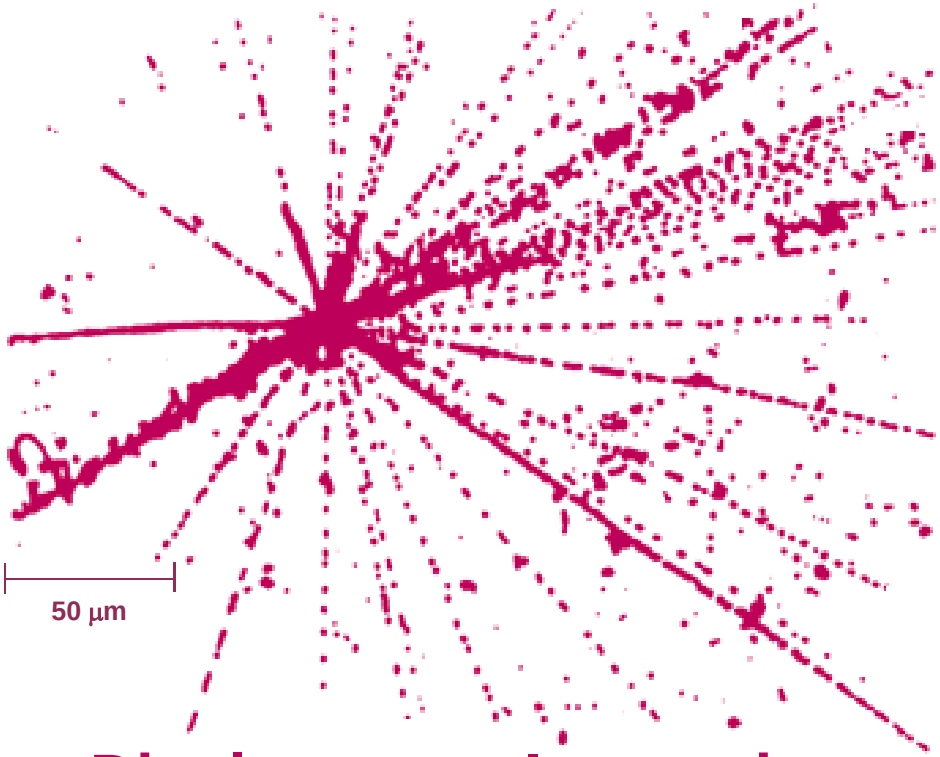
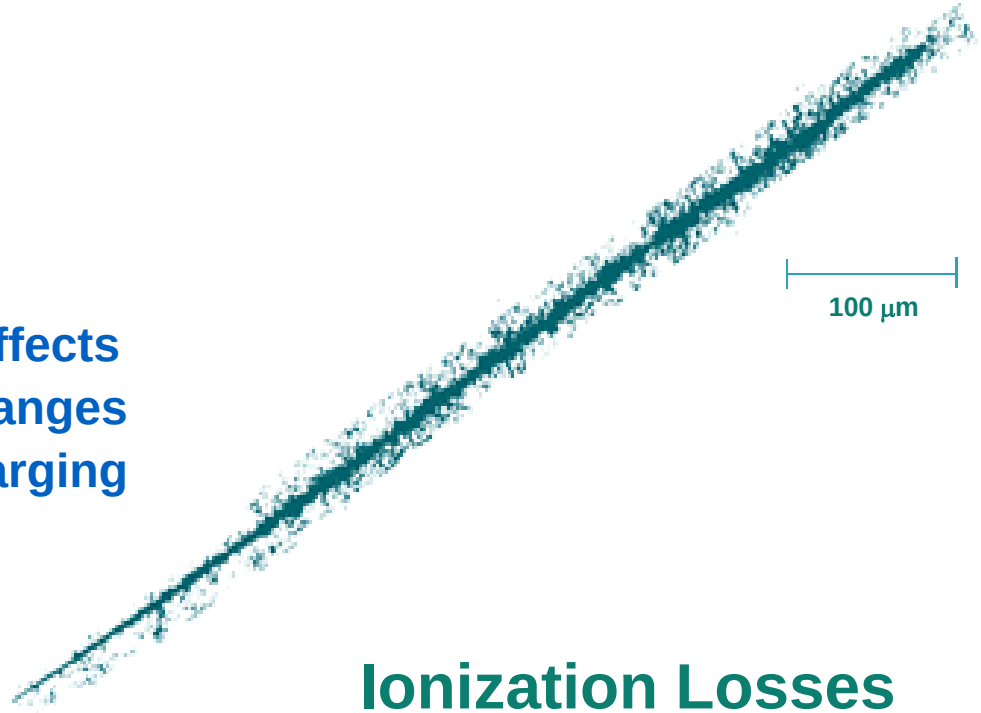


Displacement Interactions

Radiation Effects on Spacecraft Systems

Primary Sources of Damage

- Energy Loss Effects
  - Displacement Damage
  - Total Ionizing Dose
- Single Event Effects
  - SEU
  - Latchup
  - Gate Rupture
- Flux/Rate Effects
- Material Changes
- Internal Charging
- UV/EUV



Ionization Losses

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Recipe for Dosage

STEPS:

0) Assume target of density ρ, area δA, and thickness $\boxed{\delta\tau = \frac{M}{\rho\delta A}}$

1) Determine fluence (number N of particles per unit area δA normal to target surface) versus energy. Call this f(E) at energy E:

$$\boxed{f(E) = \frac{N(E)}{\delta A}}$$

2) Estimate energy change δE in crossing thickness δτ of target for particle energy E:

$$\boxed{\delta E \approx \delta\tau \left.\frac{dE}{dx}\right|_E}$$

3) Dose per particle of energy E is:

$$\boxed{D(E) \approx \frac{\delta E}{M} \approx \left.\frac{dE}{dx}\right|_E \frac{\delta\tau}{M} \approx \frac{1}{\rho}\left.\frac{dE}{dx}\right|_E \frac{1}{\delta A}}$$

4) Total dose at energy E is :

$$\boxed{D_T(E) \approx N\, D(E) \approx \frac{1}{\rho}\left.\frac{dE}{dx}\right|_E f(E)}$$

5) Integrate over the range E_0 to ∞ for total dose.

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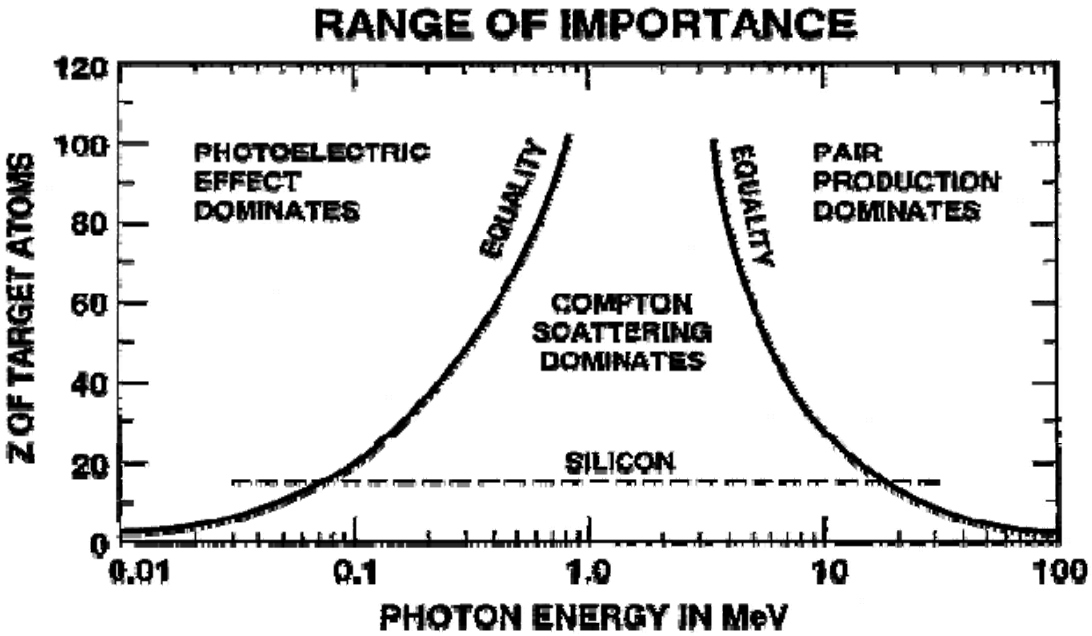
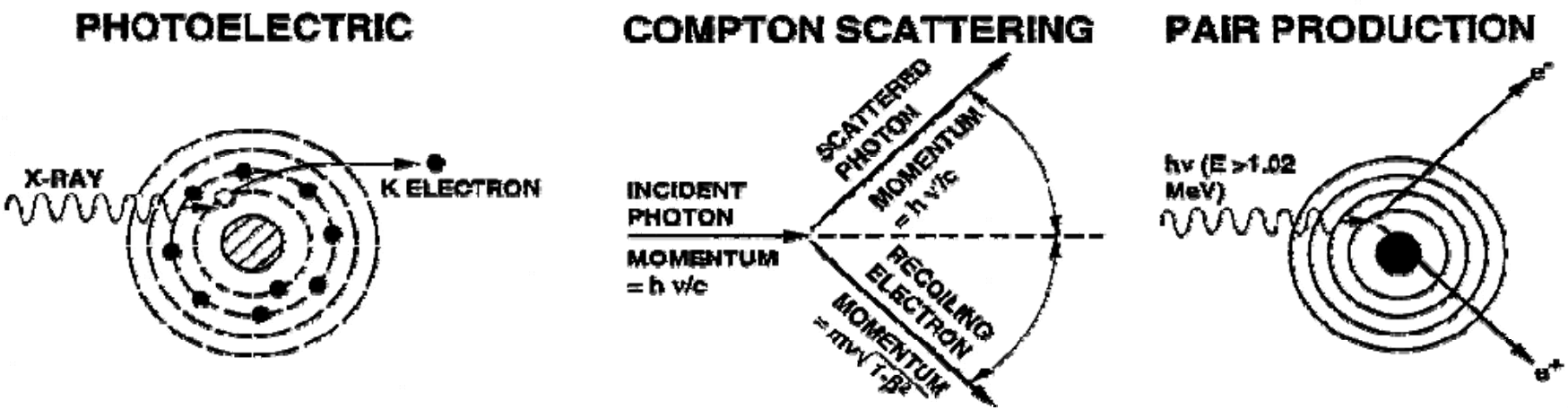
Photon Interactions with Matter





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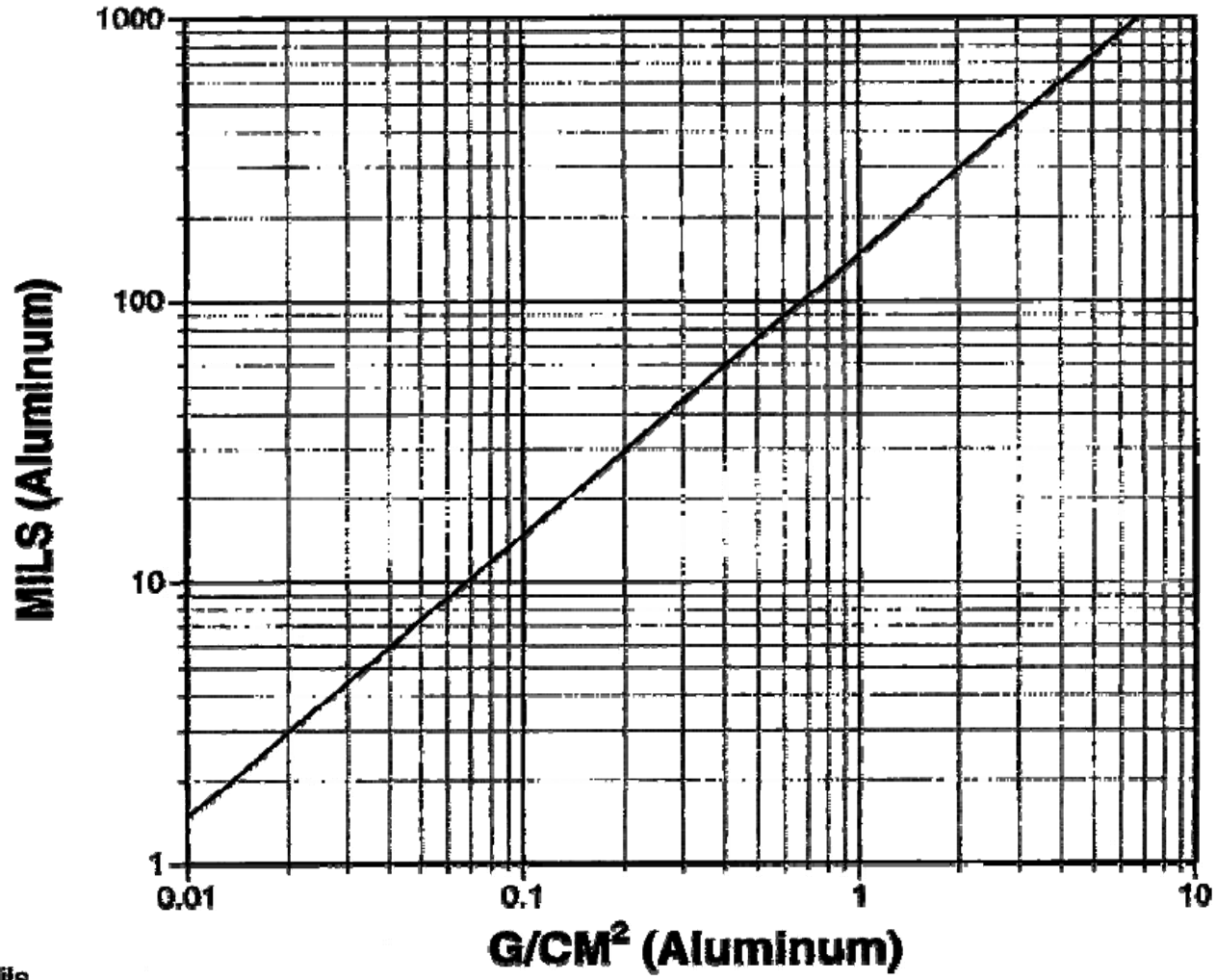
MILS TO G/CM^2 CONVERSION FOR ALUMINUM (ρ = 2.7 G/CM^3)



1 g/cm^2 = 145.8 mils
100 mils = .686 g/cm^2
1 mm = 39.3 mils

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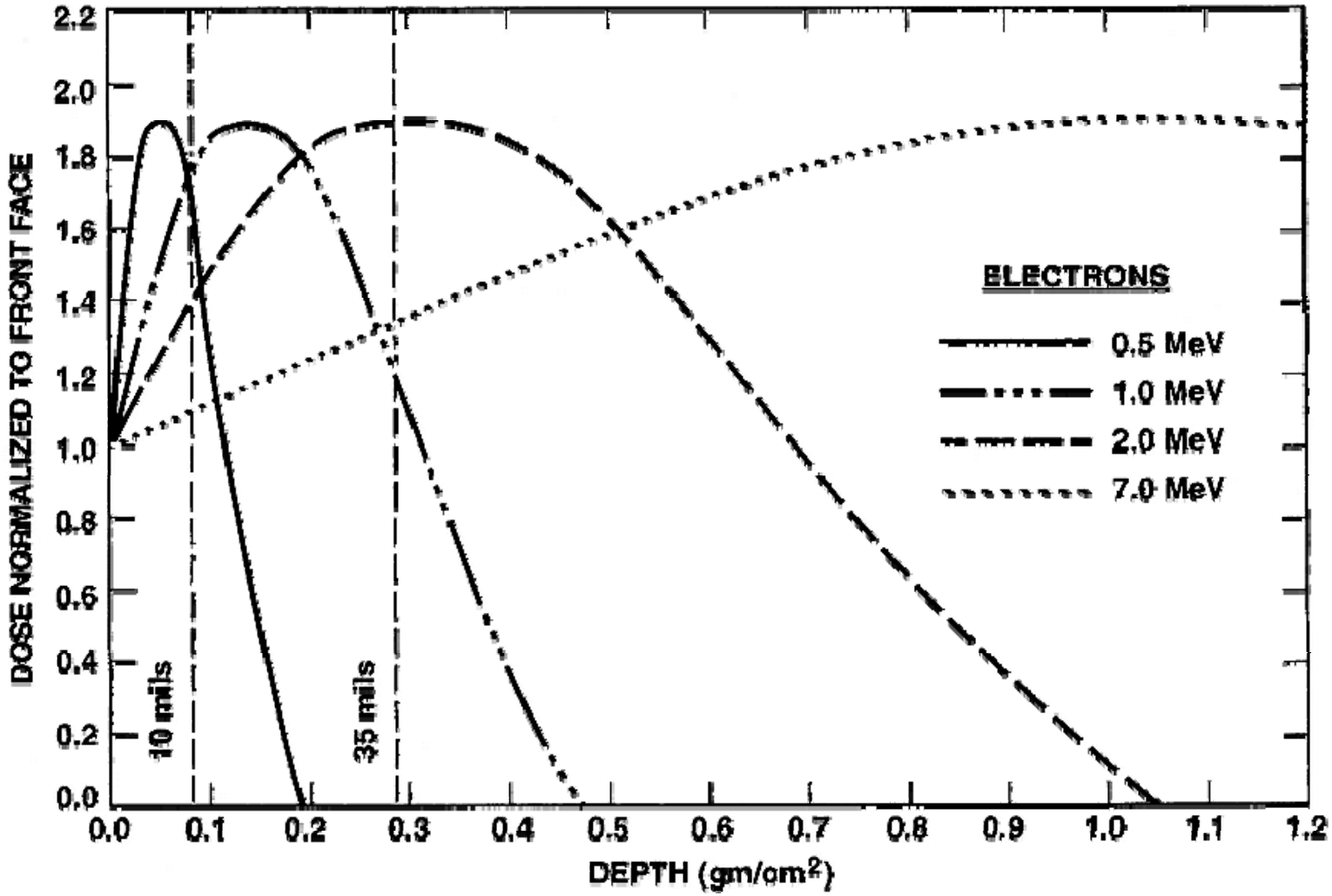
CHARGED PARTICLE INTERACTIONS (Cont'd)

ELECTRON DOSE vs DEPTH FOR CaFMg



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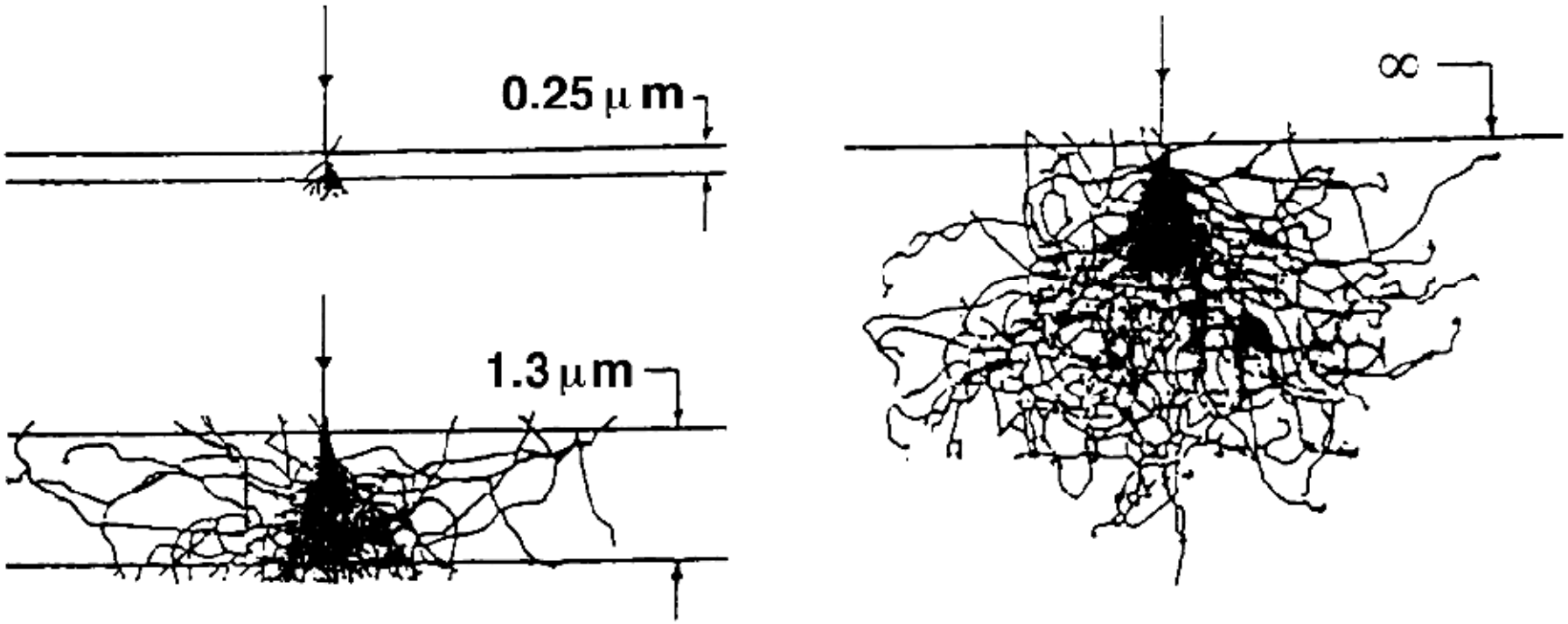
Radiation Transport: Electron Monte Carlo Simulations



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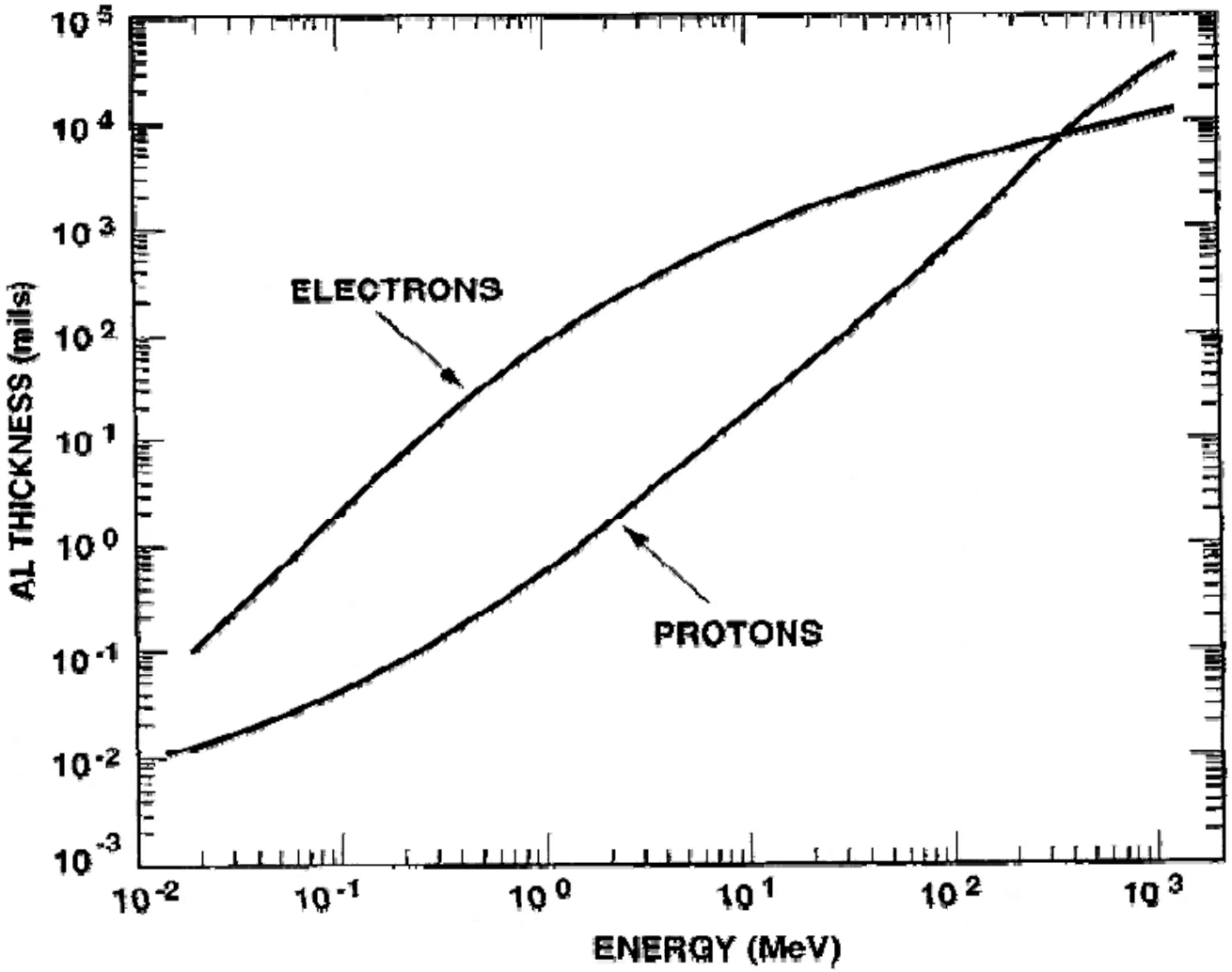
CHARGED PARTICLE INTERACTIONS

PROTON/ELECTRON ENERGY vs PENETRATION DEPTH FOR AL



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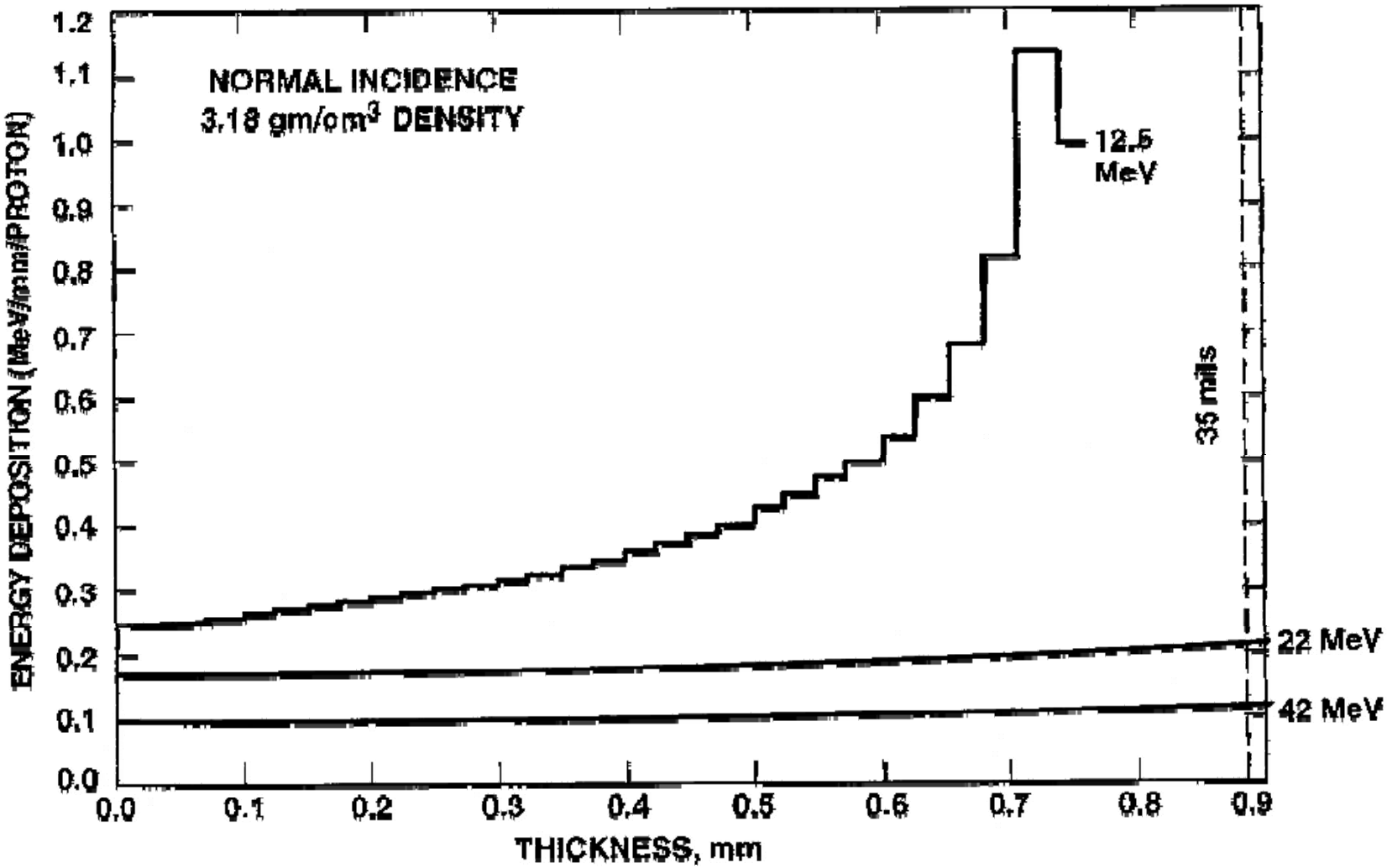
CHARGED PARTICLE INTERACTIONS (Cont'd)

PROTON DOSE vs DEPTH FOR CaF_2



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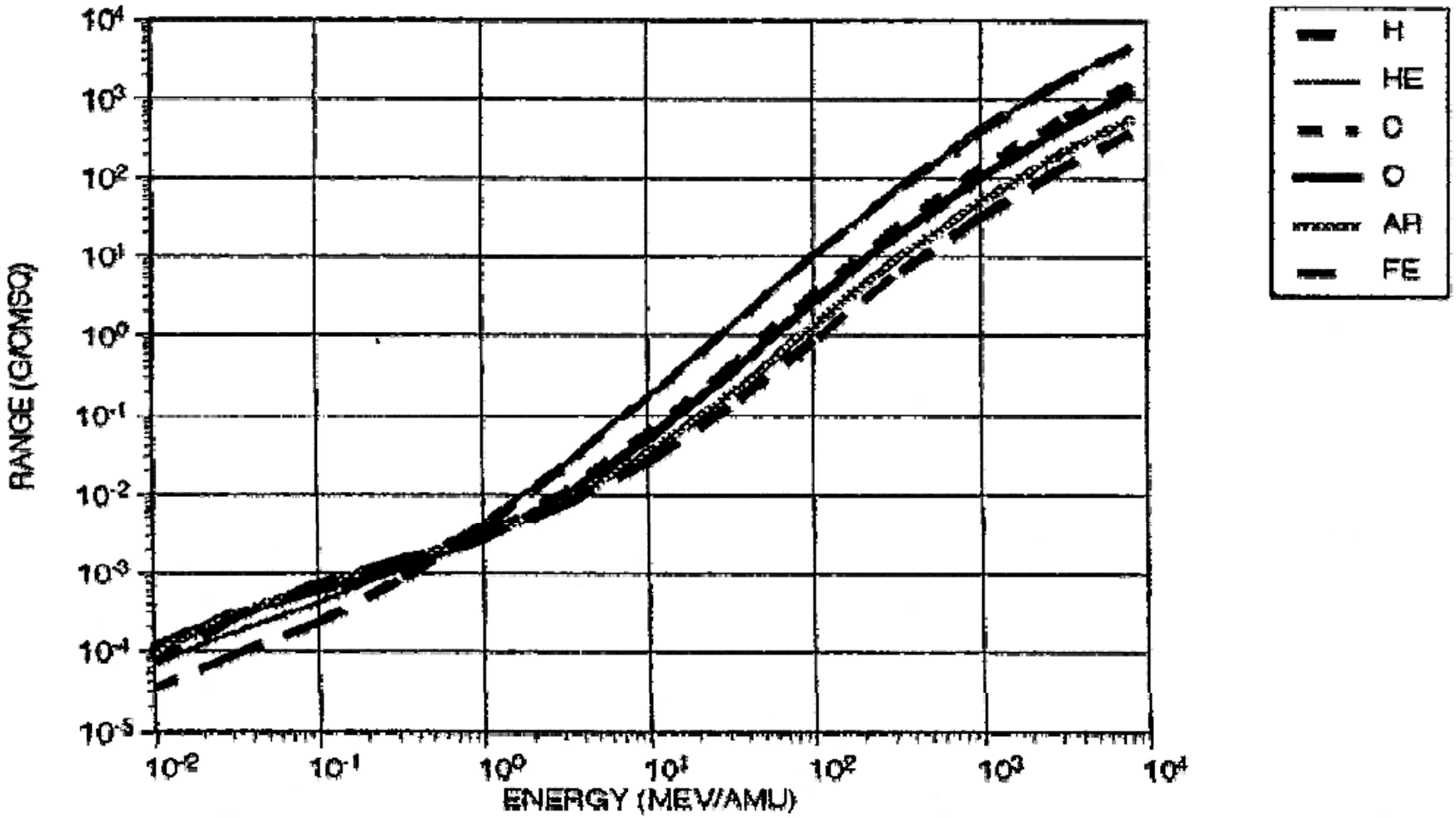
RANGE OF IONS IN ALUMINUM



Ion range versus energy in Al[32] for H, He, C, O, Ar, and Fe. The range is in units of g-cm^2 and the energy in MeV/μ.

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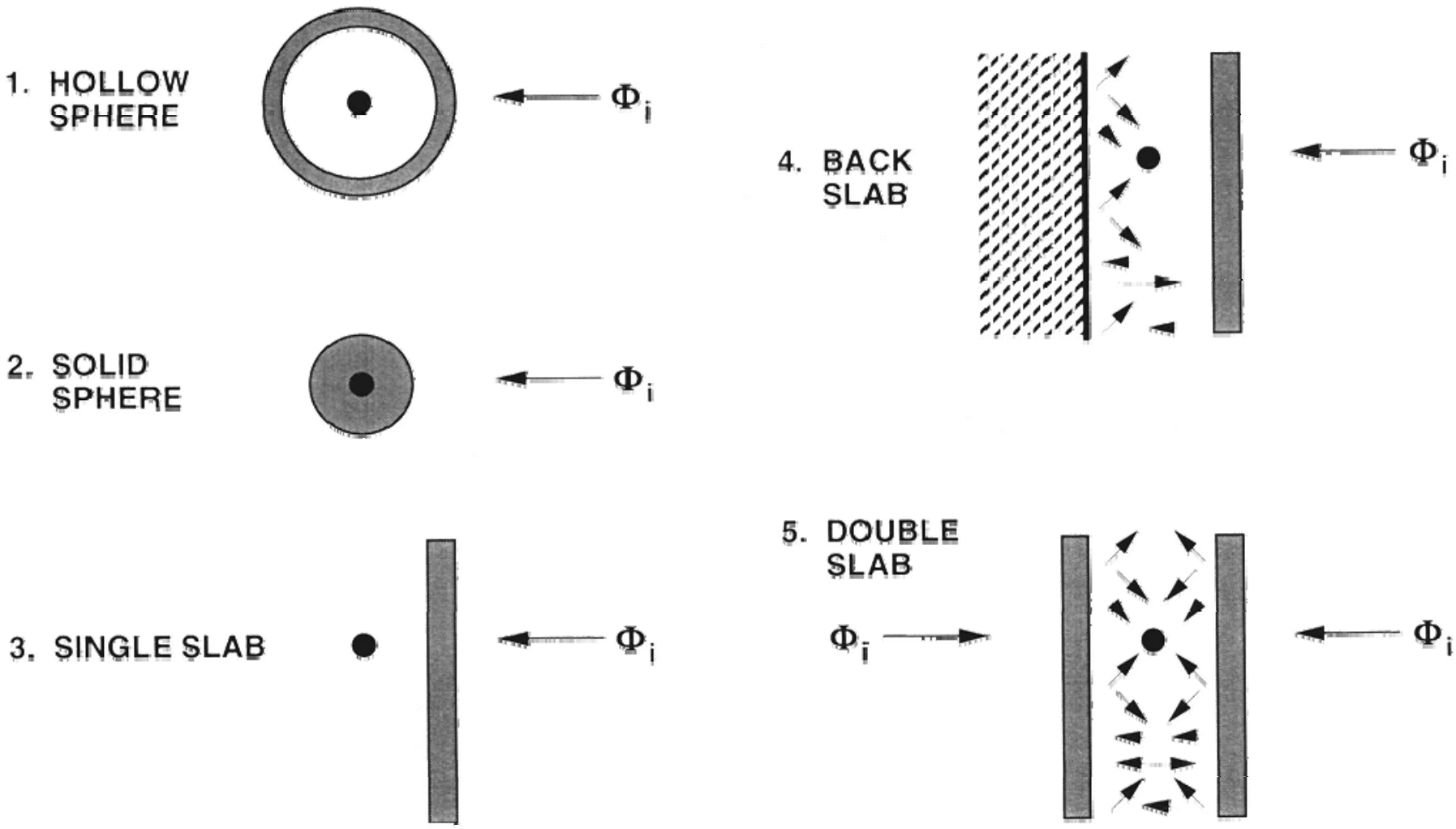
GEOMETRIC EFFECTS ON SHIELDING

GEOMETRIC CONFIGURATIONS



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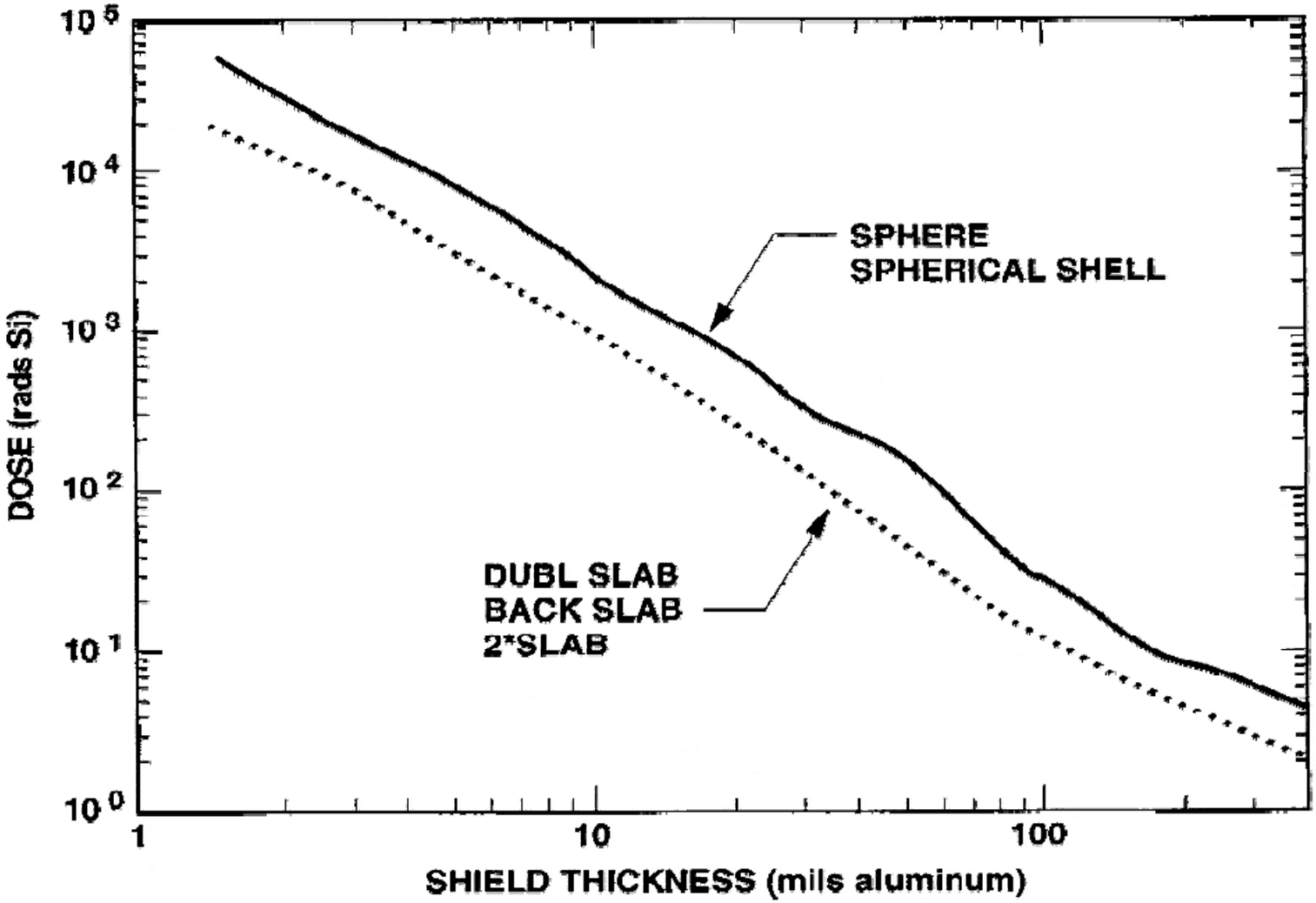
GEOMETRIC EFFECTS ON SHIELDING
RADIATION DOSE FROM TRAPPED PROTONS



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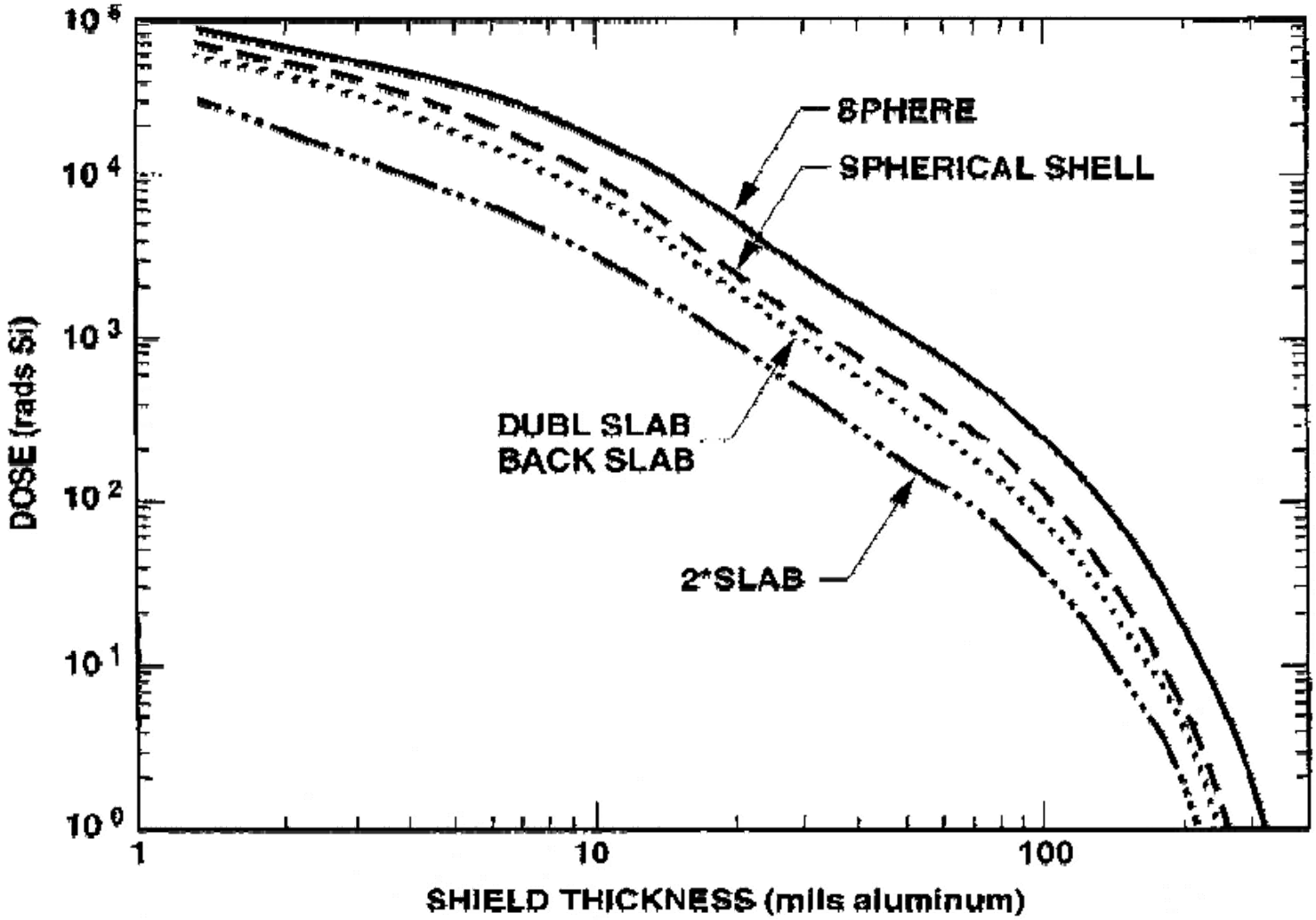
GEOMETRIC EFFECTS ON SHIELDING (Cont'd)
RADIATION DOSE FROM TRAPPED ELECTRONS



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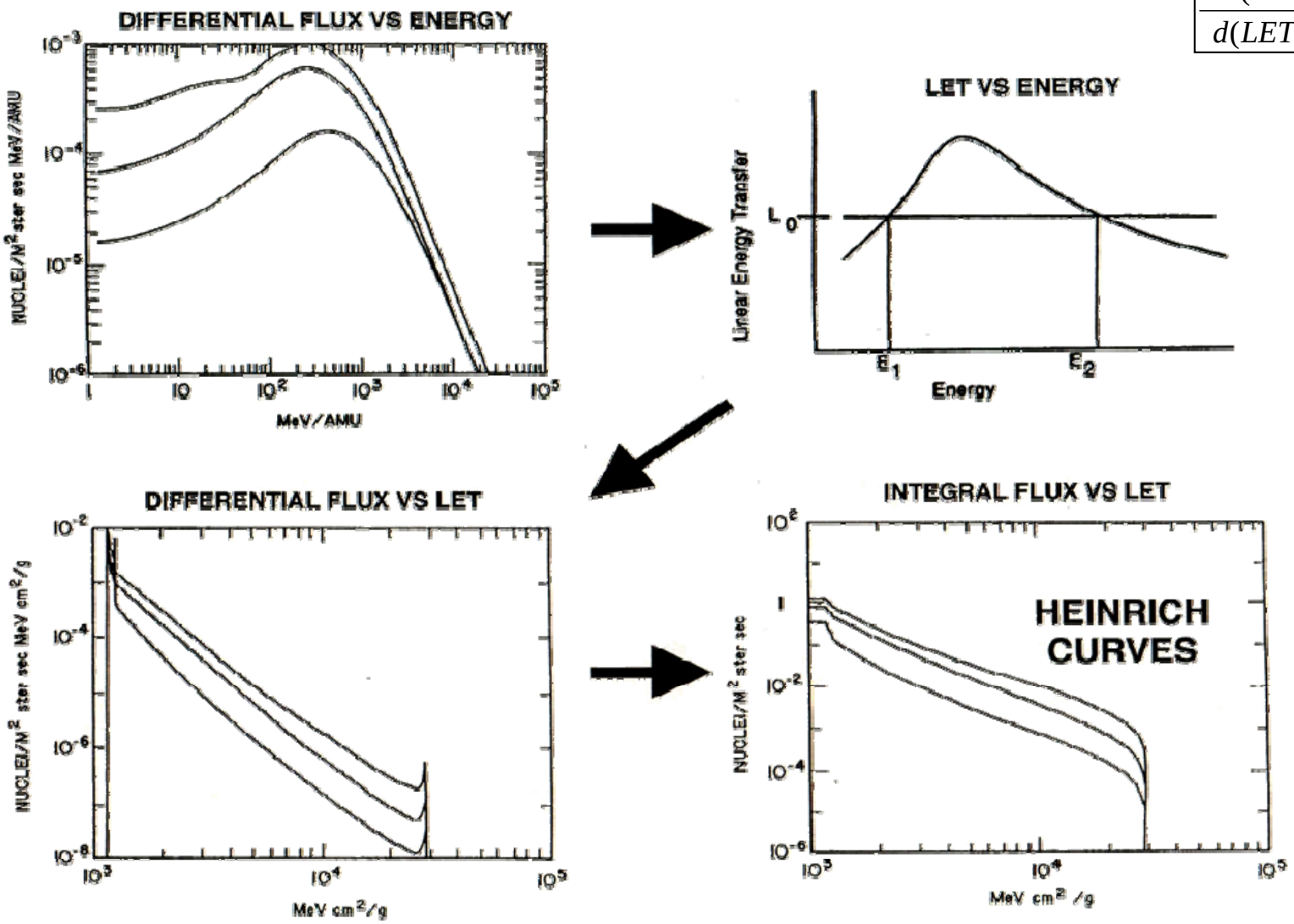
TRANSFORMING DIFFERENTIAL FLUX VS ENERGY TO INTEGRAL FLUX VS LET

$$\frac{dF(LET)}{d(LET)} = \frac{dF(E)}{dE}\frac{dE}{d(LET)}$$



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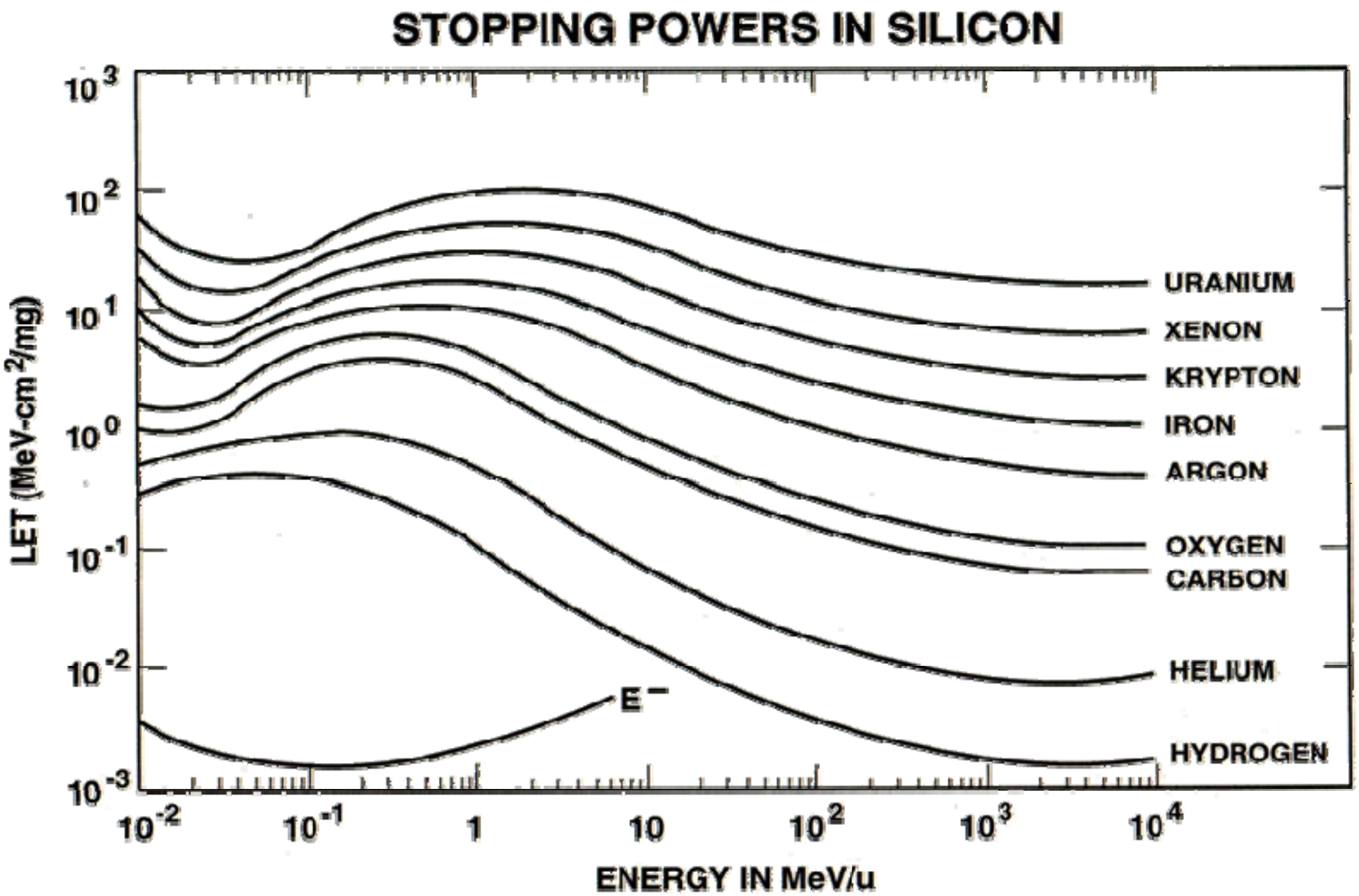
LINEAR ENERGY TRANSFER (Cont'd)
LET FUNCTION



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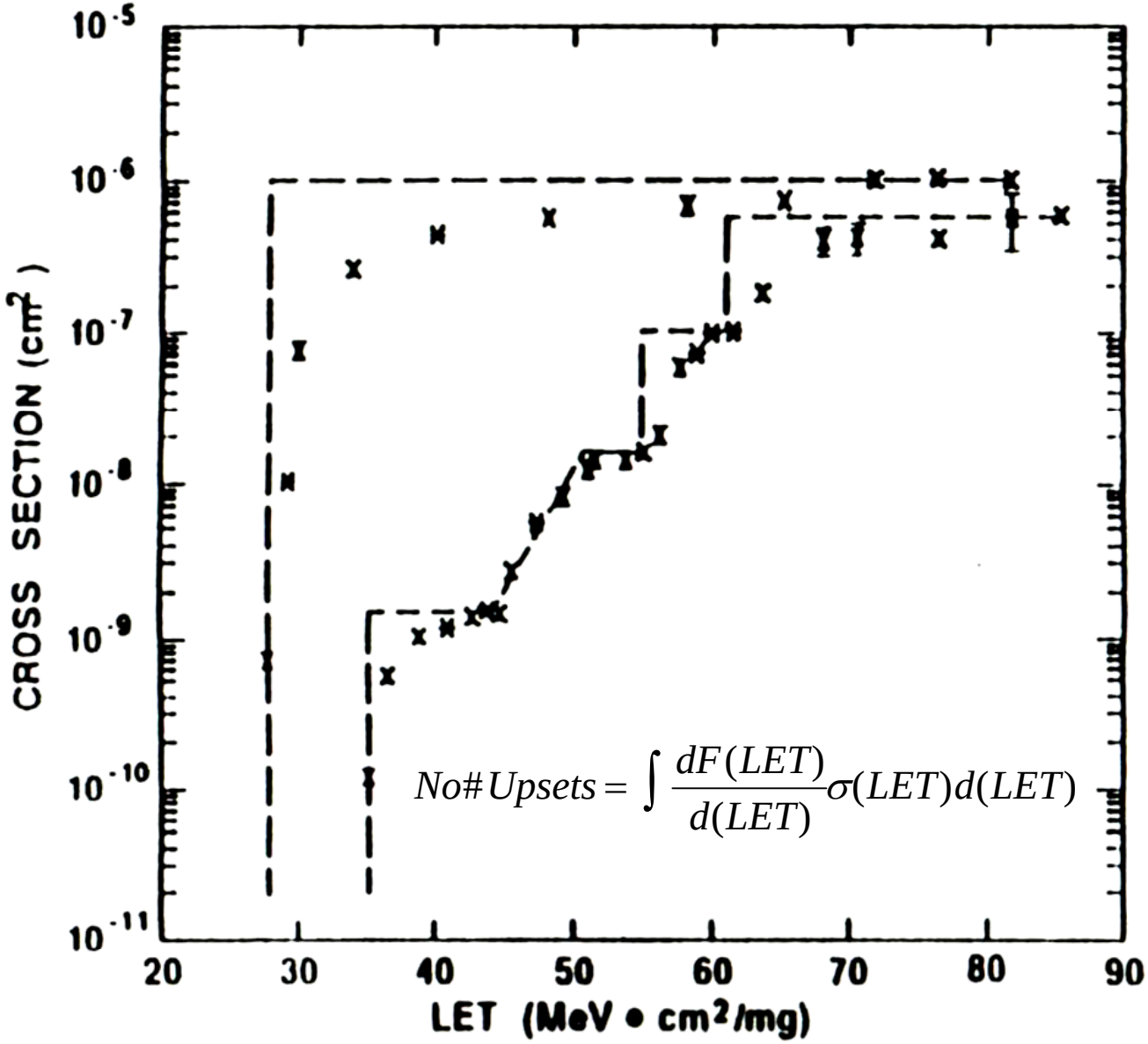
Examples of Single Event Upset Cross Sections



$$No\#Upsets = \int \frac{dF(LET)}{d(LET)} \sigma(LET) d(LET)$$

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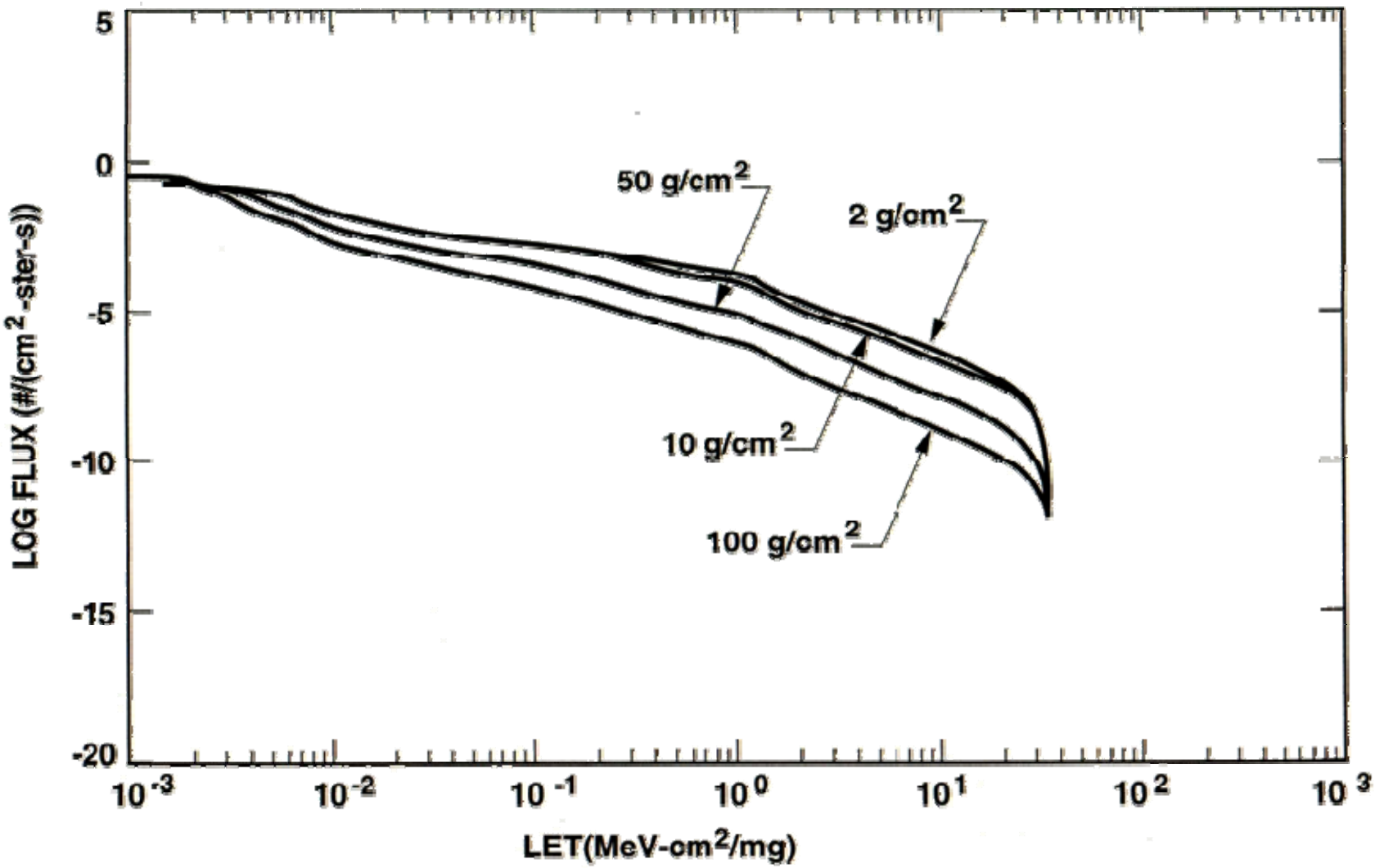
SHIELDING EFFECTS ON THE HEINRICH FLUX

GALACTIC COSMIC RAYS (Z<27)



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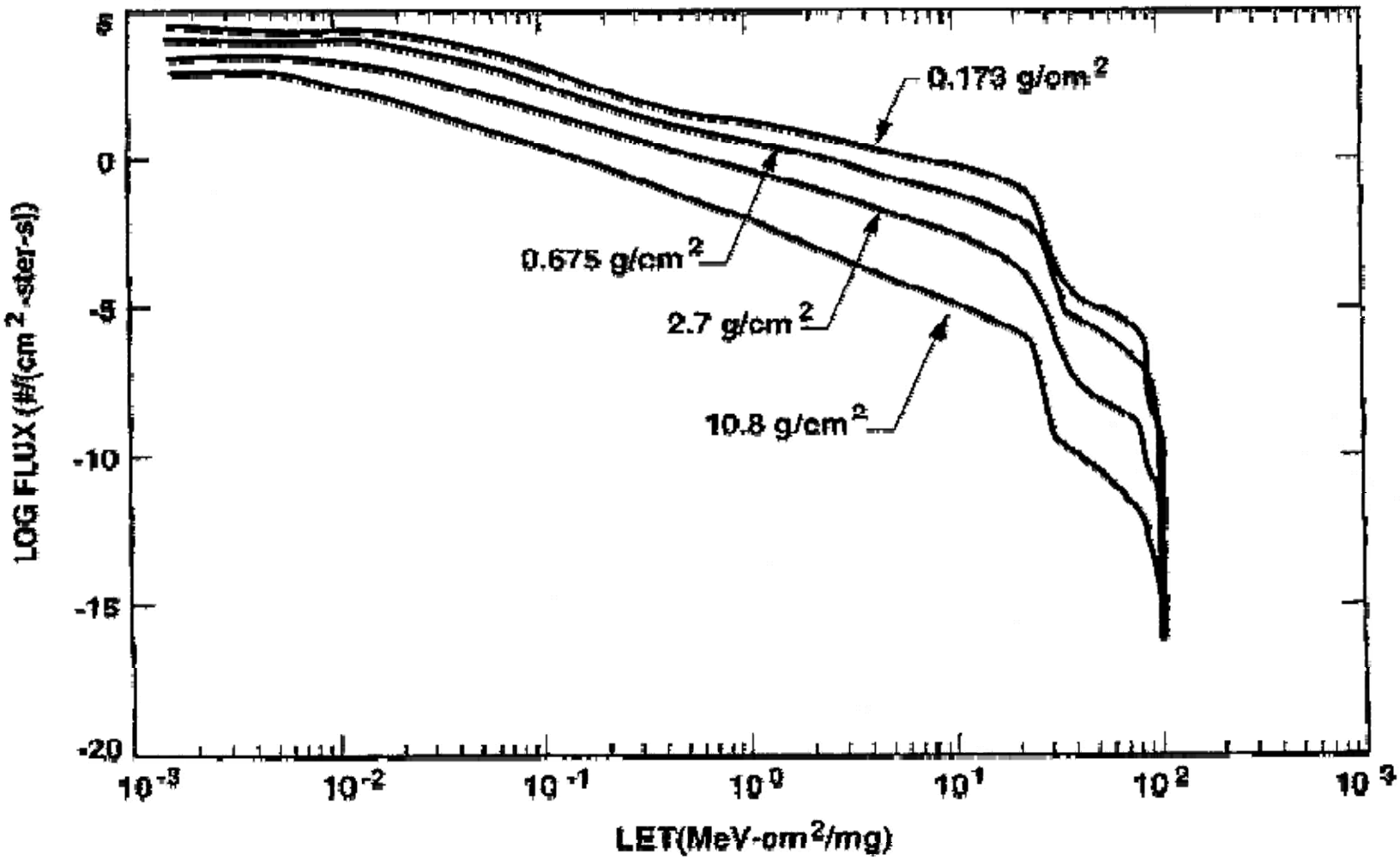
SHIELDING EFFECTS ON THE HEINRICH FLUX (Cont'd)

SOLAR PROTON EVENT



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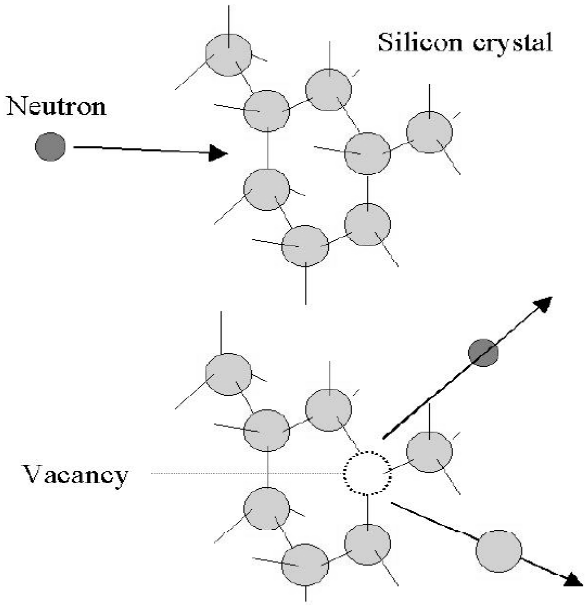
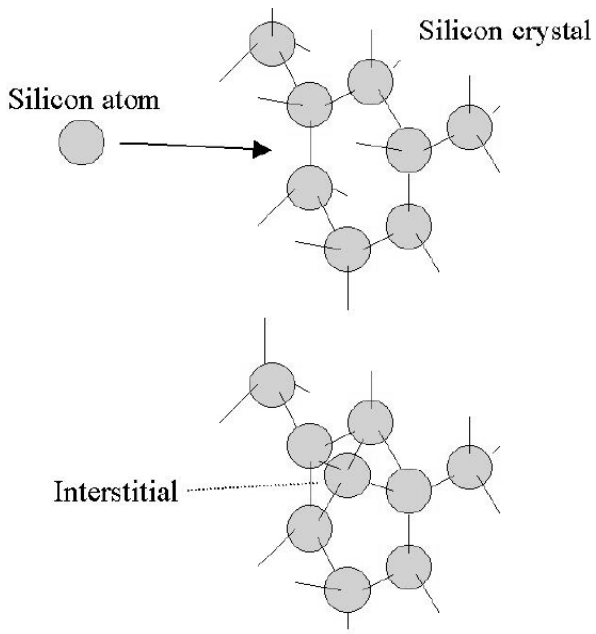
WHAT IS DISPLACEMENT DAMAGE DOSE (DDD)?

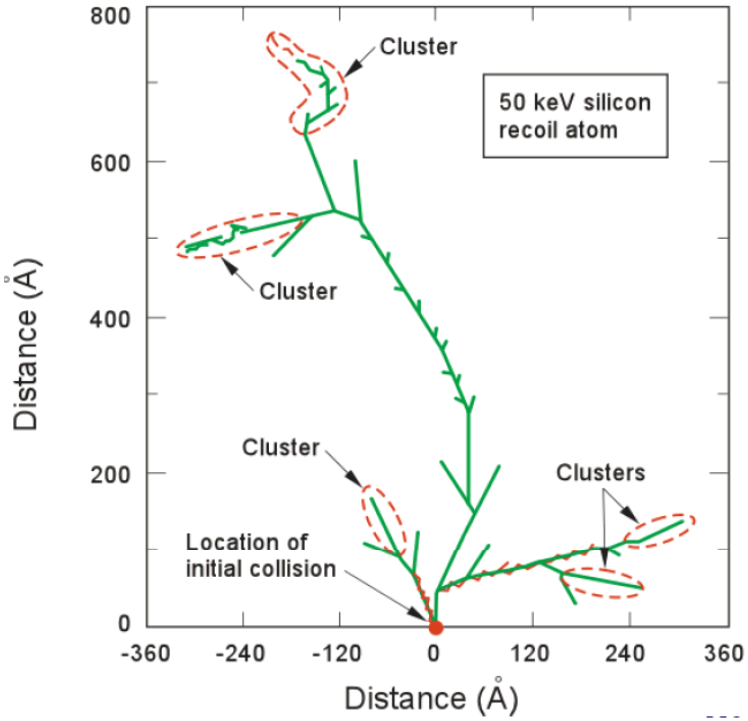
Physical process of DDD: **Displacement => Generates Vacancies => Device Property Degradation**



Displacement Damage (DD) in atomic lattice and vacancy formation due to Silicon displacement.*

Interstitial formation due to Silicon rearrangement after scattering*





Cascade damage in a silicon lattice**

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*PennsylvaniaState University

**G. P. Summers, "Displacement damage: Mechanisms and measurements,"in *IEEE NSREC Short Course, New Orleans, LA, July* 1992

Displacement Damage

- **Basic change in semiconductor lattice caused by scattering collisions**
  - Leads to alteration of electrical and optical properties
  - Minority carrier lifetime, mobility, absorption edge,
  - electro-luminescence, carrier removal
- **Over the years, there has been little concern with displacement damage (NASA only)**
  - Very minor effect in CMOS (carrier removal)
  - Usually less important than ionization for discrete transistors
  - Testing is expensive and only done when necessary
- **Why is displacement damage now important?**
  - Increased use of advanced commercial linear bipolar devices
  - High precision, high performance circuit applications
  - Second order effects are becoming important
  - More use of specialized components
  - High precision voltage references
  - Photonic devices
  - Smaller spacecraft
  - Less shielding
  - Lower design margins
  - Nuclear power sources in close proximity

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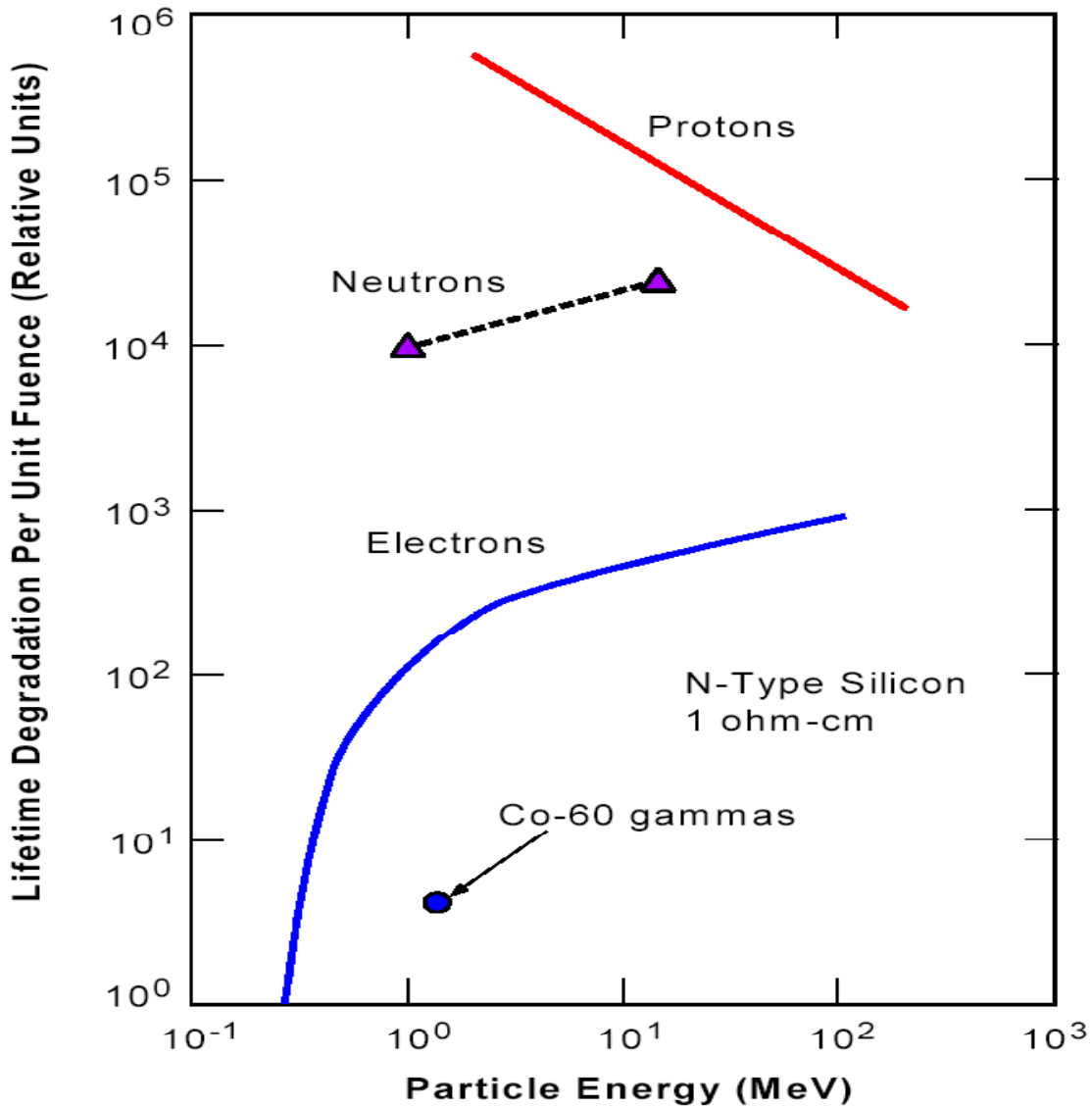
Displacement Damage Effectiveness



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Displacement Damage Concerns

- **Displacement damage effects must be dealt with separately from total dose and corresponding Co-60 testing**
  - Separate requirement for displacement damage often not given
  - People are used to thinking in terms of “dose”, whether its protons, electrons or Co-60 gamma rays that are used for testing
  - Missions with significant proton (and/or neutron) fluences must address displacement damage effects in photonic devices and sensitive linear circuits
- **Displacement damage hardness assurance is difficult because of complicated energy dependence of proton displacement damage**
- **For optocouplers, temperature effects need to be included**
- **Must also consider neutron displacement damage in missions with RTGs or reactors**

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Where to Find LETs and NIELs:

- LETs for electrons, protons, and alphas:
  - The tabulated data are available at http://physics.nist.gov/PhysRefData/Star/Text/contents.html
- LET's for heavier ions:
  - TRIM (http://www.srim.org) can be used to compute heavy ion LETs.
- Tabulated NIEL data for common device materials:
  - For electrons, I. Jun et al., to be presented at NSREC this year
  - For protons, I. Jun et al., IEEE TNS, pp. 1924-1928, December, 2003
  - For alphas, I. Jun et al., IEEE TNS, pp. 3207-3210, December, 2004

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Characteristics of Radiation Effects for Any Future Mission to the Jovian System

Effect	Characteristics
TID	Very high. Dominated by high energy electrons. Will require additional attention.
Dose rate	Can be very high, especially during Io fly-bys or Europa orbits. Will require additional attention.
DDD	Typical level. Could be important for selected devices at Jupiter
SEE	Typical level. Trapped heavy ions at Jupiter are not expected to be a design driver.
Charging	Internal charging is a major issue due to high energy electrons if not properly designed. Will require additional attention.
Transient or Secondary radiation	Important design consideration for sensors and detectors. Must include secondary particles from high energy electron interactions with materials.

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