National Aeronautics and Space Administration
Jet Propulsion Laboratory
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Space Weather Impacts on Spacecraft and Mitigation Strategies

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Outline

- **INTRODUCTION**
  - OUTLINE
  - WHY DO WE CARE?
  - PROCESS OVERVIEW
- **SPACE WEATHER IMPACTS**
  - SPACECRAFT CHARGING
  - PLASMA INTERACTIONS
  - INTERNAL ELECTROSTATIC DISCHARGE
  - RADIATION INTERACTIONS
- **SUMMARY**
  - CONCLUSION
  - REFERENCS

Introduction

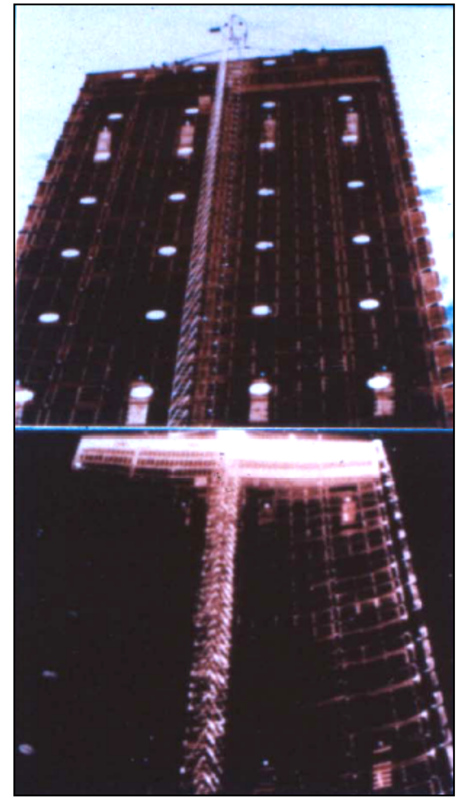
"An Ounce of Prevention Is Worth a Kilogram of Cure"

BACKGROUND

Spacecraft are growing in complexity and sensitivity to environmental effects. The spacecraft engineer must understand and take these effects into account in building reliable, survivable, and affordable spacecraft. Too much protections, however, means unnecessary expense while too little will potentially lead to early mission loss. The ability to balance cost and risk necessitates an understanding of how the environment impacts the spacecraft and is a critical factor in its design. This course is intended to address both the space environment and its effects with the intent of providing practical means for mitigating or at least limiting the worst aspects of spacecraft environment interactions.

Space Environment Interactions
WHY DO WE CARE?

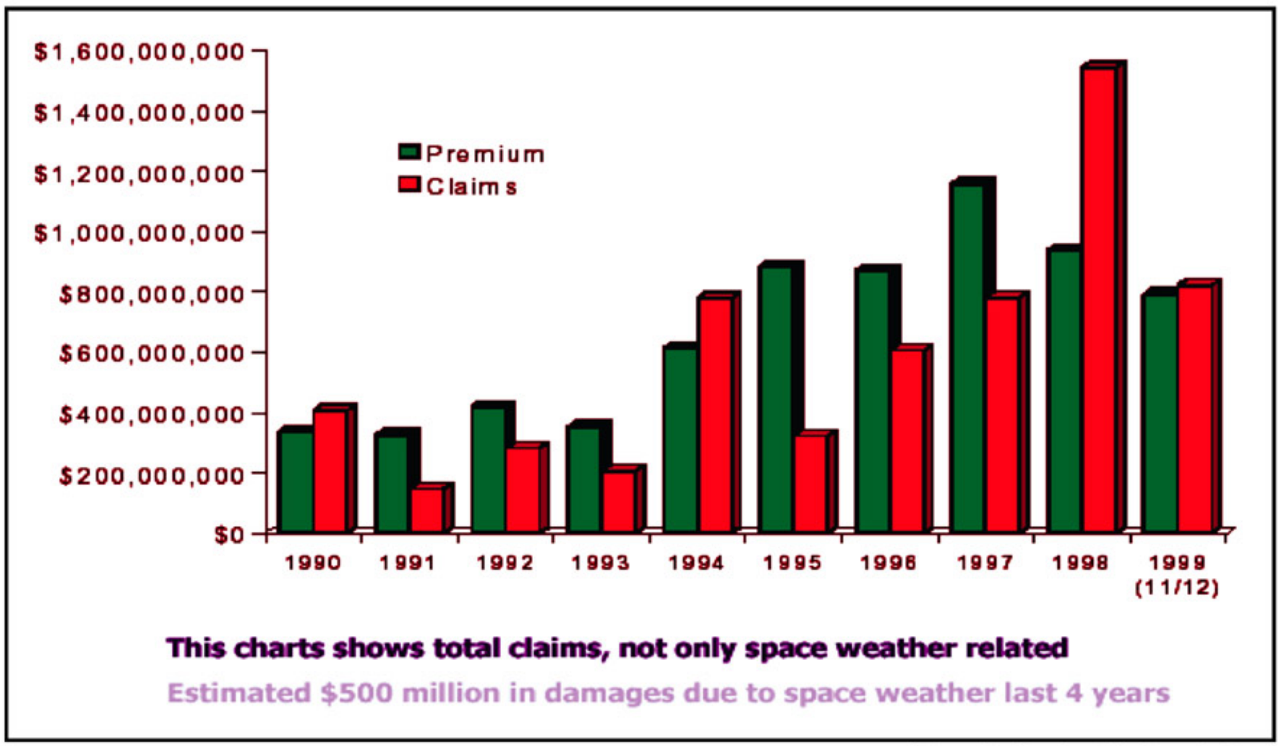
- The Space Environment impacts everything from spacecraft operations to the Earth's power grid
- Spacecraft loss or damage is very expensive, particularly with growing reliance of many Earth-based functions on space systems
- Although the Space Environment and its interactions have been studied since the dawn of the space age, there are still many unknowns
- With careful design, many space interactions problems can be limited at a relatively low cost



Thermal Effects on ISS Solar Array Prototype

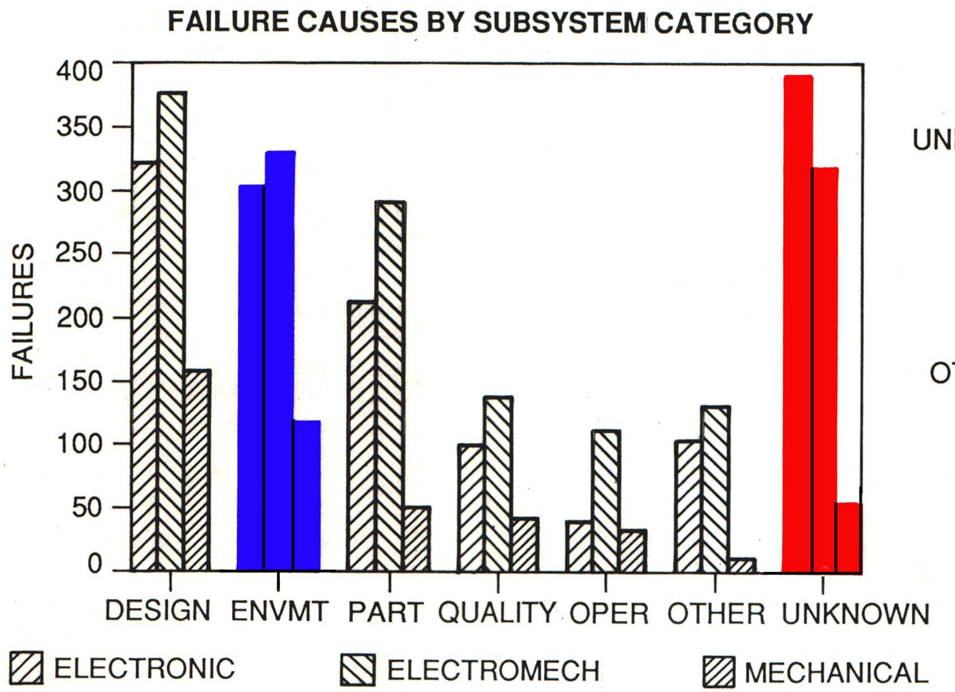
Impact of Space Weather on Spacecraft Costs

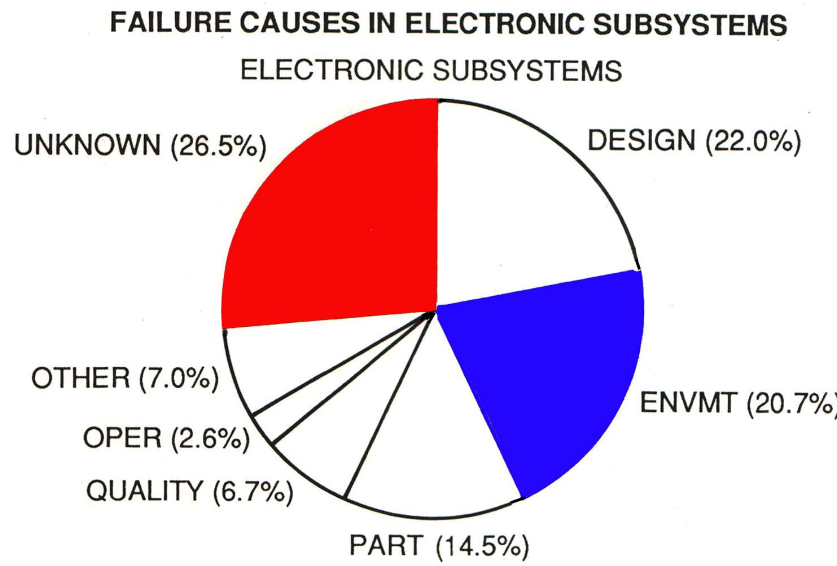
- The 600 satellites currently in orbit are worth $50-100 billion with 235 insured for $20 billion
- 1500 space payloads are expected to be launched in the next 10 years with a potential insured value of $80 billion!



After E. Daly, Alpbach Summer School

Subsystem In-flight Failure Causes (Hecht, 1985)





Impact of the Space Environment on Space Systems+

Distribution by Anomaly Diagnosis

Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	**162**
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	**85**
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	**16**
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	**36**

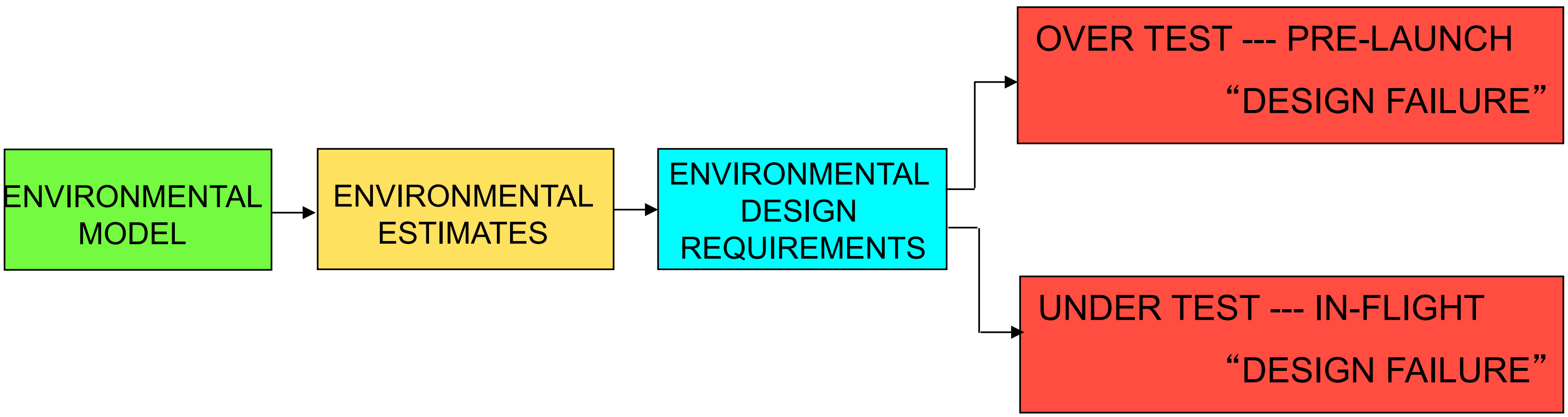
+Koons, H.C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The Impact of the Space Environment on Space Systems", presented at Charging Conference, Nov 1998.

Missions Lost/Terminated Due to Space Environment

Vehicle	Date	Diagnosis
DSCS II (9431)	Feb 73	Surface ESD
GOES 4	Nov 82	Surface ESD
DSP Flight 7	Jan 85	Surface ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	Surface ESD
MSTI	Jan 93	Single Event Effect
Hipparcos*	Aug 93	Total Radiation Dose
Olympus	Aug 93	Micrometeoroid Impact
SEDS 2*	Mar 94	Micrometeoroid Impact
MSTI 2	Mar 94	Micrometeoroid Impact
IRON 9906	1997	Single Event Effect
INSAT 2D	Oct 97	Surface ESD

*Mission had been completed prior to termination

Impact Of Space Environment and Testing On Spacecraft Failures



An Integrated Process

Integrated Approach to Environment Mitigation

STEP 1
ENVIRONMENTS VS INTERACTIONS

INTERACTIONS

ENVIRONMENTS	CUMMULATIVE RAD EFFECTS	SINGLE EVENT UPSETS	LATCH-UP	SURFACE CHARGING/WAKES	INTERNAL CHARGING	POWER LOSS	VxB	SURFACE DAMAGE	CONTAMINATION	GLOW	PARTICLE IMPACTS	TORQUES	THERMAL
NEUTRAL ATMOSPHERE													
E,B FIELDS				ES			e					E	
ULTRAVIOLET RADIATION				S				S	S				
INFRARED RADIATION								S					S
SOLAR WIND PLASMA				s								s	
IONOSPHERIC PLASMA				S		e	e						
AURORA PLASMA				E									
TRAPPED RADIATION	E	Ep	E		E								
GALACTIC COSMIC RAY		P	p										
SOLAR PROTON EVENTS	Sp	Sp	Sp										
METEOROIDS						s					SEP	S	
DEBRIS											s		

Legend: X = Major Effect; x = Observable Effect; E,e = Europa; P,p = Pluto Express; S,s = Solar Probe

STEP 2
INTERACTIONS VS DESIGN OPTIONS

DESIGN OPTIONS

INTERACTIONS	SHIELDING	POSTIONING	MATERIAL PROPERTIES	ELECTRONIC PARTS	CIRCUIT/SYSTEM DESIGN	GROUNDING	TRAJECTORY	OPERATIONAL PROCEDURES	CONSTRUCTION METHODS
CUMMULATIVE RAD EFFECTS	3	3	2	3	3		3	1	
SINGLE EVENT UPSETS	2	1		3	3		2	2	
LATCH-UP	2	1		3	3		2	2	
SURFACE CHARGING/WAKES	3	3	3	1	3	3	3	2	3
INTERNAL CHARGING	3	2	3	2	3	3	3	2	3
POWER LOSS	3	3	3						1
VxB		3				3	2		
SURFACE DAMAGE		3	3						1
CONTAMINATION	3	3	3			2		2	3
GLOW		3					2	3	1
PARTICLE IMPACTS	3	3	2				3		
TORQUES		3	3				2	3	
THERMAL	3	3	3				1	3	

STEP 3
DESIGN OPTIONS VS FACTORS

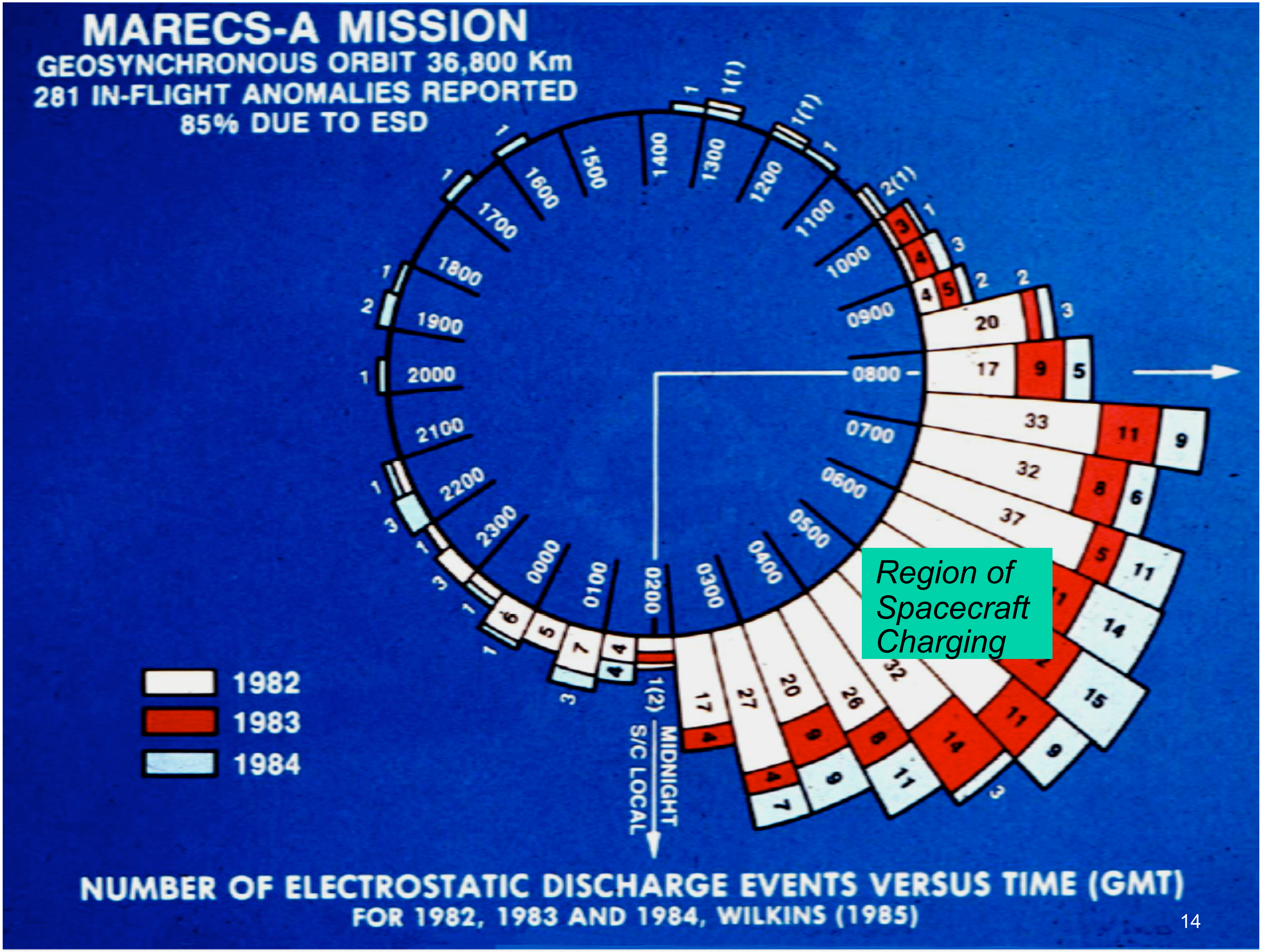
FACTORS

DESIGN OPTIONS	COST	WEIGHT	POWER	COMPLEXITY	RELIABILITY	AVAILABILITY	USABILITY	SPECIAL ISSUES (RPS)
SHIELDING	3	3	2	3	3		3	3
POSTIONING	2	1	1	3	1	2	3	3
MATERIAL PROPERTIES	3	2		2	2	3	1	3
ELECTRONIC PARTS	2			2	3	2	3	
CIRCUIT/SYSTEM DESIGN	3	2	3	3	3	2		3
GROUNDING	2		2	3	2		2	
TRAJECTORY	1		2	2	2			3
OPERATIONAL PROCEDURES	3		1	2	2		3	3
CONSTRUCTION METHODS	1		2	3	2		1	2

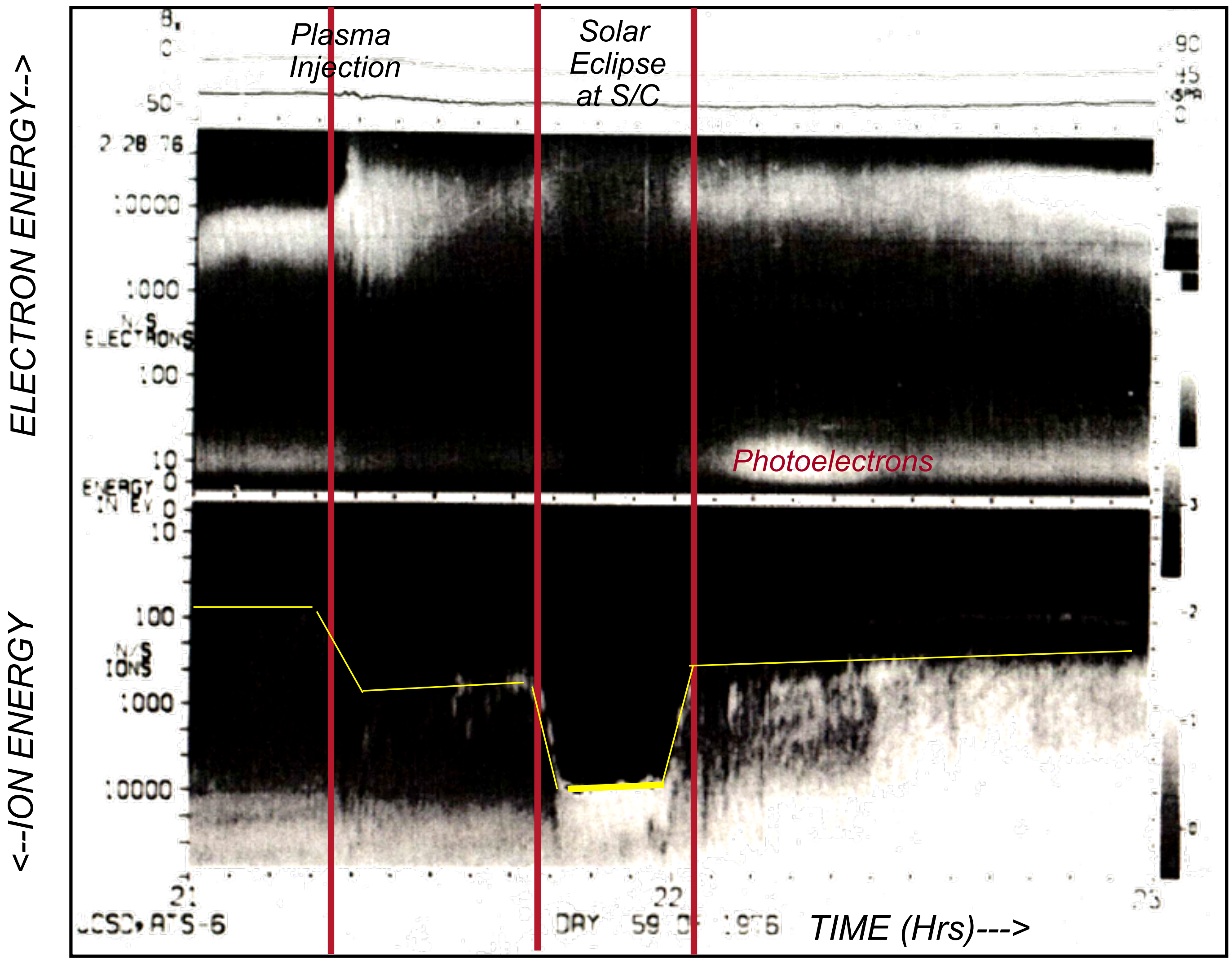
Legend: 3 = Major Effect; 2 = Observable Effect; 1 = Minor Effect

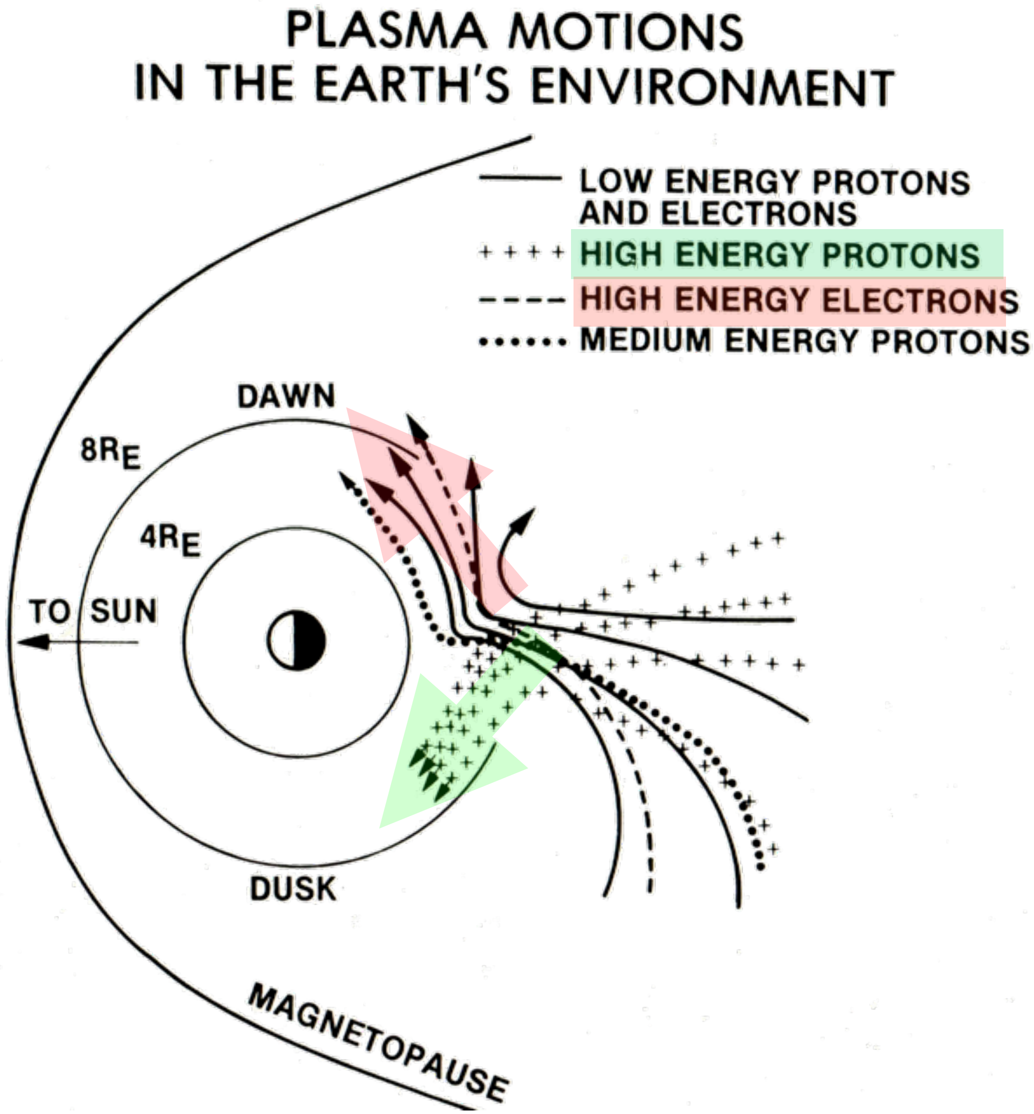
Space Weather Impacts

Spacecraft Charging

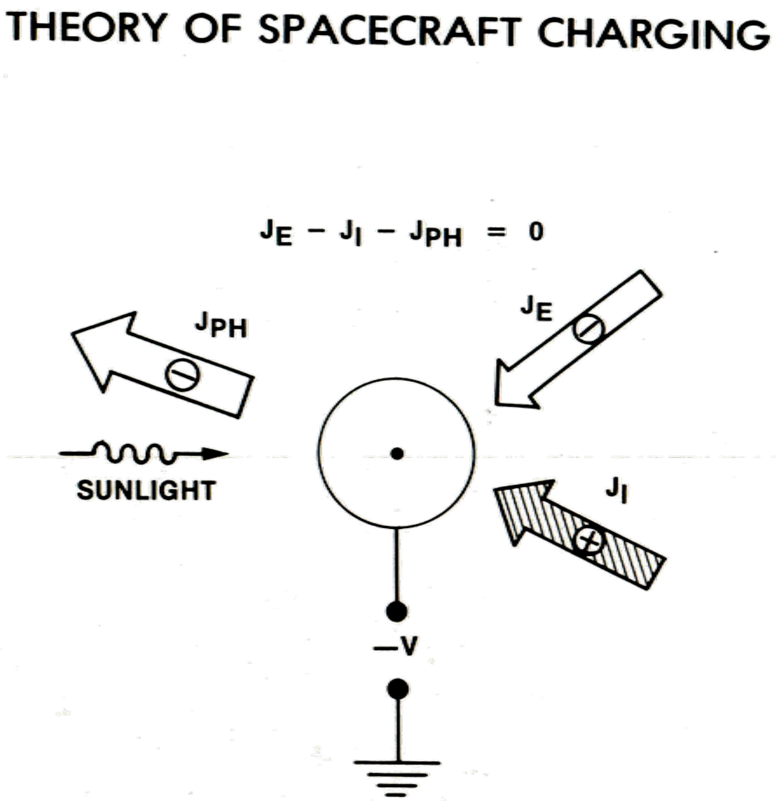

MARECS-A MISSION
GEOSYNCHRONOUS ORBIT 36,800 Km
281 IN-FLIGHT ANOMALIES REPORTED
85% DUE TO ESD
Region of Spacecraft Charging
MIDNIGHT S/C LOCAL
1982
1983
1984
NUMBER OF ELECTROSTATIC DISCHARGE EVENTS VERSUS TIME (GMT)
FOR 1982, 1983 AND 1984, WILKINS (1985)

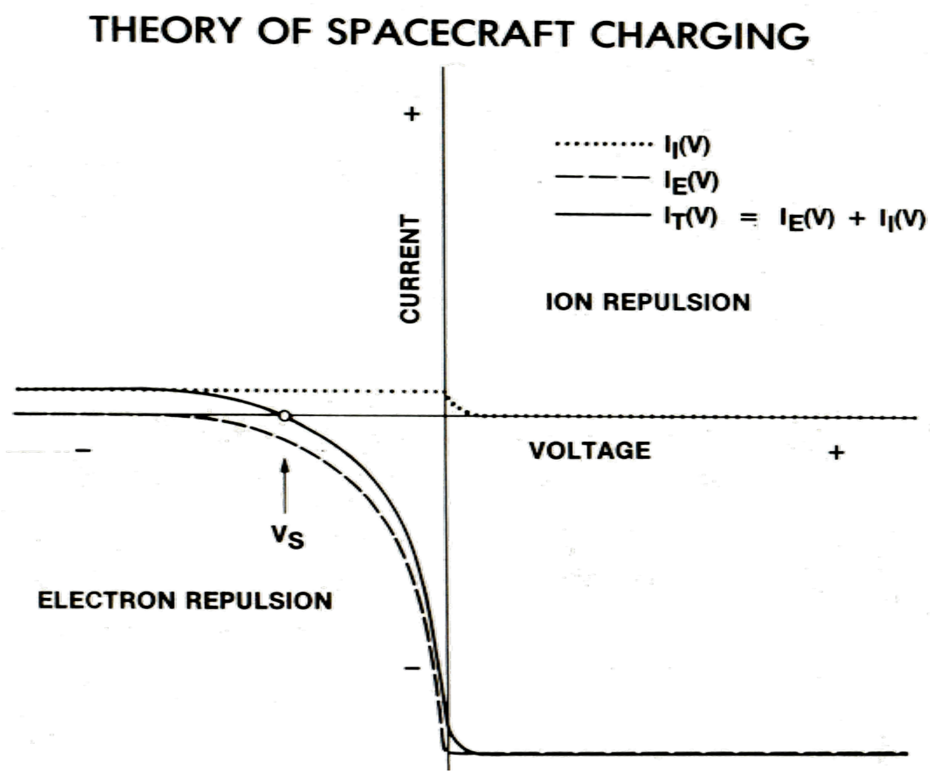
ATS-6 Spectrogram of Geosynchronous Charging




PLASMA MOTIONS
IN THE EARTH'S ENVIRONMENT
LOW ENERGY PROTONS AND ELECTRONS
HIGH ENERGY PROTONS
HIGH ENERGY ELECTRONS
MEDIUM ENERGY PROTONS
DAWN
8RE
4RE
TO SUN
DUSK
MAGNETOPAUSE

Theory of Spacecraft Charging: A Simple Picture …





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:

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

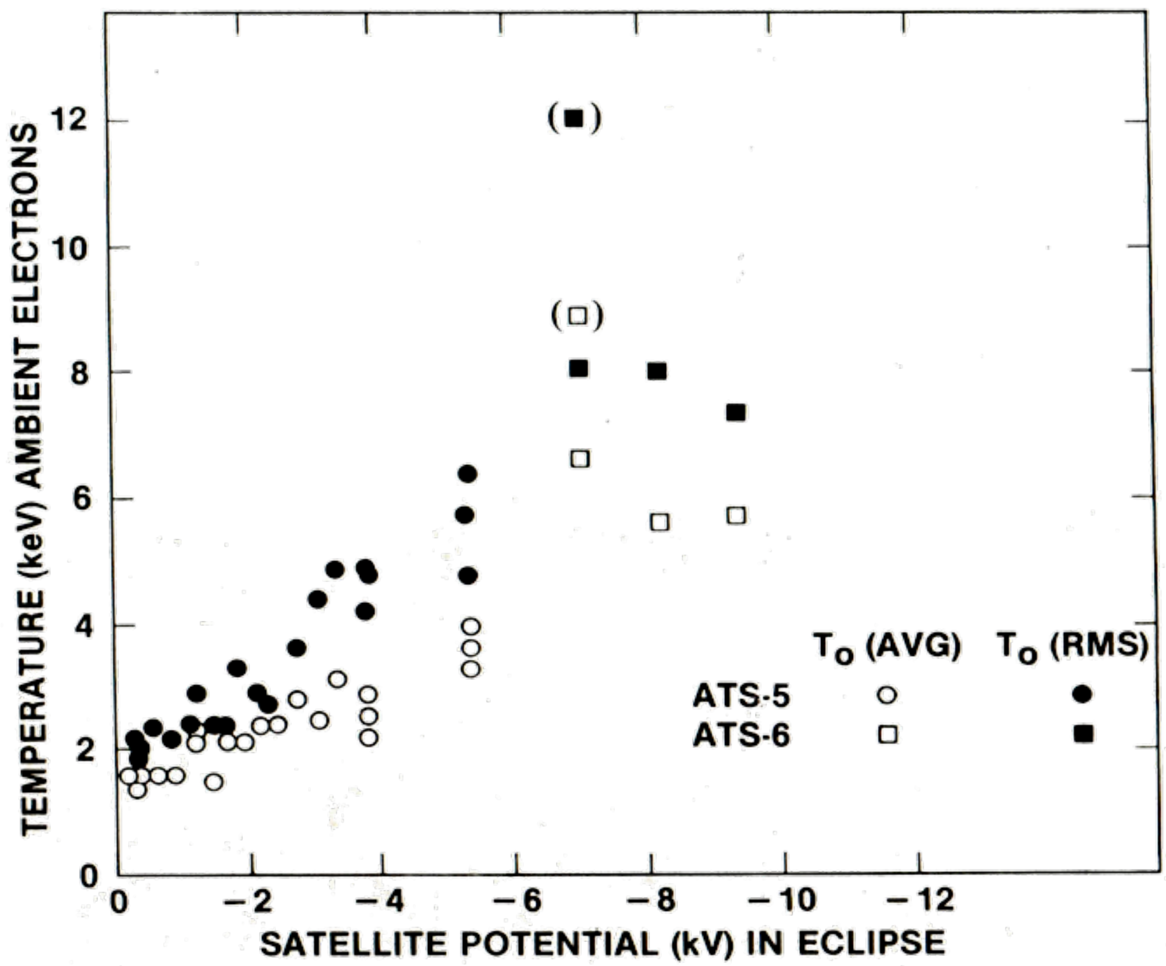
FOR CURRENT BALANCE:

$$J_T(V) = 0$$

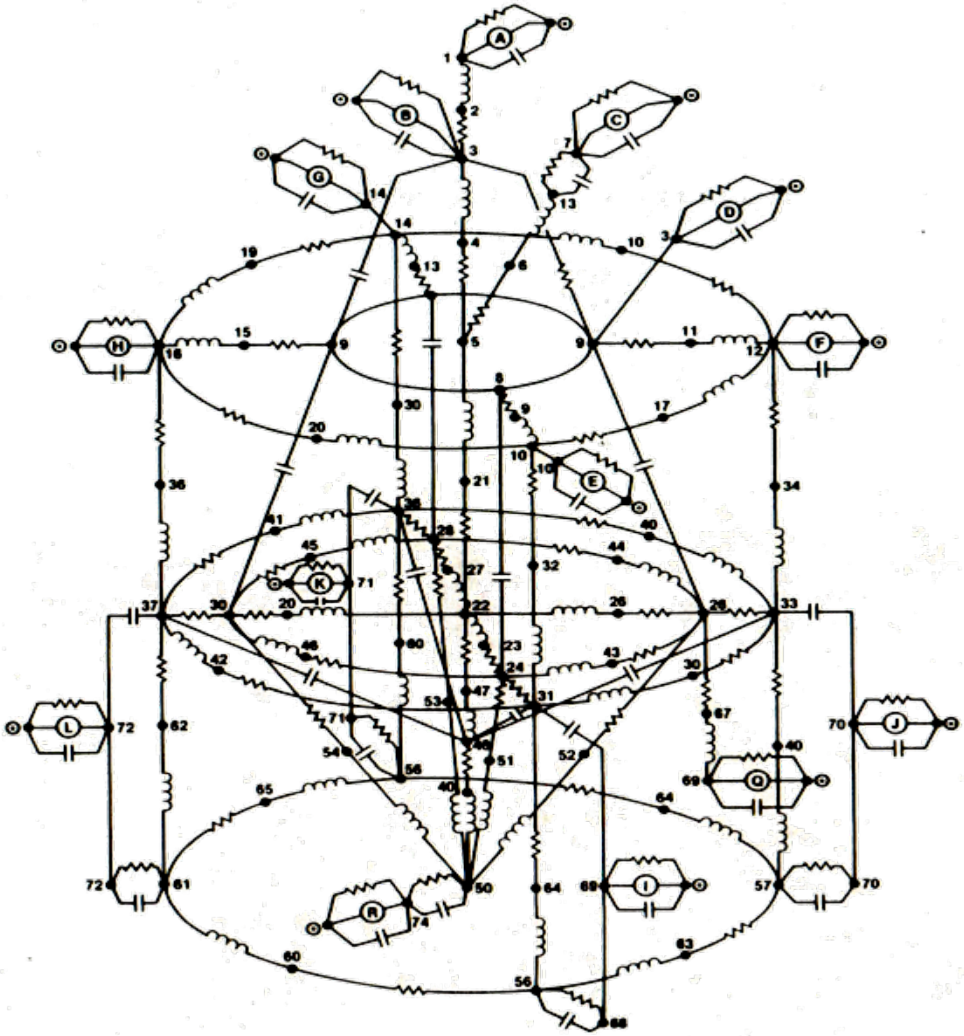
THIS IMPLIES:

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

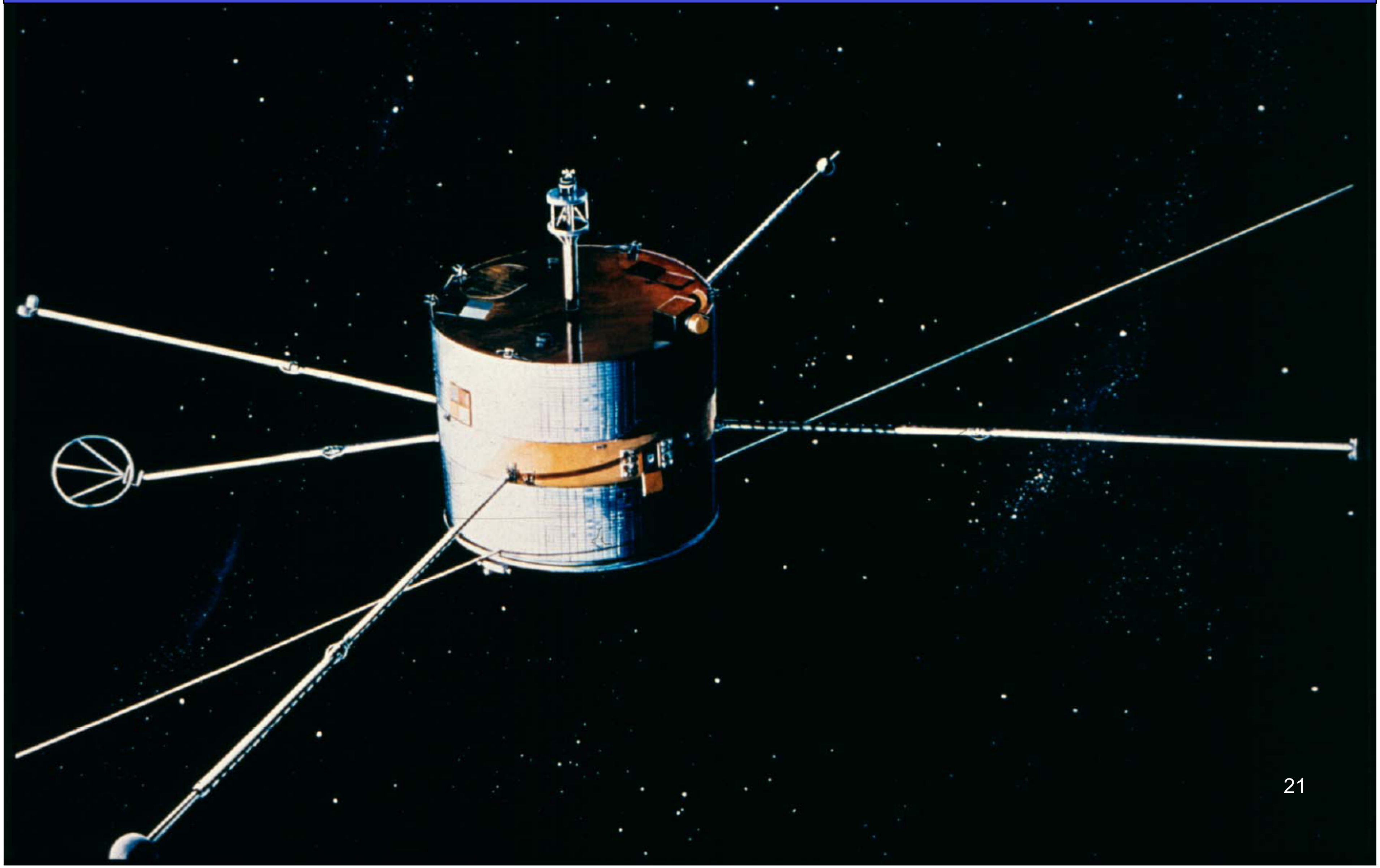
Spacecraft Charging Observations: Plasma Temperature vs Potential



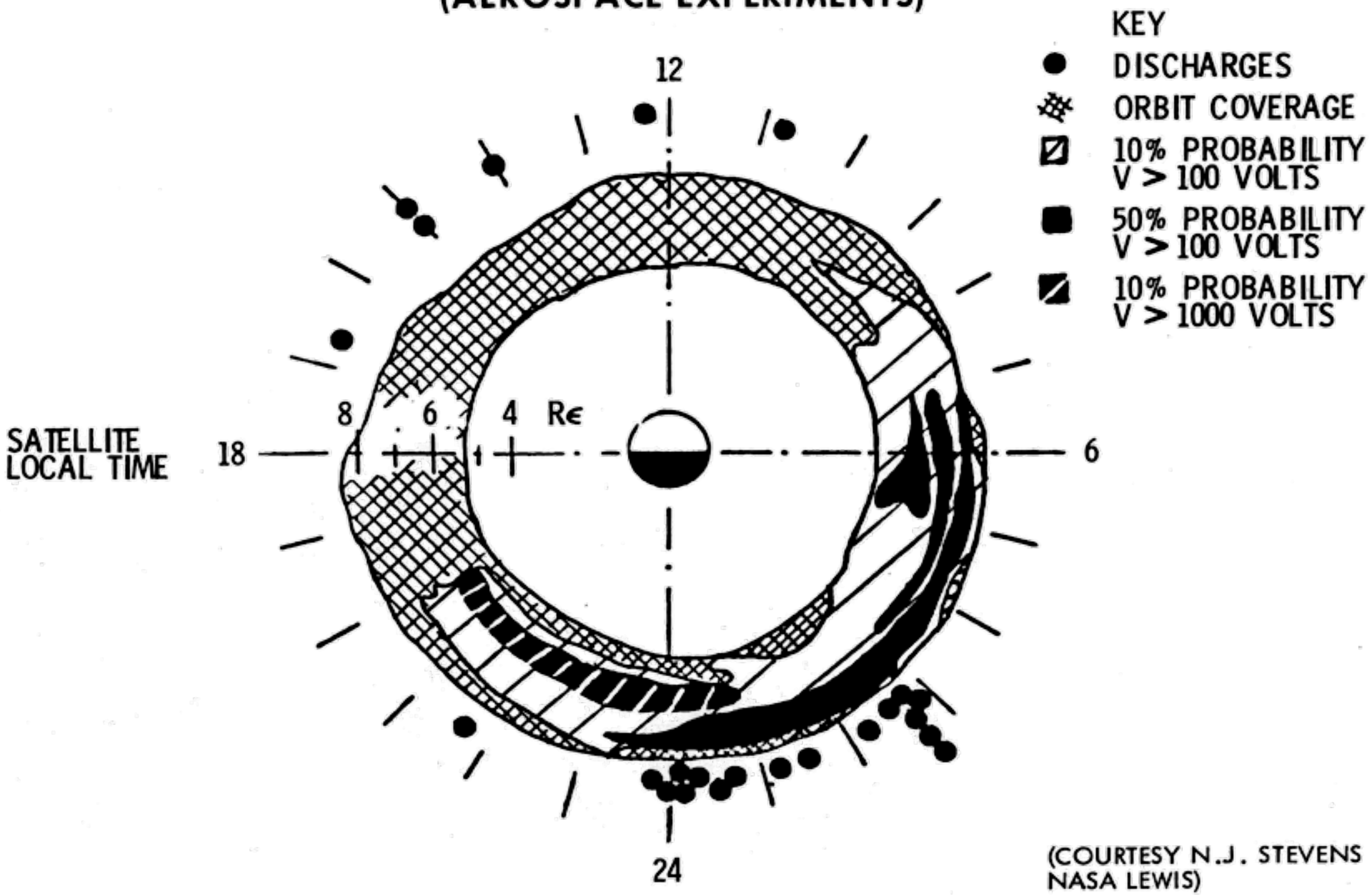
FINITE ELEMENT MODEL OF PIONEER-VENUS SPACECRAFT



A Charging Milestone: The P78-2 SCATHA Mission

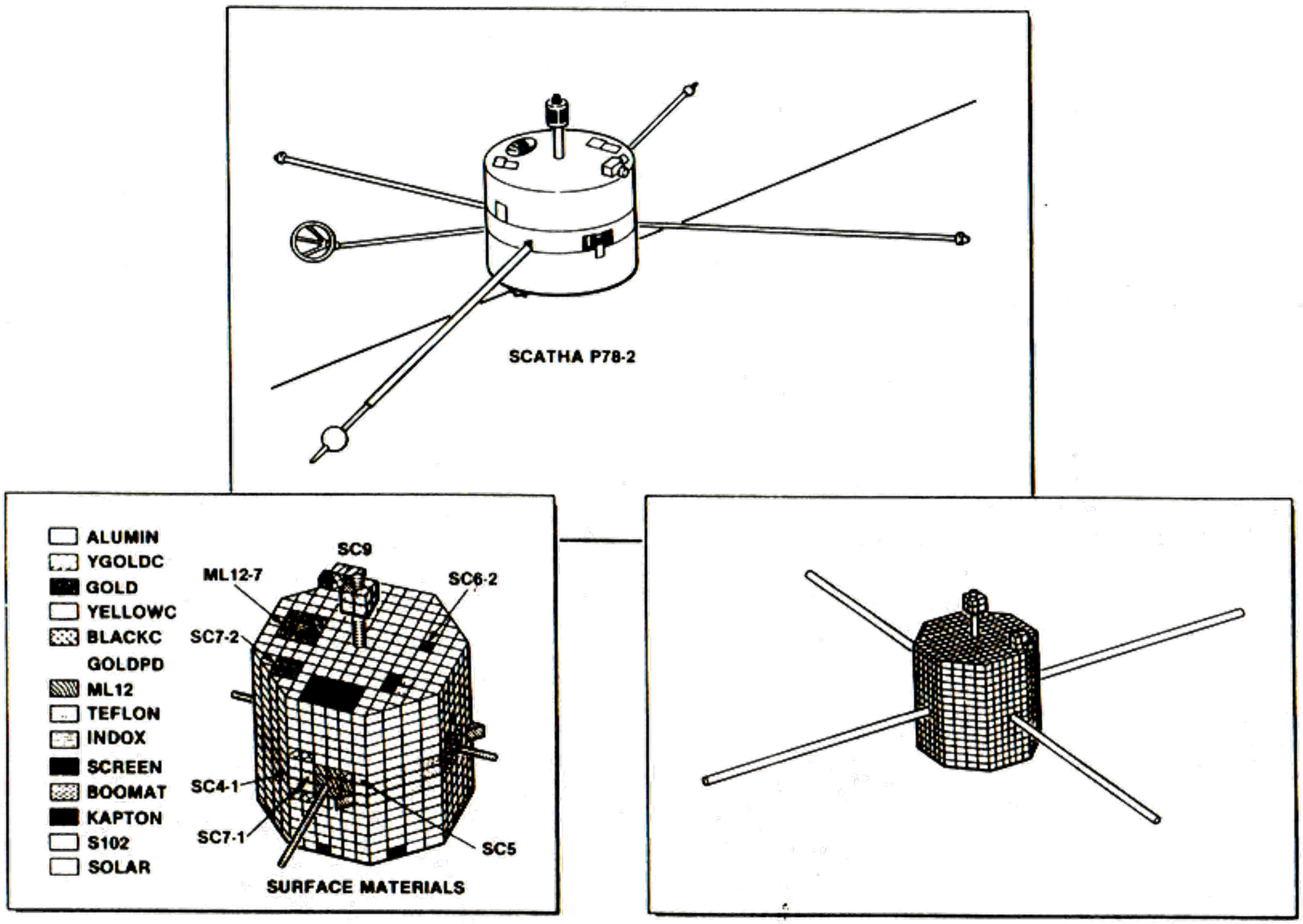


SUMMARY OF SCATHA CHARGING/DISCHARGING DATA (AEROSPACE EXPERIMENTS)



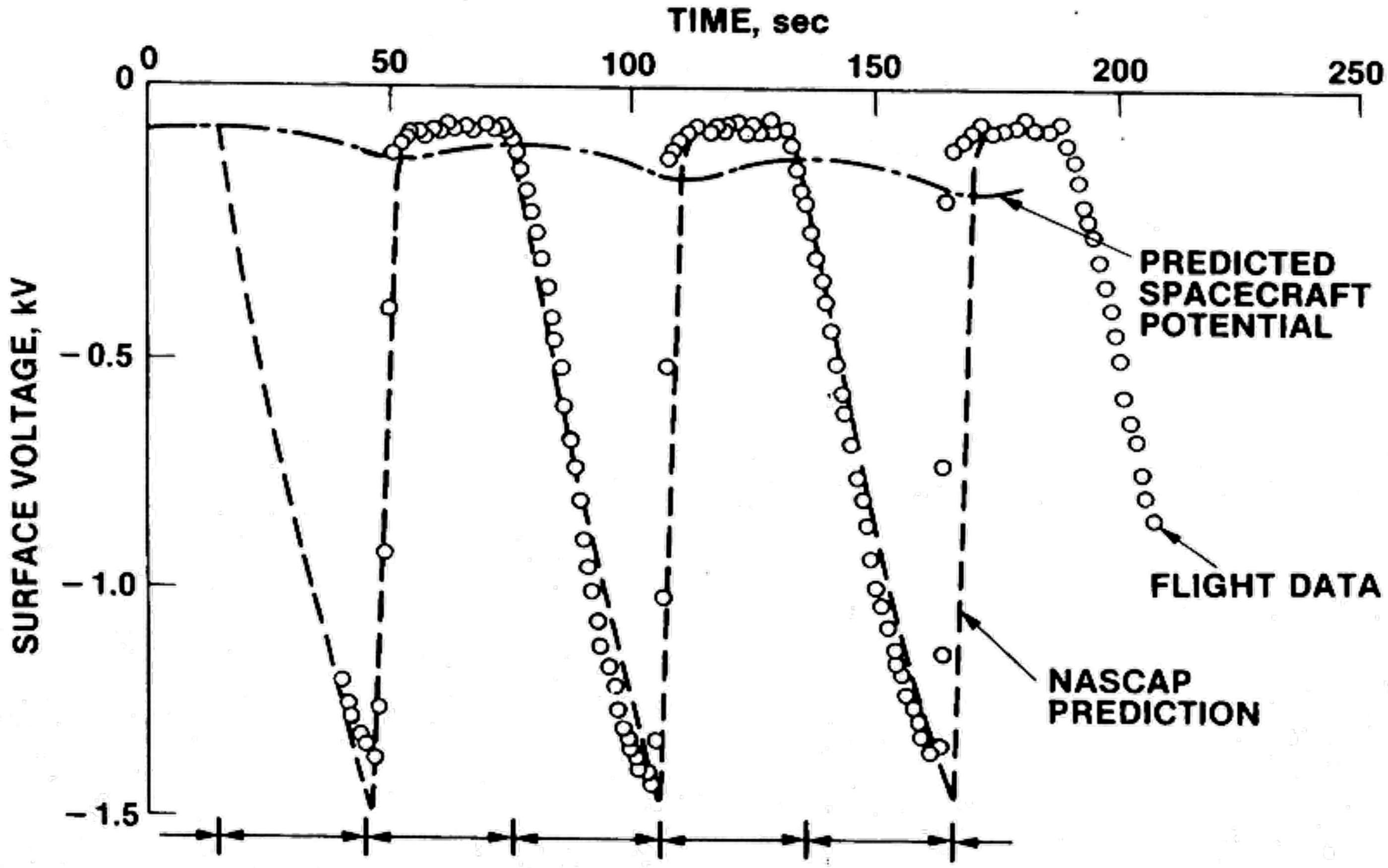
(COURTESY N.J. STEVENS NASA LEWIS)

THE "NASCAP" SPACECRAFT CHARGING CODE

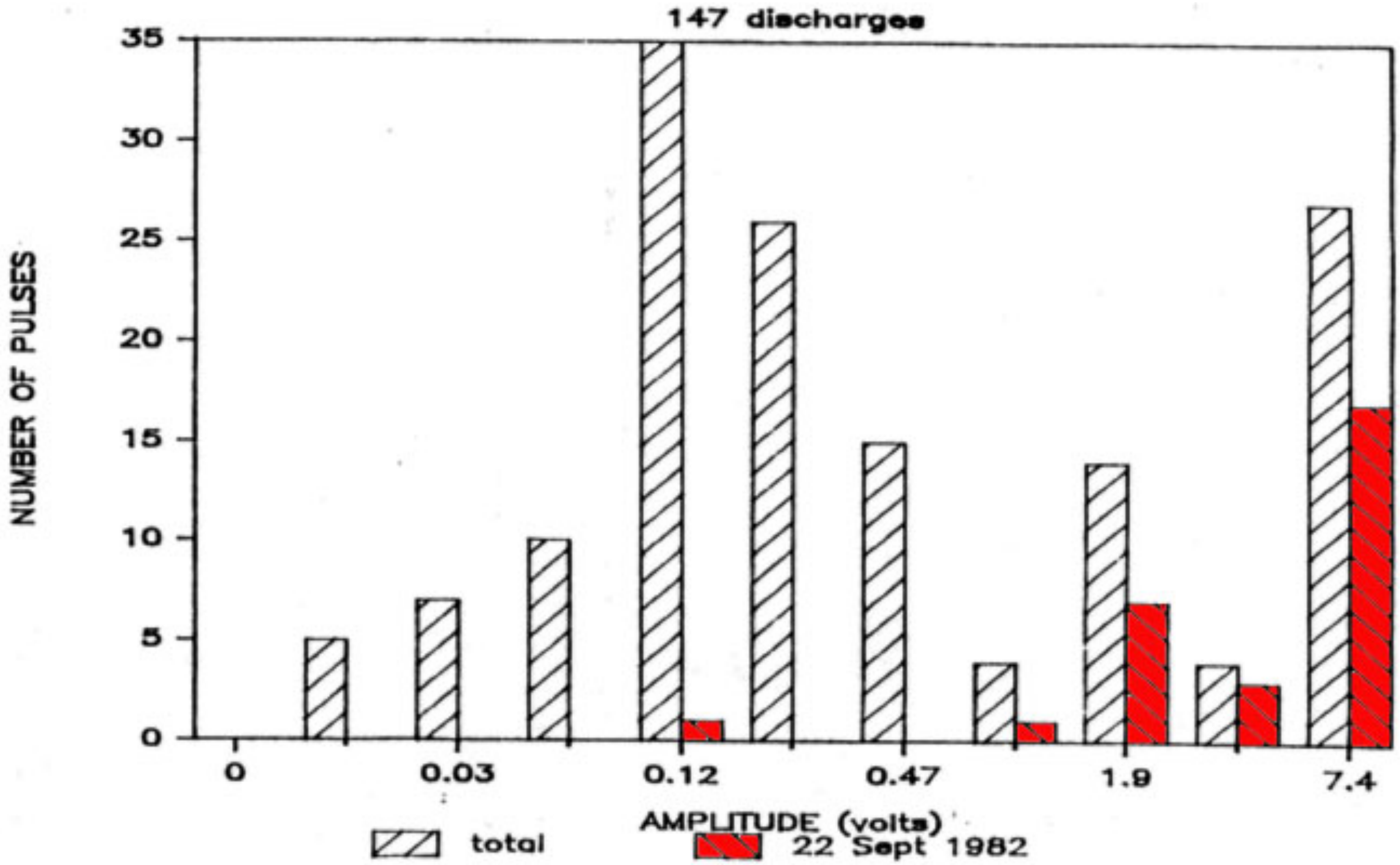


NASCAP MODELS

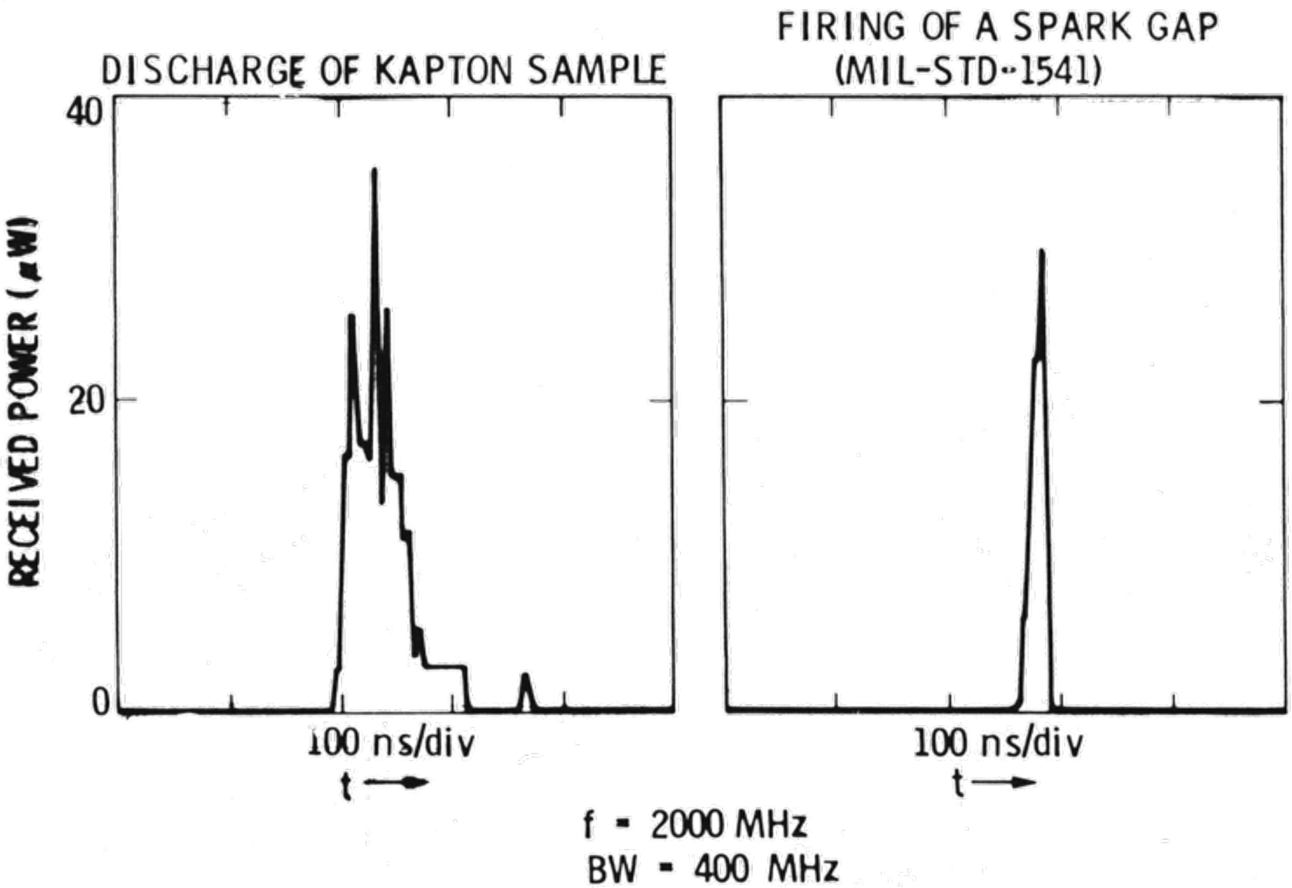
SCATHA KAPTON POTENTIALS VERSUS NASCAP PREDICTIONS



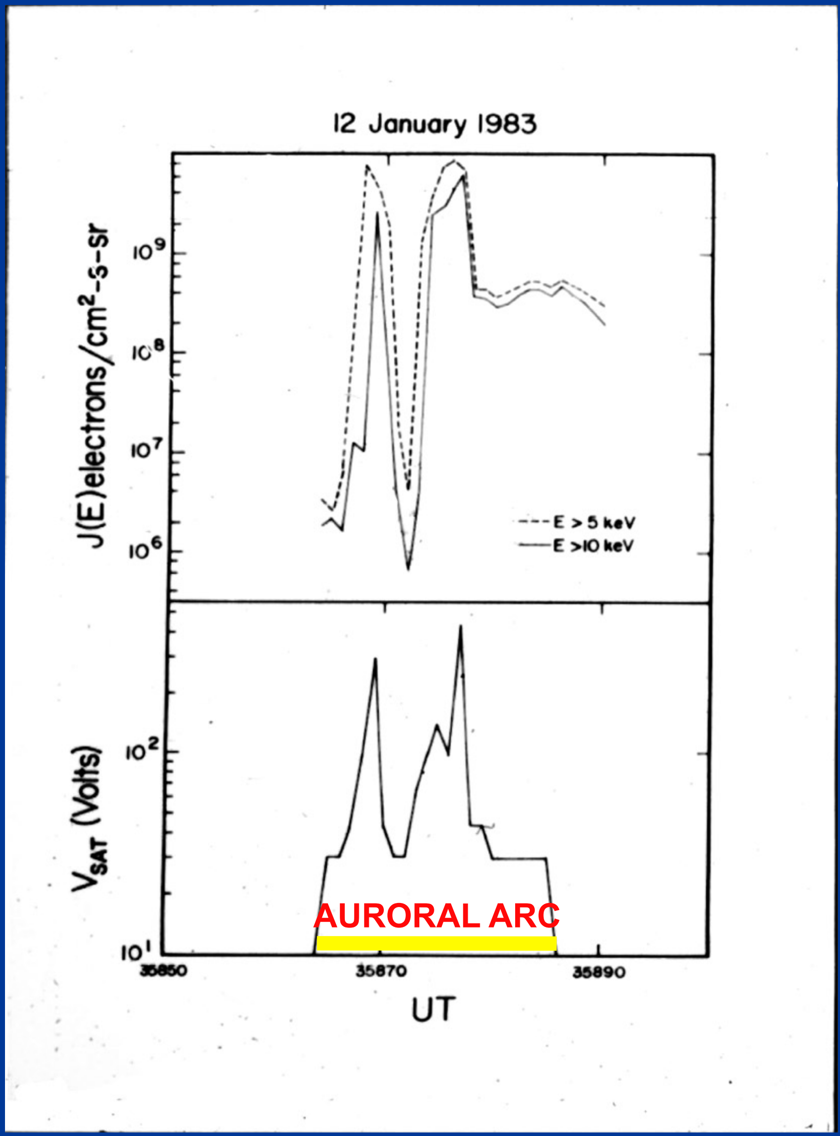
SCATHA Arc Discharge Pulses For 1979 To 1982

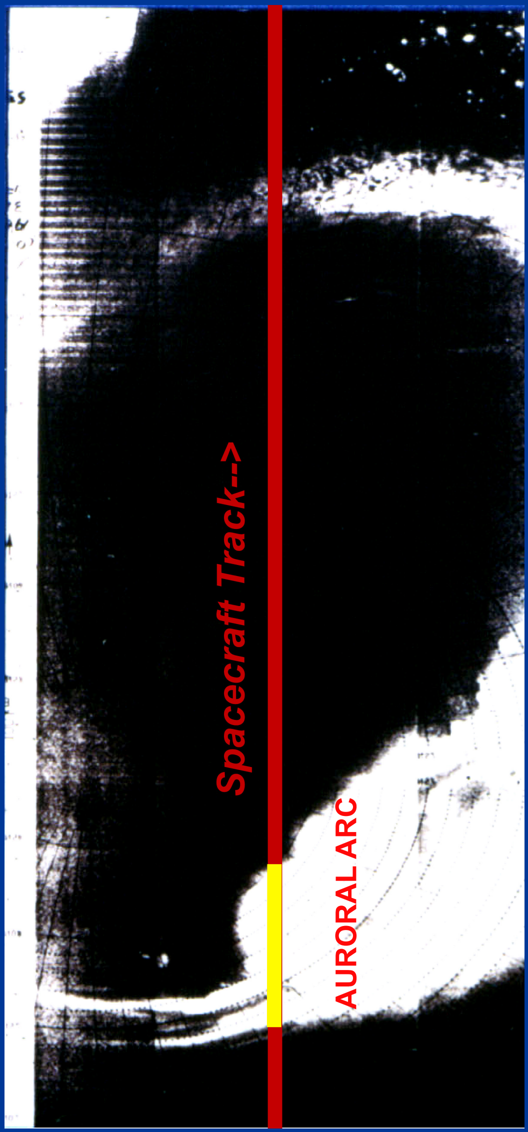


COMPARISON OF RF PULSES GENERATED BY THE DISCHARGE OF KAPTON SAMPLE AND BY THE FIRING OF A SPARK GAP

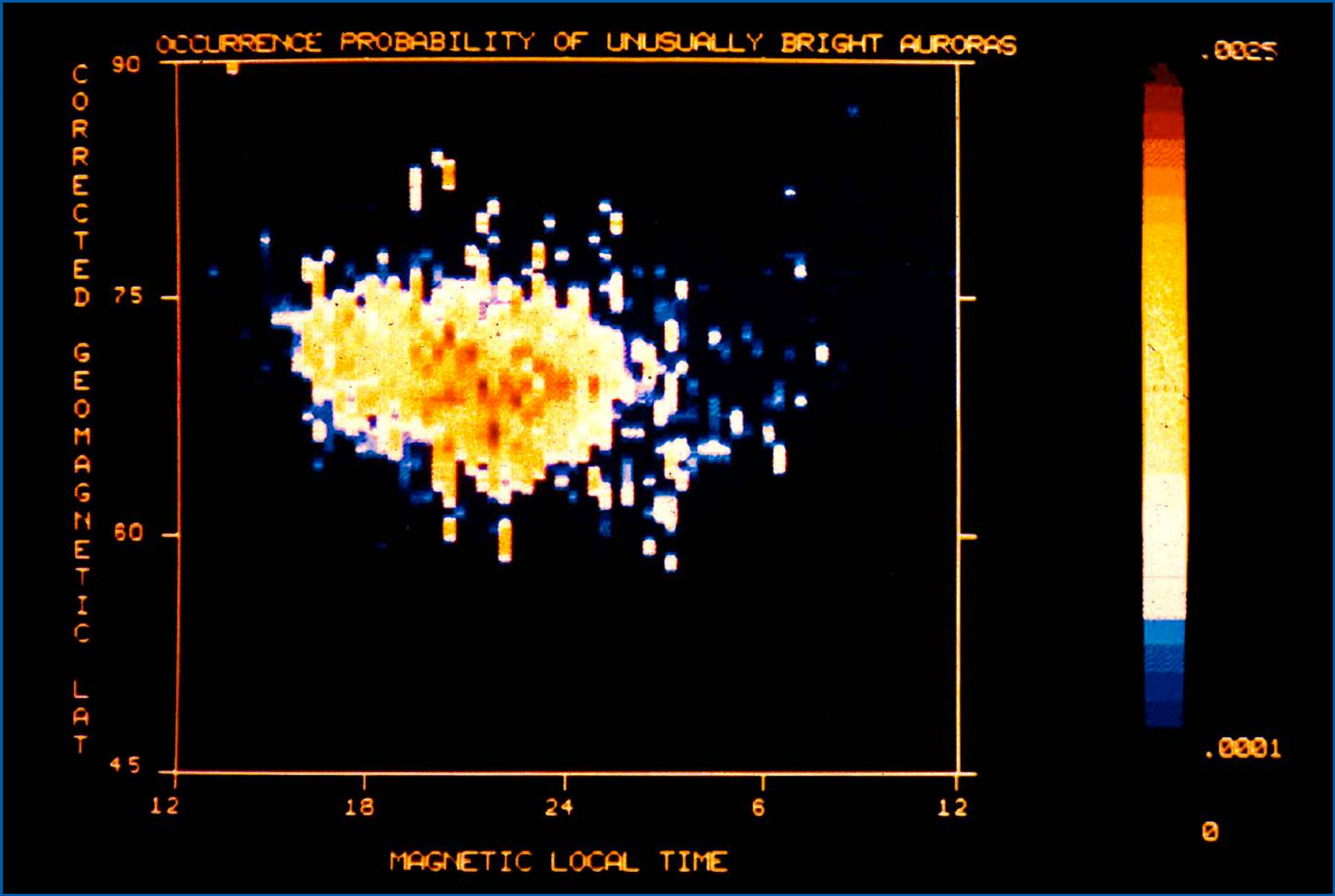


DMSP Low Altitude Spacecraft Charging



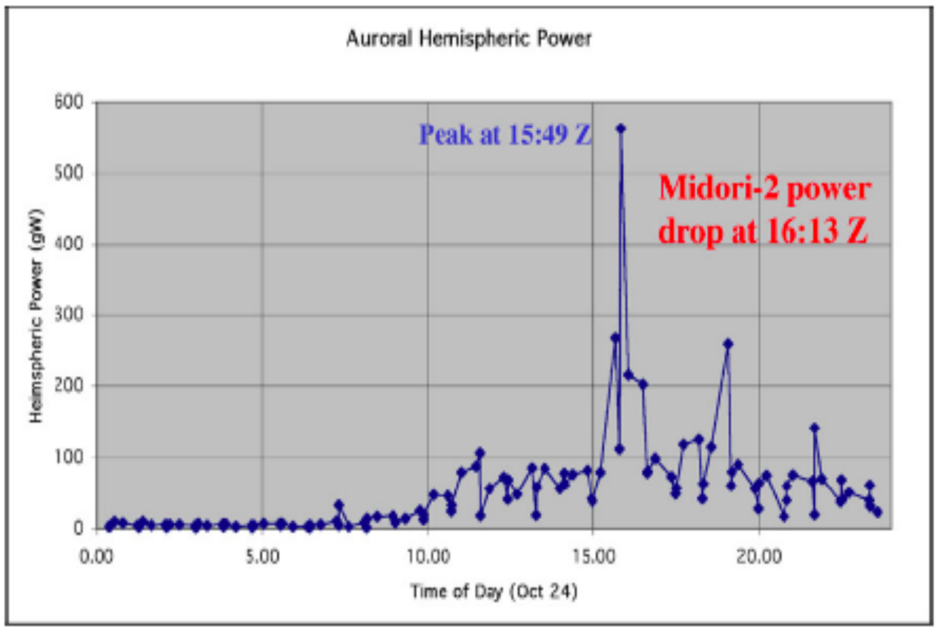


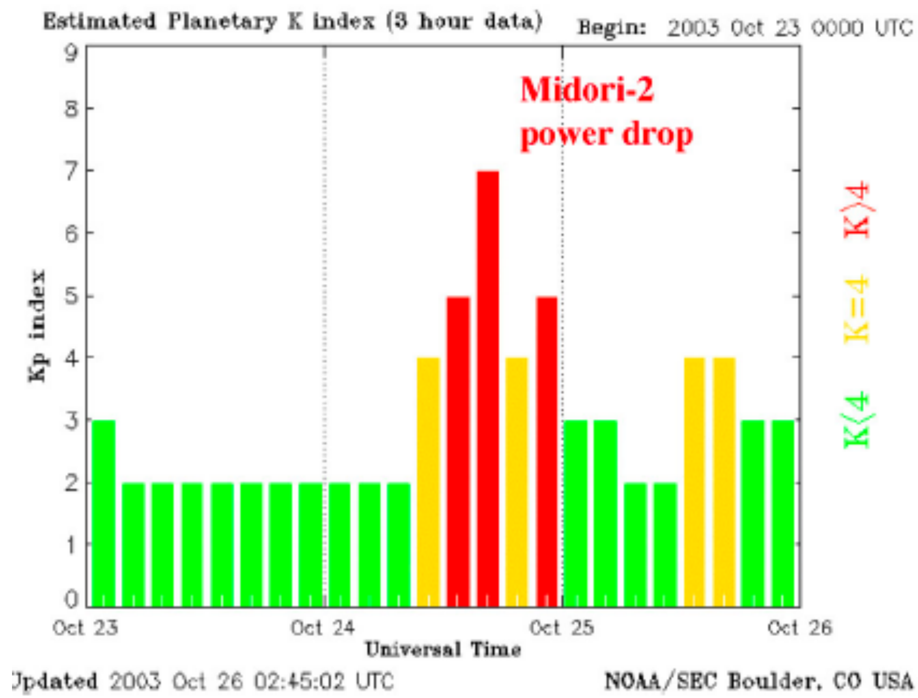
TIROS-N/NOAA-6 Measurements of Bright Aurora



Auroral Effects on JPL Ops, Oct. 24, 2003

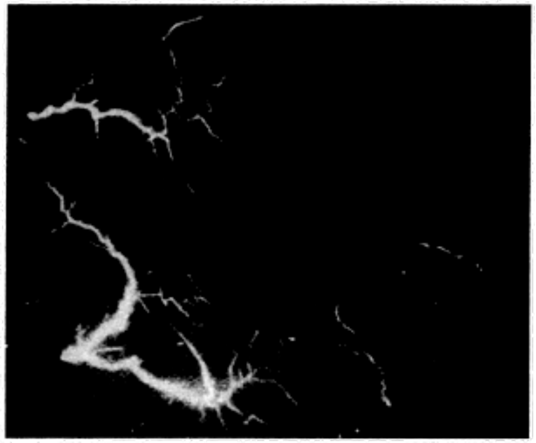
Lessons Learned: Geophysical Indices Critical to Rapid Anomaly Resolution for JPL Missions



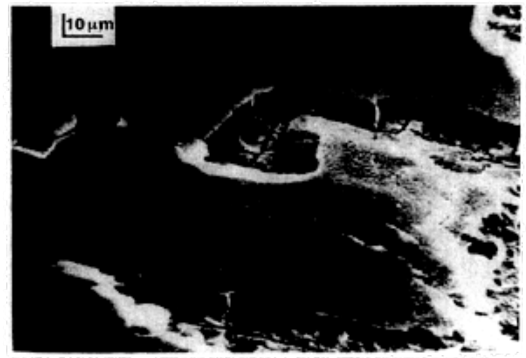


Oct 24: ADEOS-Midori-2 (JPL SeaWinds Instrument) Failed. Attributed to Spacecraft Surface Charging

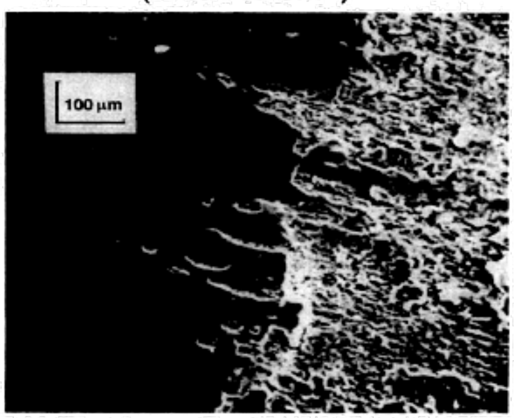
SURFACE DISCHARGE EFFECTS (K.G. BALMAIN, 1980)



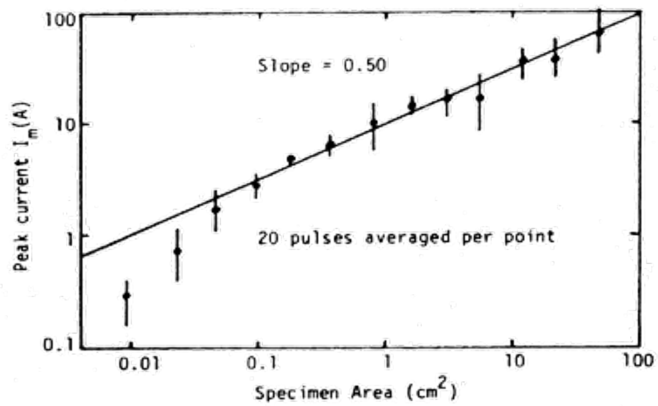
ARC DISCHARGE ON MYLAR (area=48 cm^2)



MAGNIFIED VIEW OF ELECTRON MICROSCOPE IMAGE



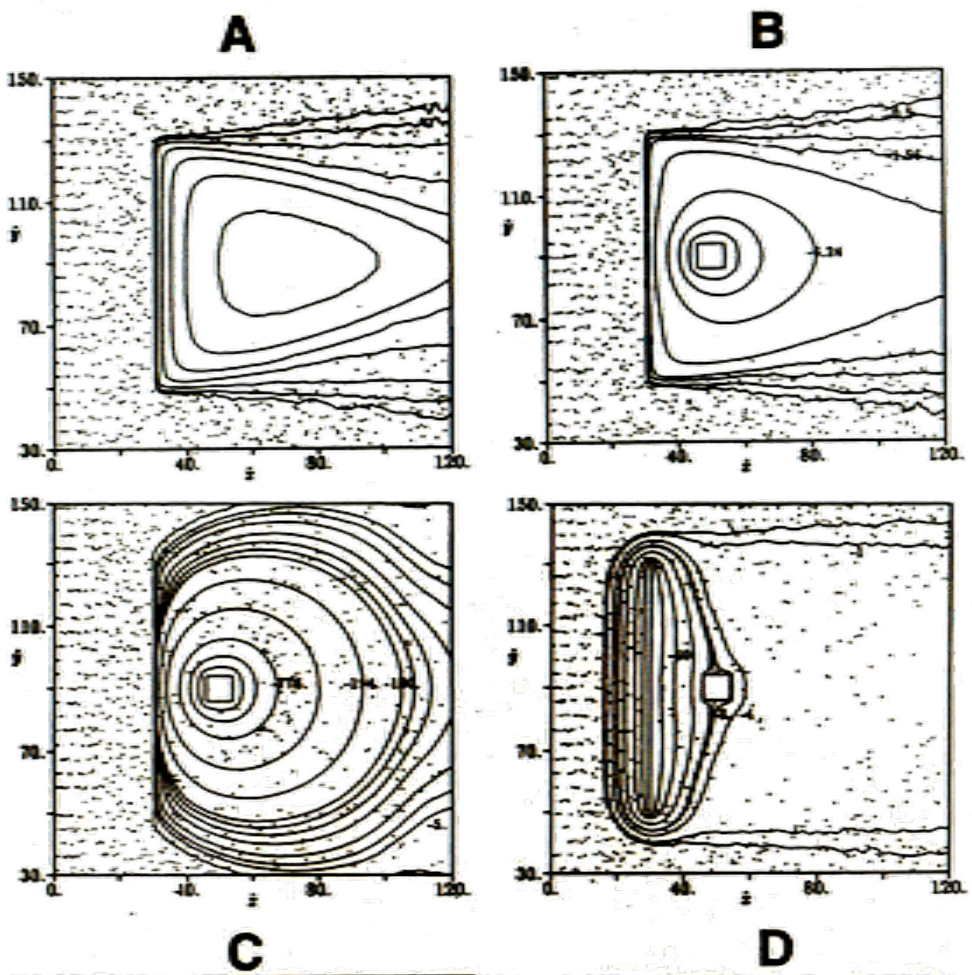
ELECTRON MICROSCOPE IMAGE OF ARC DAMAGE



PEAK ARC CURRENT VS AREA (CURRENT~LENGTH)

Plasma Interactions

MULTIBODY CHARGING AT LOW ALTITUDES*



A. AMBIENT CHARGING

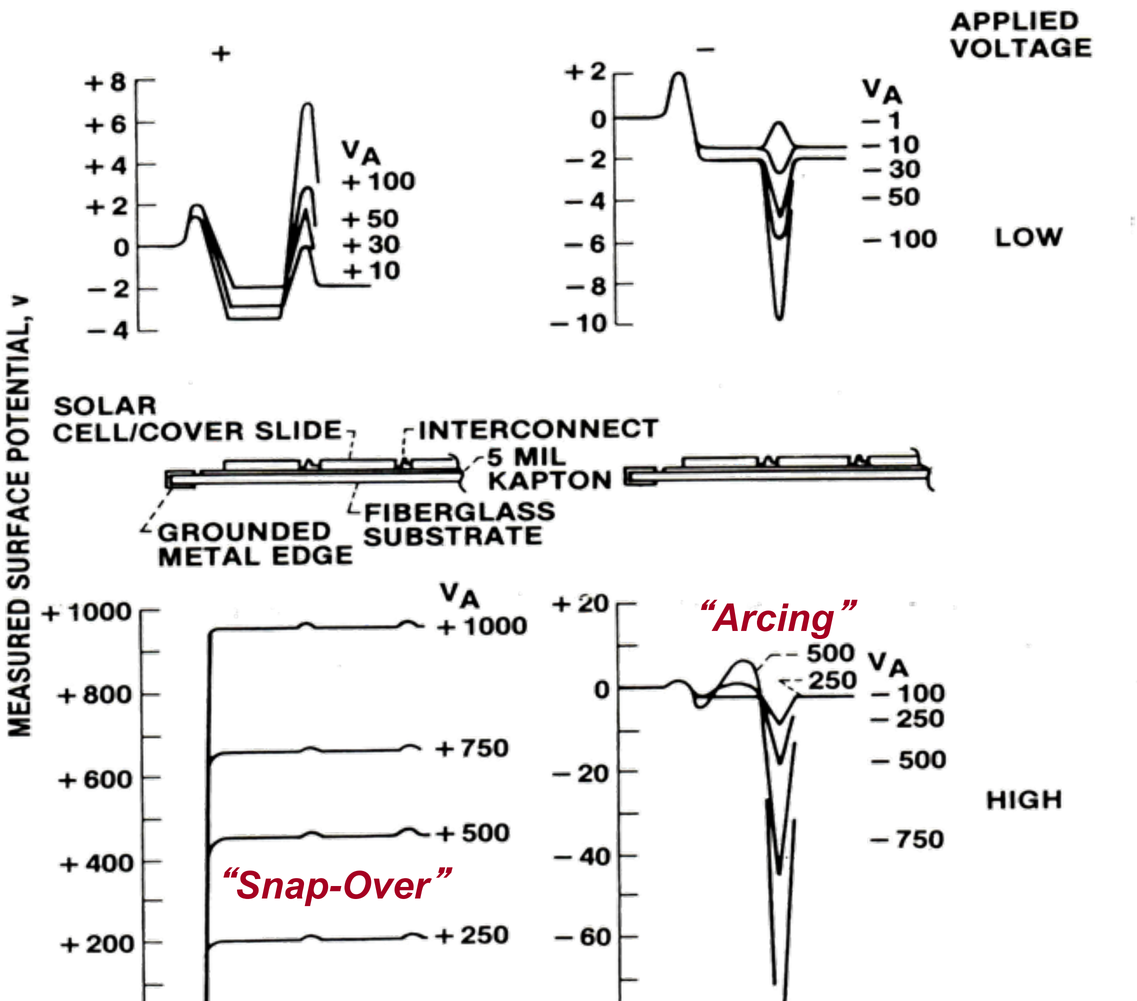
B. MULTIBODY CHARGING

C. AURORAL CHARGING

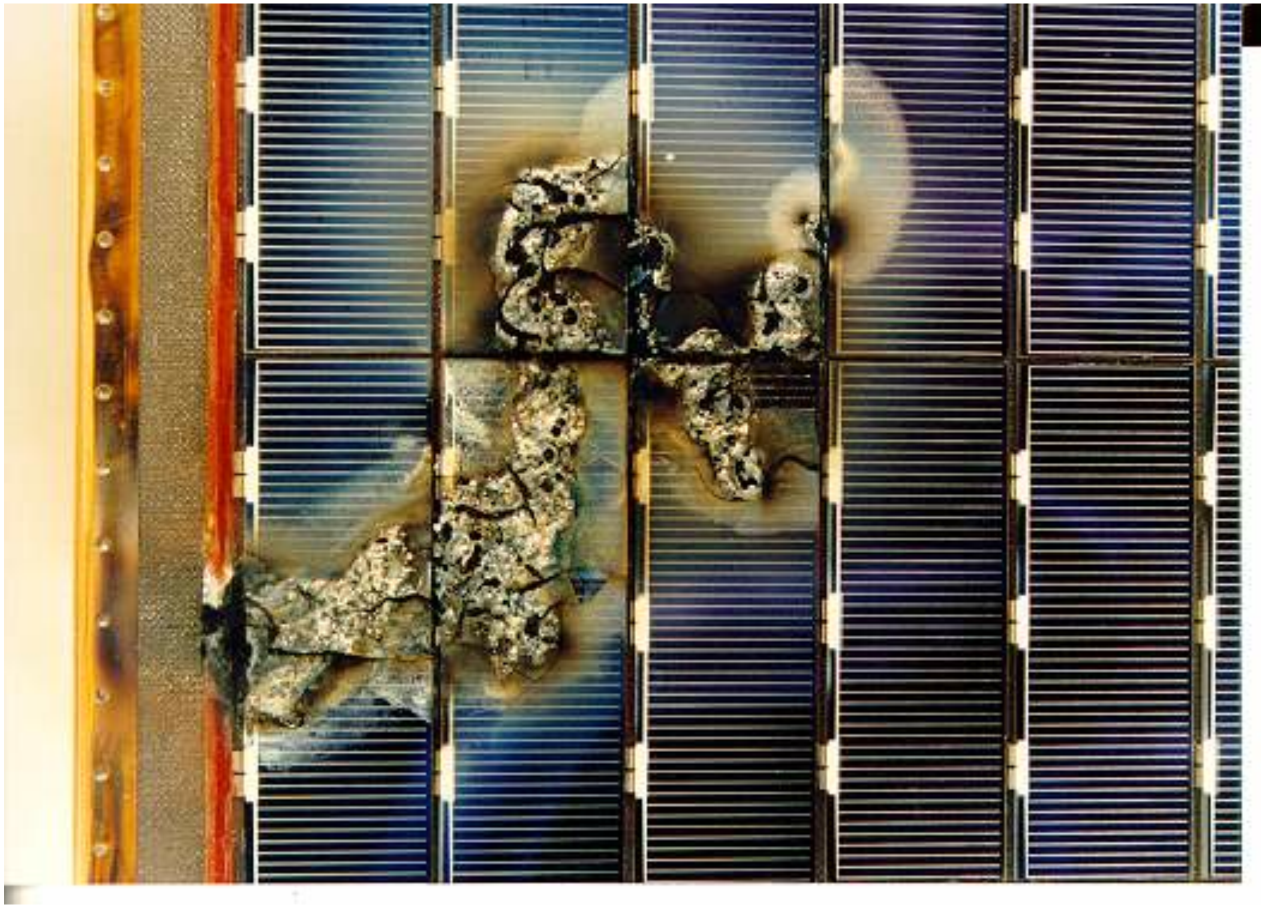
D. BIASED + AURORAL

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

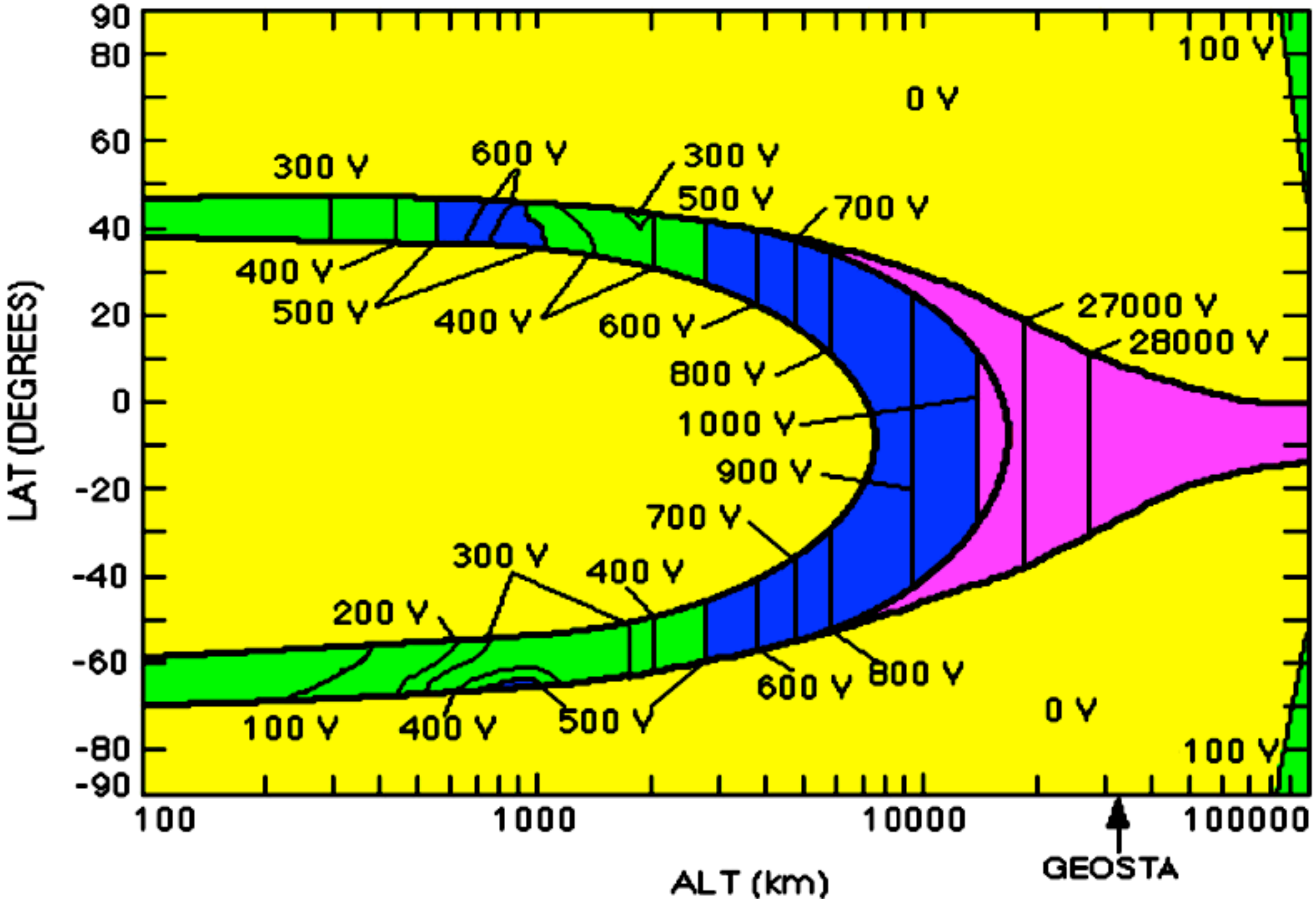
Surface Potential Profiles for Biased Solar Cells



Results of a Discharge on the European Eureca Solar Array



Worst Case Surface Potentials in the Earth's Environment in the Absence of Sunlight (Evans et al., 1989)



Design Guidelines for Assessing and Controlling Spacecraft Charging Effects

GENERAL DESIGN GUIDELINES:

- Ground all conductive spacecraft elements
- Use conductive surface materials
- Shield all circuitry (Faraday Cage Concept)
- Filter circuits near ESD sources
- Develop, document and follow procedures

Material Considerations in Controlling Charging

SURFACE COATINGS AND MATERIALS TO BE AVOIDED FOR SPACECRAFT USE

Material	Comments
Anodyze	Anodyzing produces a high-resistivity surface to be avoided. The surface is thin and might be acceptable if analysis shows stored energy is small
Fiberglass material	Resistivity is too high
Paint (white)	In general, unless white paint is measured to be acceptable, it is unacceptable
Mylar (uncoated)	Resistivity is too high
Teflon (uncoated)	Resistivity is too high. Teflon has a demonstrated long-time charge storage ability and causes catastrophic discharges
Kapton (uncoated)	Generally unacceptable, due to high resistivity. However, in continuous-sunlight applications if less than 0.13 mm (5 mils) thick, Kapton is sufficiently photoconductive for use
Silica cloth	Has been as antenna radome. It is a dielectric, but because of numerous fibers, or if used with embedded conductive materials, ESD sparks may be individually small
Quartz and glass surfaces	It is recognize that solar cell coverslides and second-surface mirrors have no substitutes that are ESD acceptable. Their use must be analyzed and ESD tests performed to determine their effect on neighboring electronics.

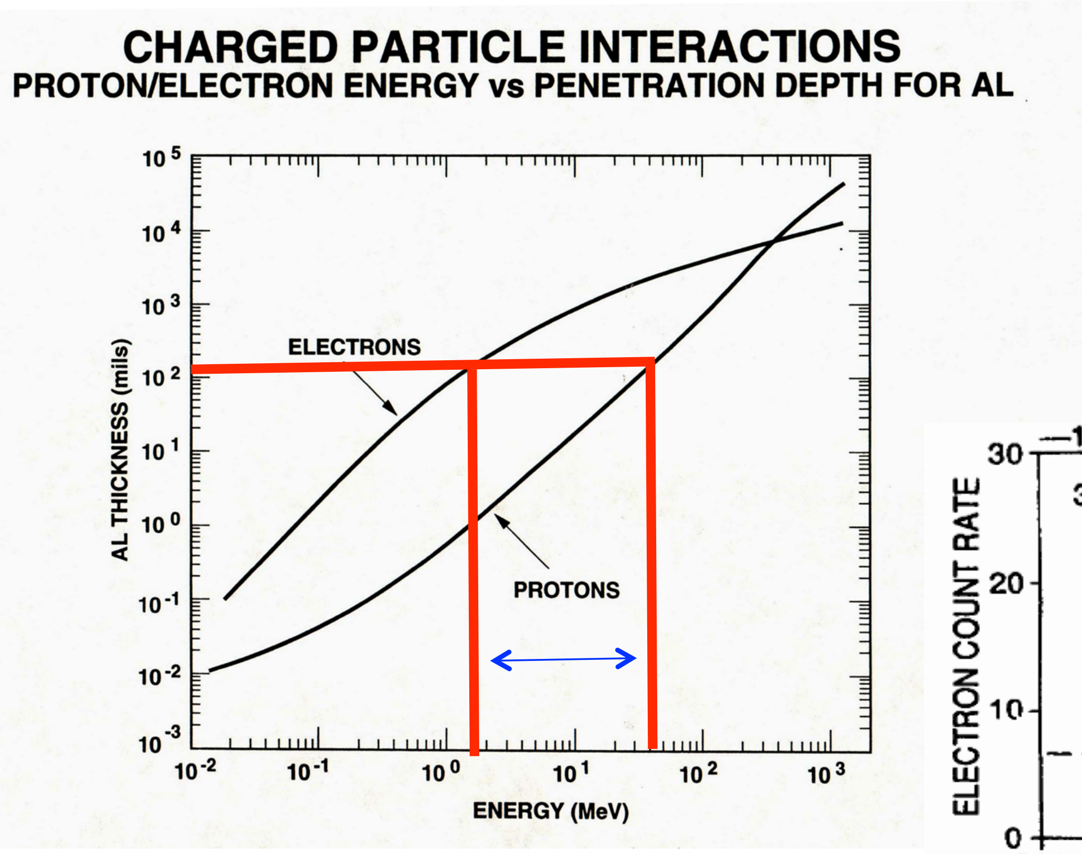
SURFACE COATINGS AND MATERIALS ACCEPTABLE FOR SPACECRAFT USE

Material	Comments
Paint (Carbon black)	Work with manufacturer to obtain paint that satisfies ESD conductivity requirements of section 3.1.2 and thermal, adhesion, and other needs
GSFC NS43* paint (yellow)	Has been used in some applications where surface potentials are not a problem (apparently will not discharge)
Indium tin oxide (250 nm)	Can be used where some degree of transparency is needed; must be properly grounded; for use on solar cells, optical solar reflectors and Kapton
Zinc orthotitanate paint (white)	Possibly the most conductive white paint; adhesion difficult without careful attention to applications procedures
Alodyne	Conductive conversion coatings of magnesium, aluminum etc., are acceptable

*GSFC denotes Goddard Space Flight Center

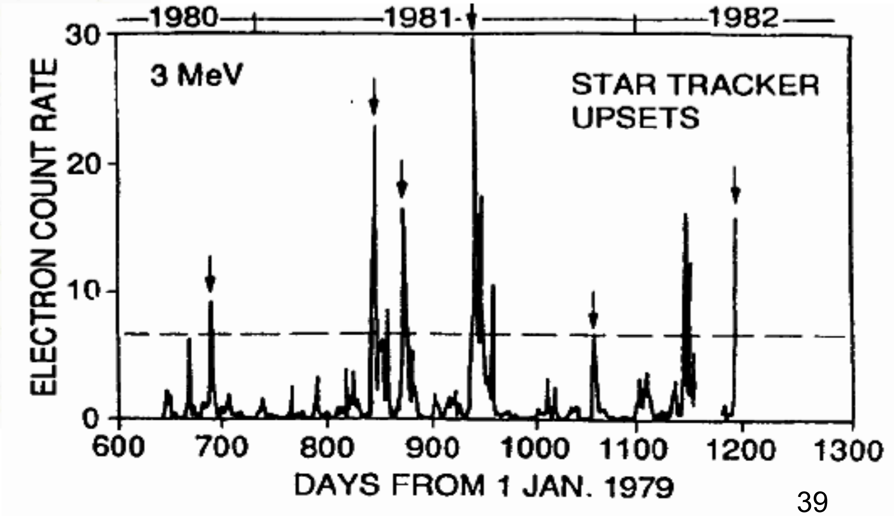
Internal Electrostatic Discharge (IESD)

Internal Electrostatic Discharge—Satellite Killer …

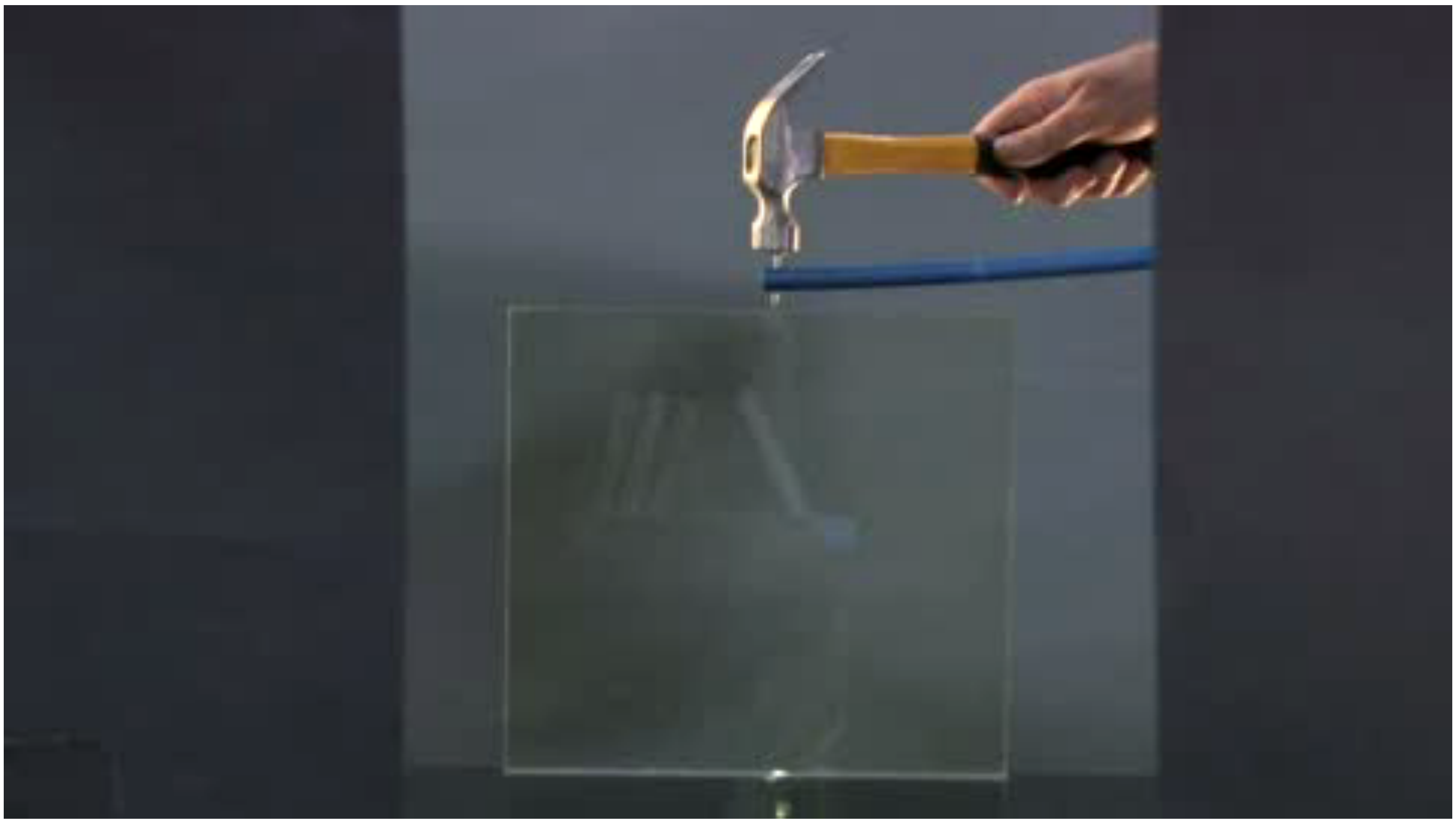


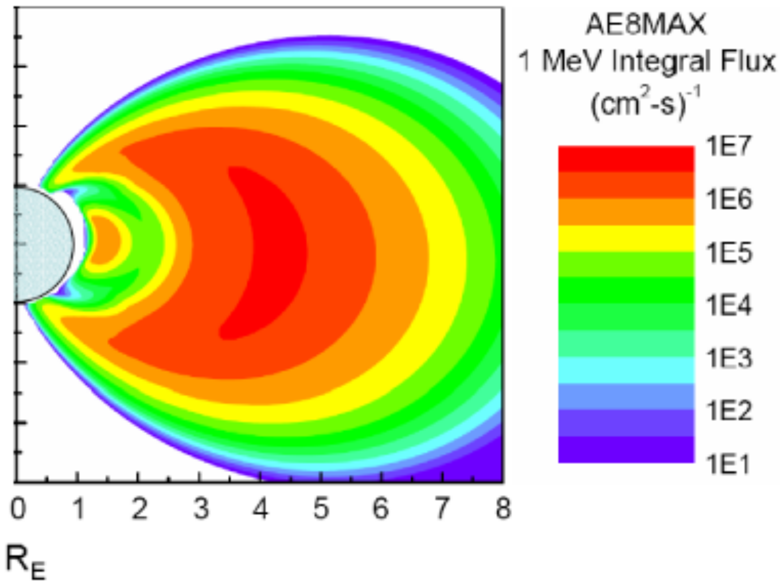
DISCHARGE IN DIELECTRIC

Lichtenberg Pattern



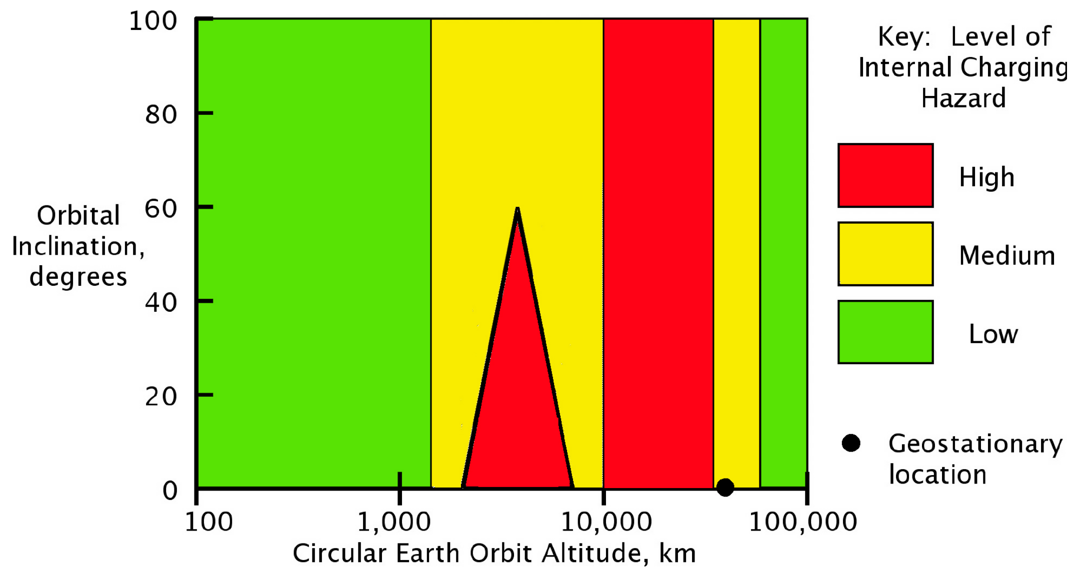
Internal Electrostatic Discharge—The Movie





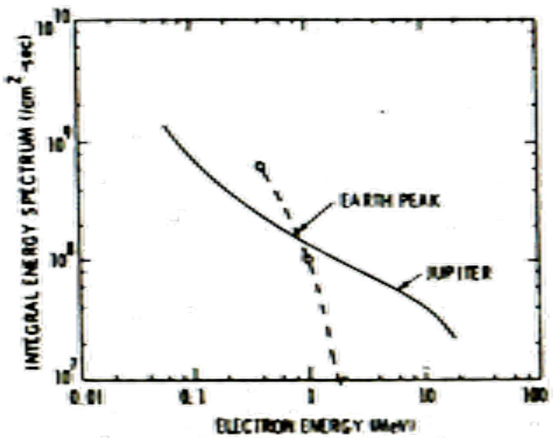
Regions in Earth's Environment of Concern for Internal Charging

RULE OF THUMB: 10^{10} e/cm^2 in <10 Hrs = 1 IESD

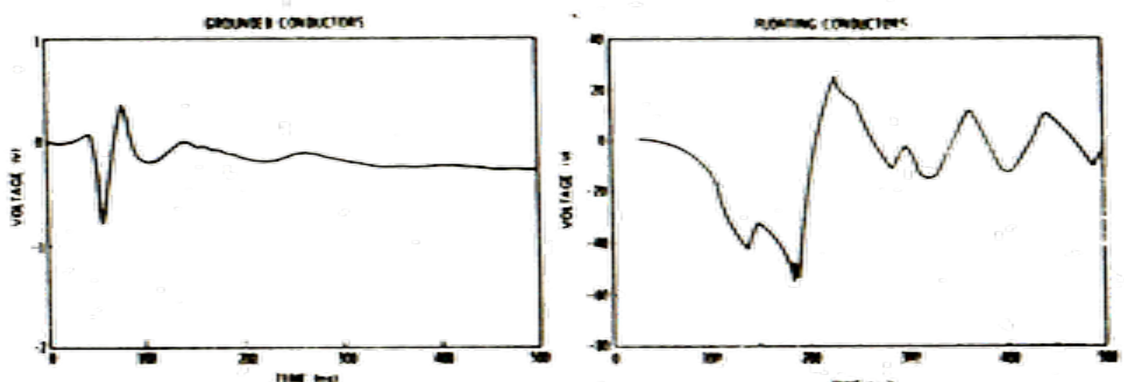


GALILEO INTERNAL ELECTROSTATIC DISCHARGE (IESD) PROGRAM

- PHENOMENON - ENERGETIC ELECTRONS >0.1 MeV CAN PENETRATE S/C SHIELDING AND DEPOSIT THEIR CHARGE ON COMPONENTS
- CONCERN - PROBABLE CAUSE OF POR's DURING VOYAGER 1's ENCOUNTER WITH JUPITER
- THREAT - ESD EVENTS OCCUR RIGHT AT THE COMPONENTS, EFFICIENT COUPLING OF EMI INTO CIRCUITS
- APPROACH - R&D TEST AND ANALYSIS PROGRAM TO IDENTIFY THE THREATS
- DESIGN GUIDELINES - ALL CONDUCTIVE SURFACES SHOULD HAVE A RESISTANCE $<10^{12}$ ohm TO GROUND
  - CONDUCTORS WITH SURFACE AREA >3 cm^2 NOT ALLOWED
  - CONDUCTORS WITH A LENGTH OF >25 cm NOT ALLOWED



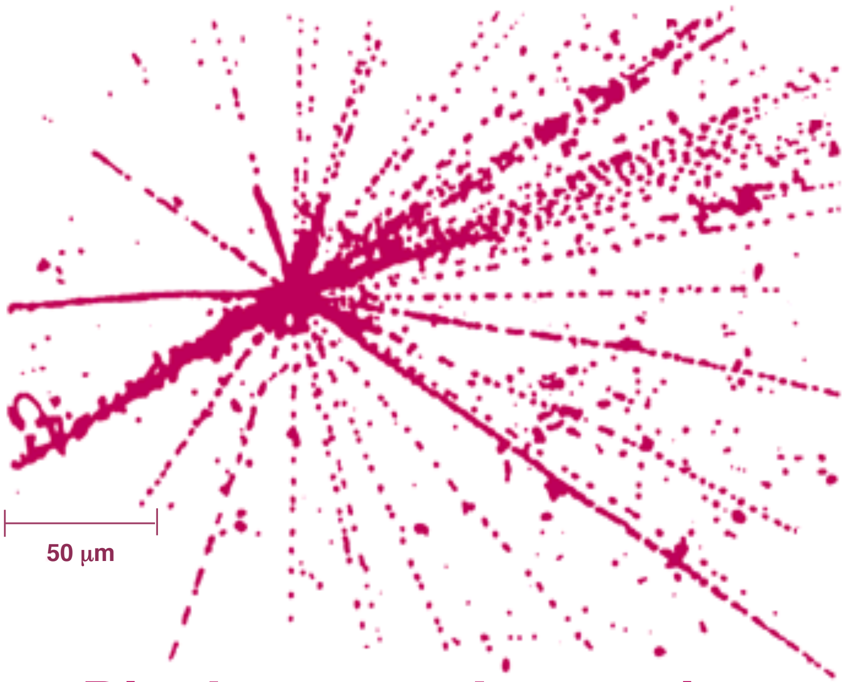
COMPARISON OF ENERGETIC ELECTRON ENVIRONMENTS



SIGNALS INDUCED ON VICTIM CIRCUITS

Radiation Interactions

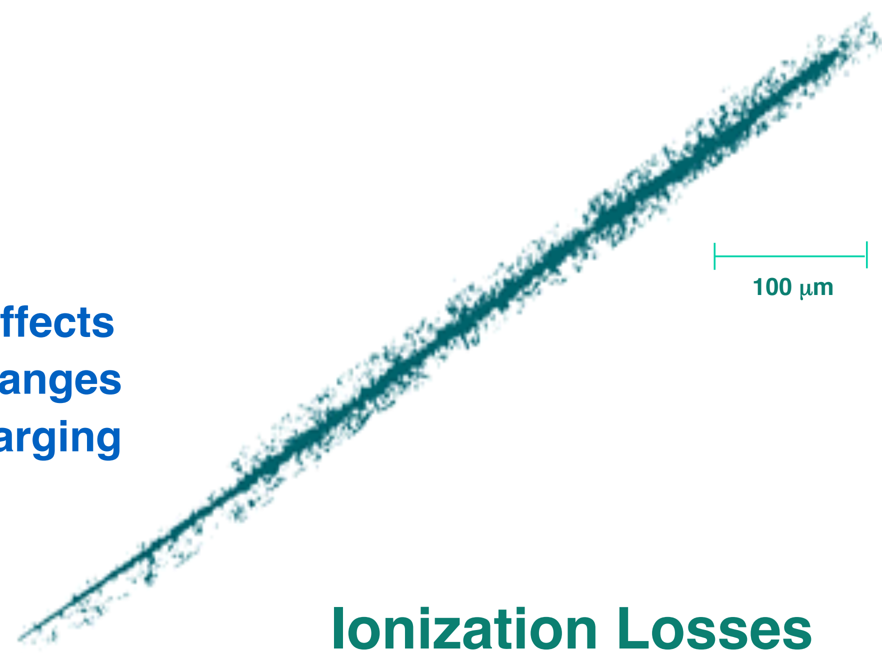
Radiation Effects on Spacecraft Systems



Displacement Interactions

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

Recipe for Dosage

STEPS:

0) Assume target of mass M, density ρ, area δA, and thickness τ

$$\boxed{\delta\tau = \frac{M}{\rho\,\delta A}}$$

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

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

2) Estimate energy change δE in crossing target thickness $\delta\tau$ for particle energy E:

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

3) The dose per particle of energy E is approximated by:

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

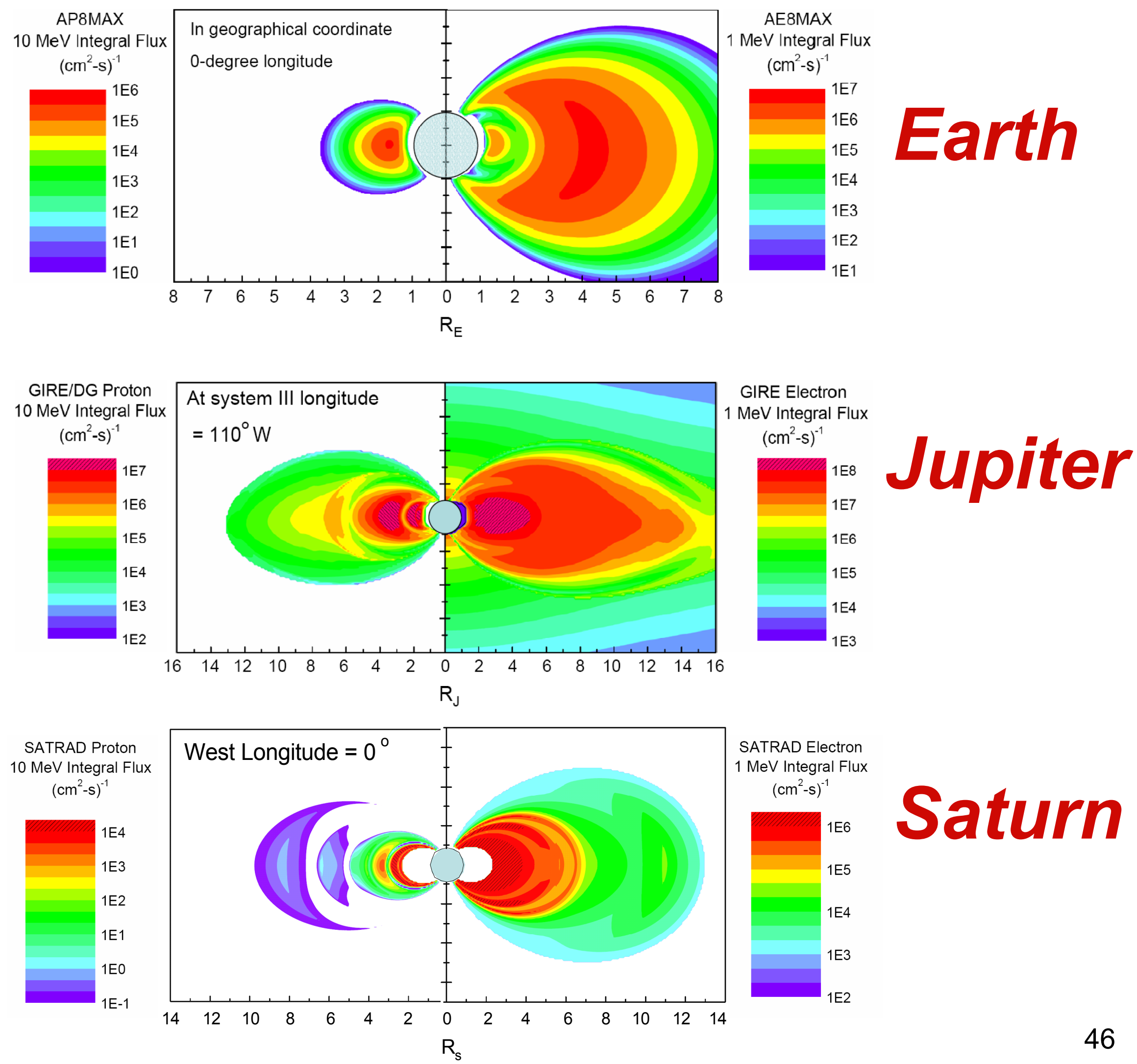
"LET"

4) The total dose at energy E is:

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

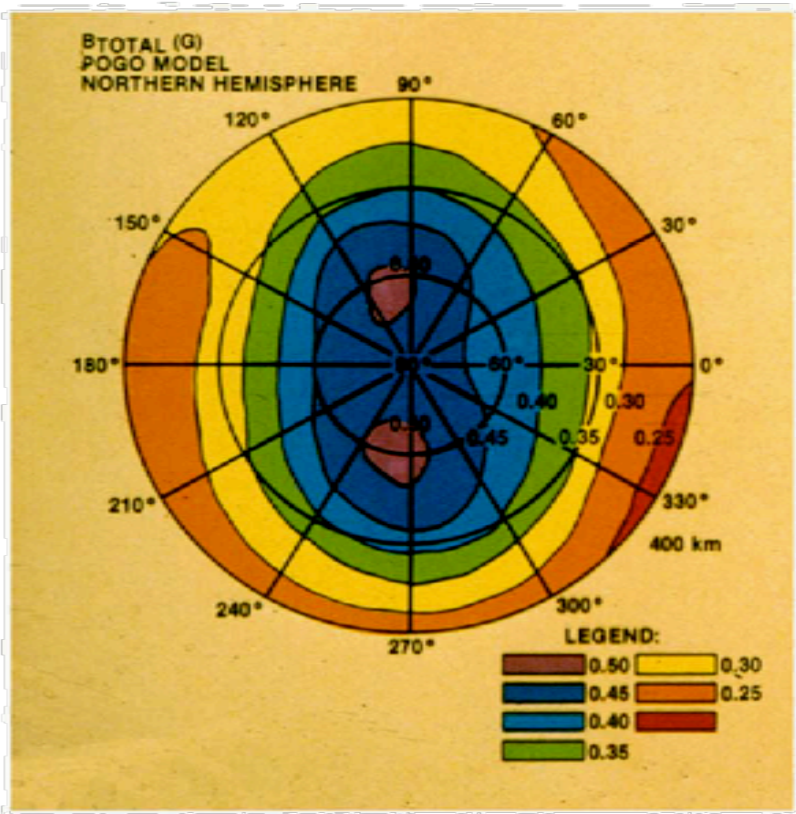
5) Finally, for total Integral dose, integrate over the range E_0 to ∞.

TRAPPED RADIATION BELTS

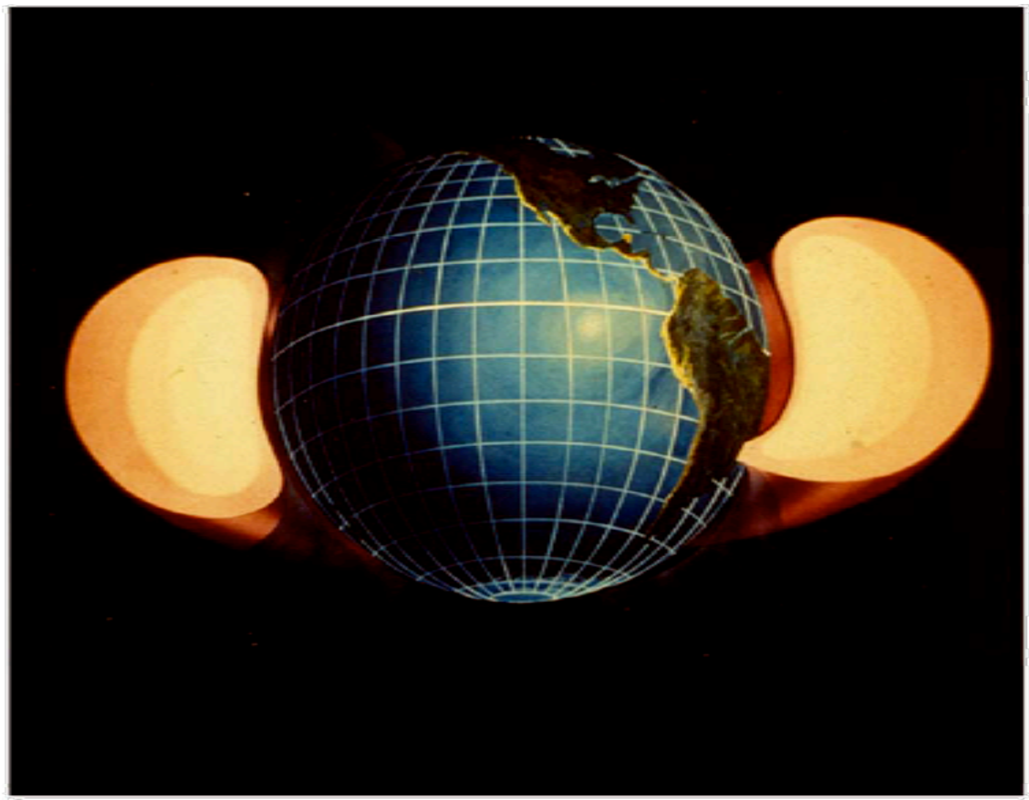


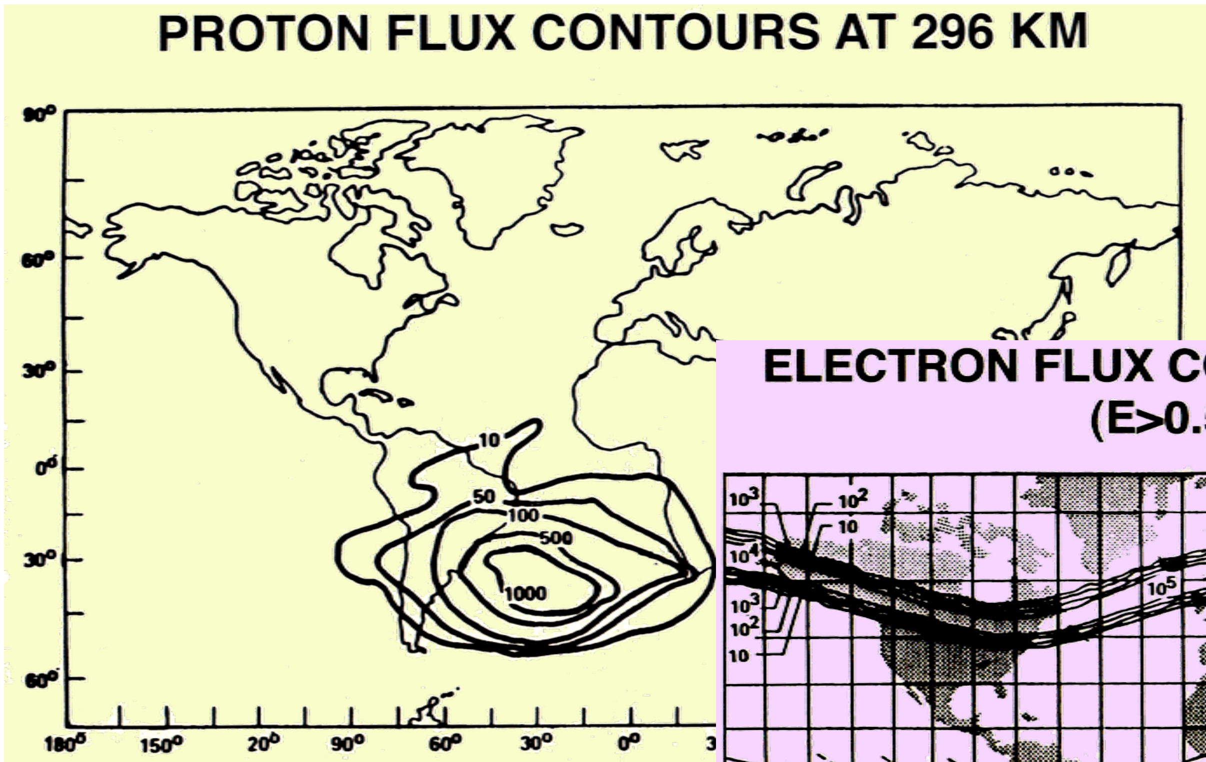
THE MAGNETIC FIELD OF THE EARTH

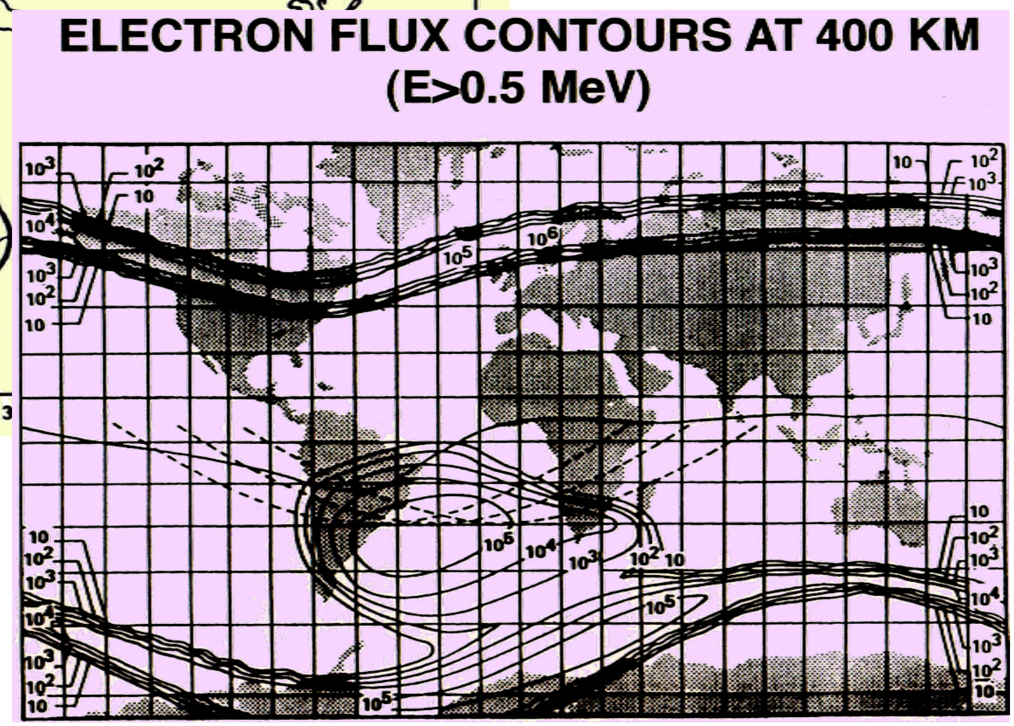
MAGNETIC INTENSITY AT THE EARTH'S SURFACE



THE SOUTH ATLANTIC ANOMALY

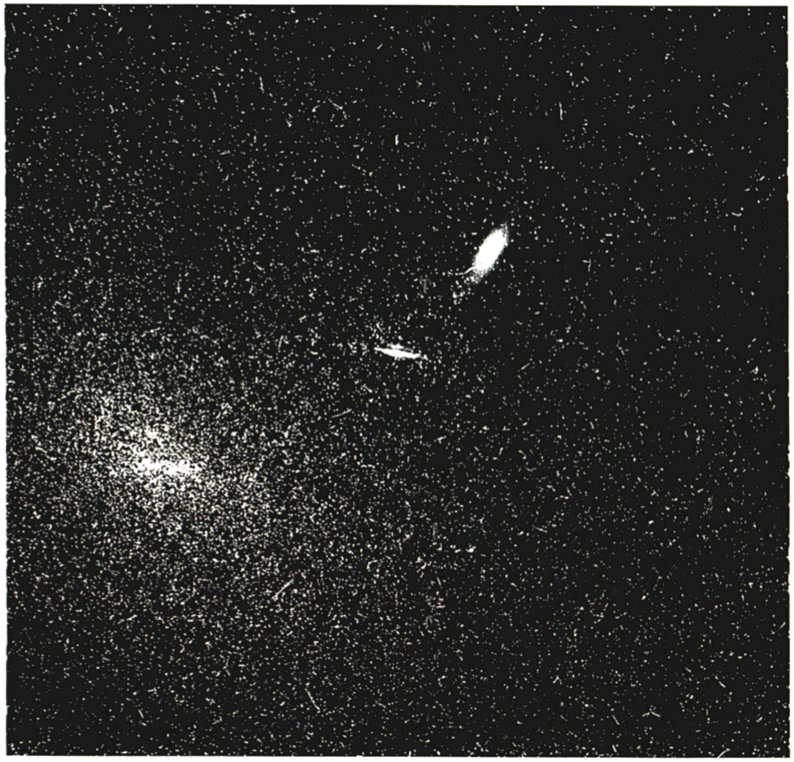



PROTON FLUX CONTOURS AT 296 KM
90°
60°
30°
0°
30°
60°
10
50
100
500
1000
180°
150°
20°
90°
60°
30°
0°


ELECTRON FLUX CONTOURS AT 400 KM
(E>0.5 MeV)
10³
10²
10
10⁴
10⁵
10⁶

Wide-field Planetary Camera CCD

Proton Events In South Atlantic Anomaly

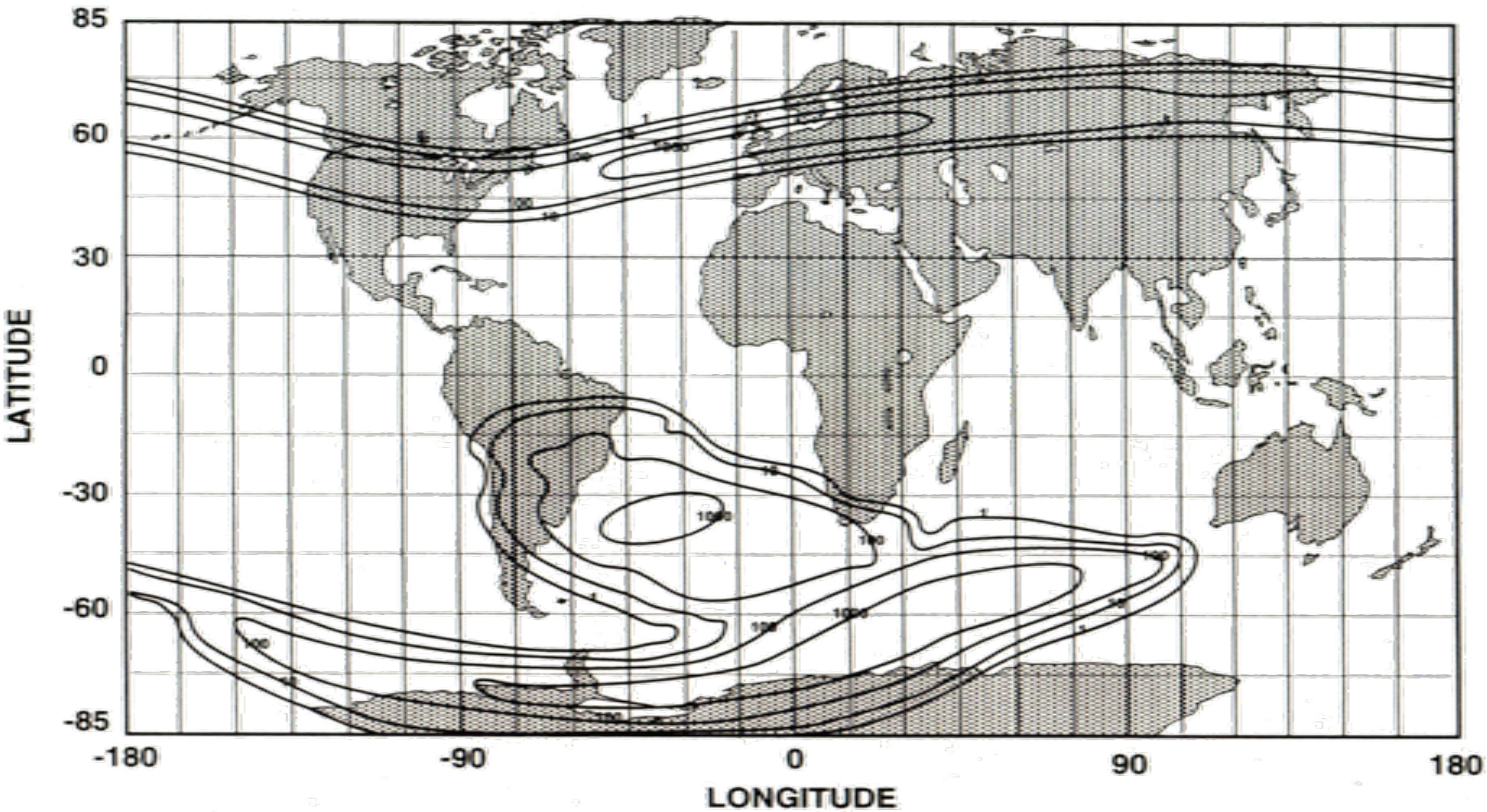


Wide-field Planetary Camera CCD

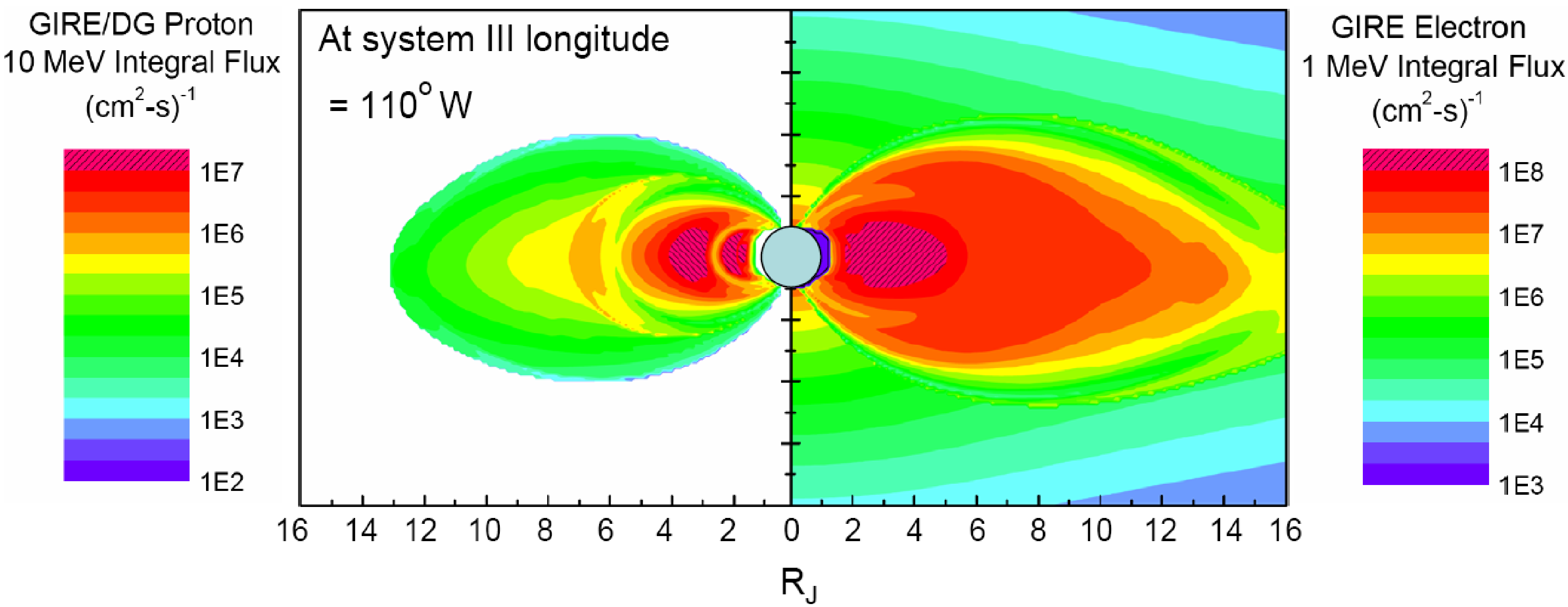
Galactic Cosmic Ray "Nuclear Shower"

THE SOUTH ATLANTIC ANOMALY

TOTAL DOSE AT 500 KM ALTITUDE: AE8-MIN
(EPOCH OF B&L: 1964)
SPHERICAL ALUMINUM SHIELD: 0.2 G/CM^2 (UNITS: rads/s x 10^{-6})

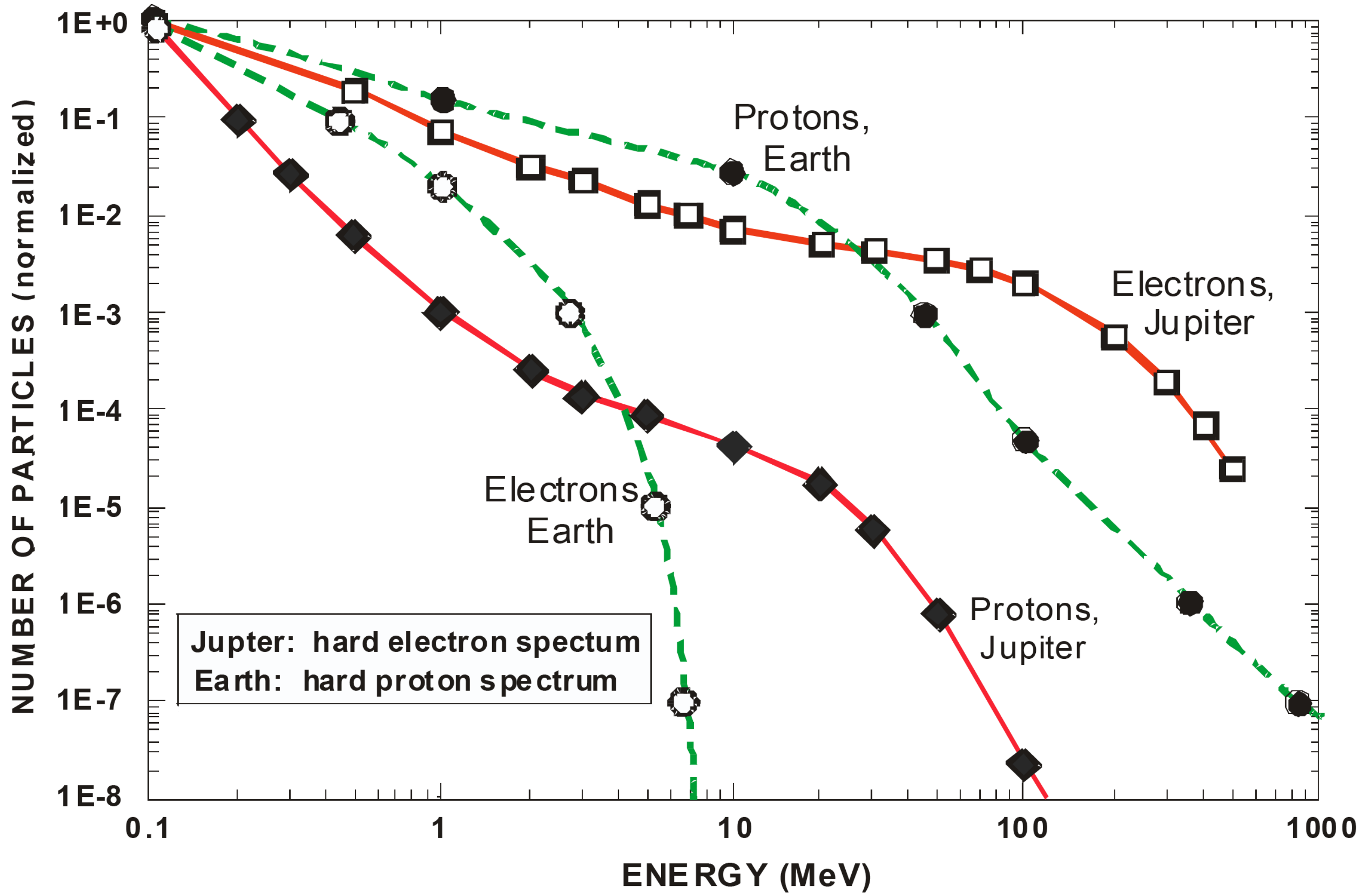


Divine/GIRE Jovian-Trapped Radiation Models



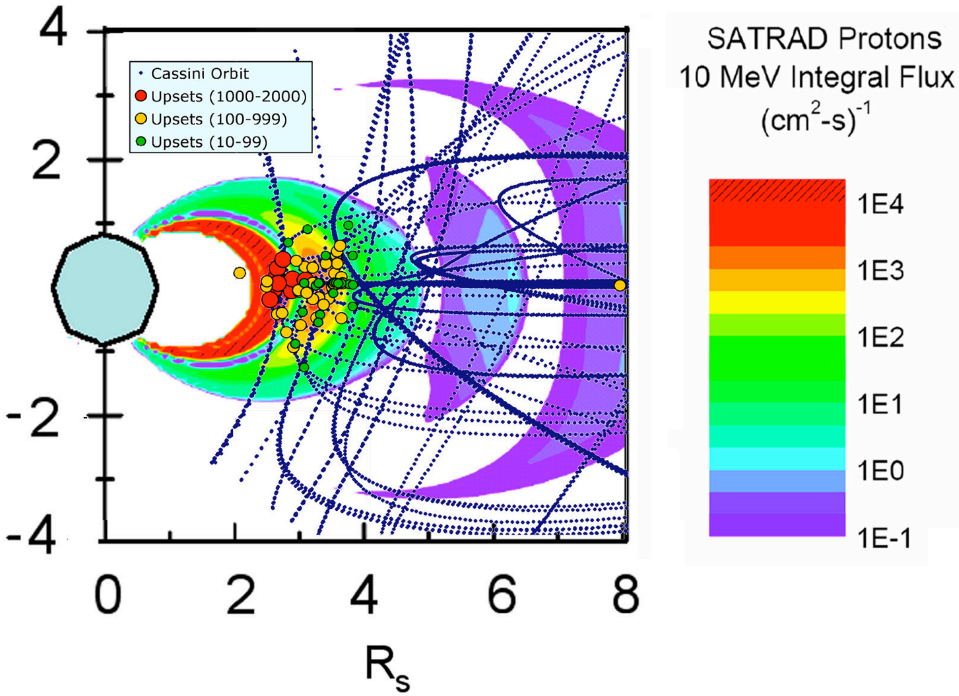
Contour plots of ≥1 MeV electron and ≥10 MeV proton integral fluxes at Jupiter. Coordinate system used is jovi-centric. Models are based on Divine/GIRE models. Meridian is for System III 110° W.

Comparisons Between Jovian and Terrestrial Radiation Spectra

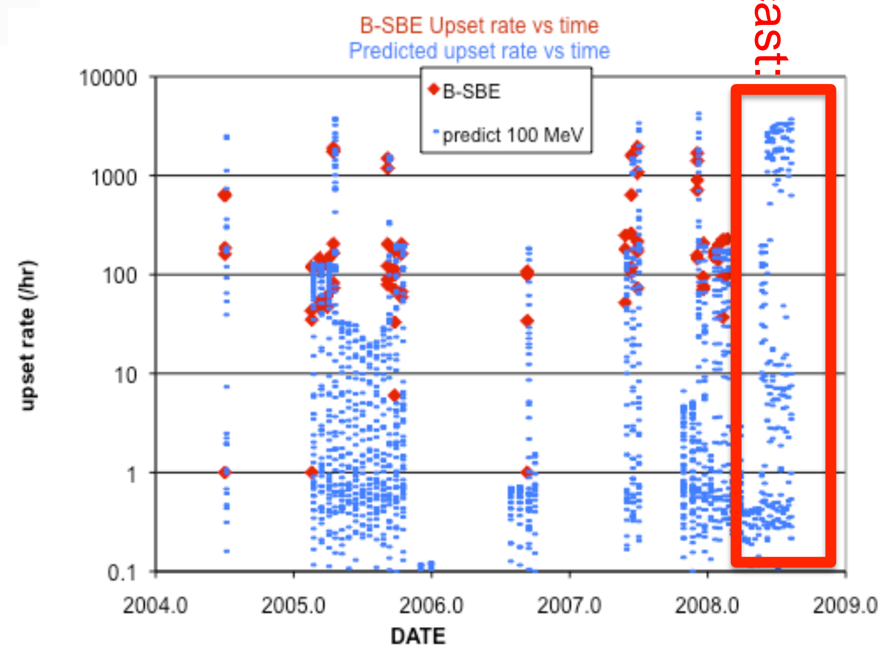


COURTESY A. JOHNSTON

Trapped Proton Effects on Cassini



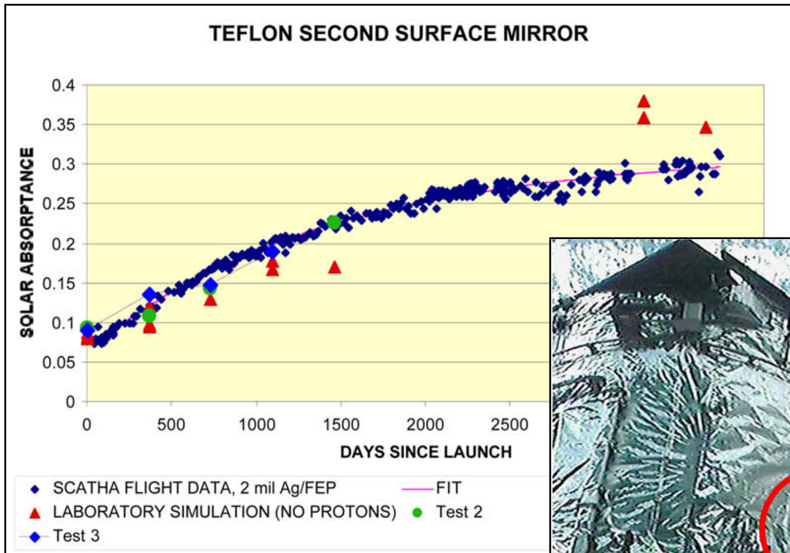
Upsets along Cassini orbital traces overlaid on SATRAD >10 MeV proton fluxes



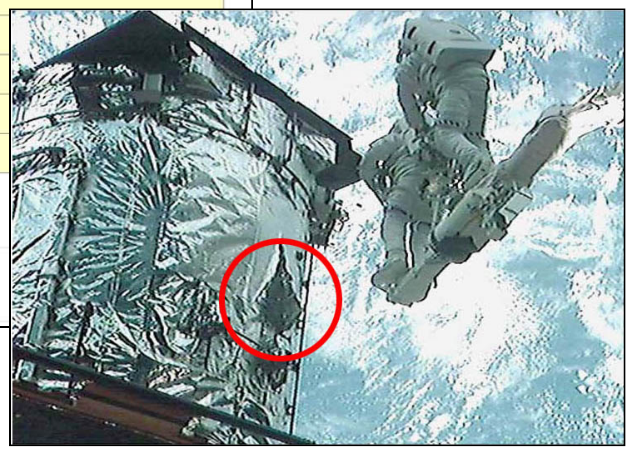
Observed (through mid-2008) vs predicted (SATRAD >100 MeV proton fluxes) hourly upsets

Lessons Learned: Radiation belt models can predict upsets and drive Ops planning

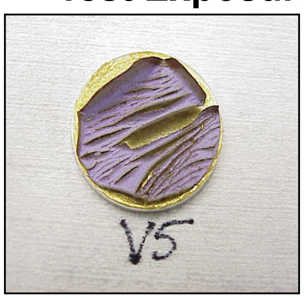
Radiation Effects on Materials

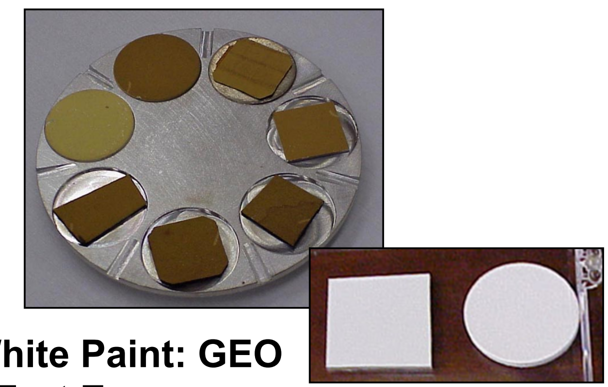


Silver Teflon: Flight Data



Tedlar: 3-4 Yrs GEO Test Exposure





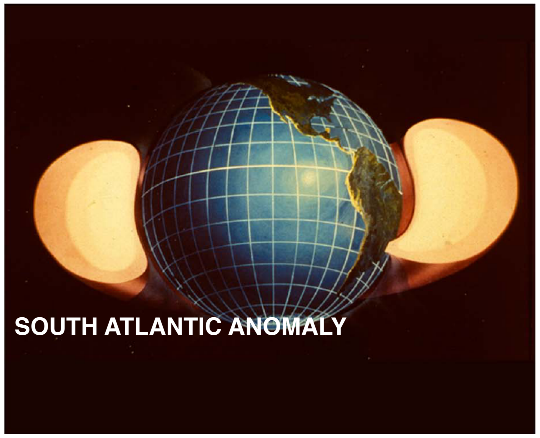
White Paint: GEO Test Exposure

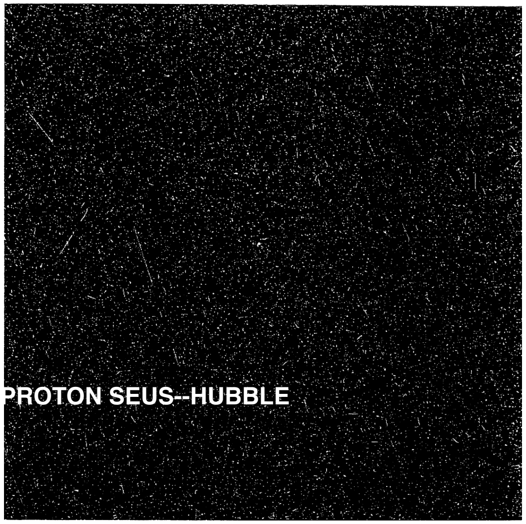
Materials suffer from UV/ EUV and particle radiation (Grads on surfaces!) through changes in:

- **Dimensions**
- **Tensile strength**
- **Conductivity**
- **Transmission**
- **Reflectance**
- **Decomposition**

Adapted from Meshishnek et al., 2004
Courtesy of the Aerospace Corporation

Radiation Effects





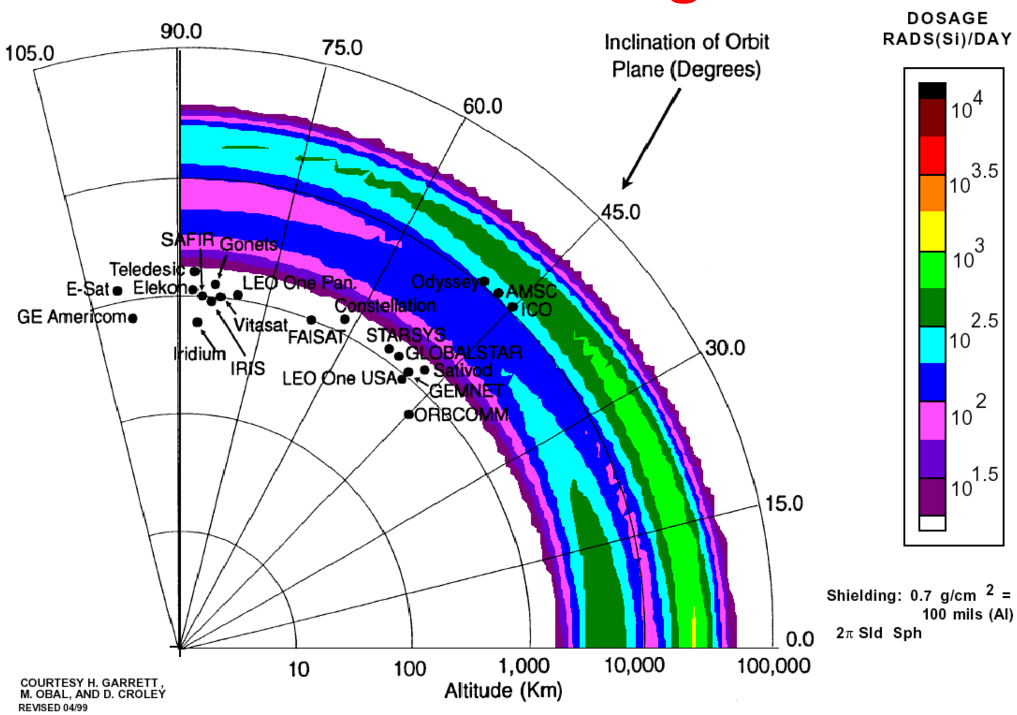
RADIATION EFFECTS ON MATERIALS

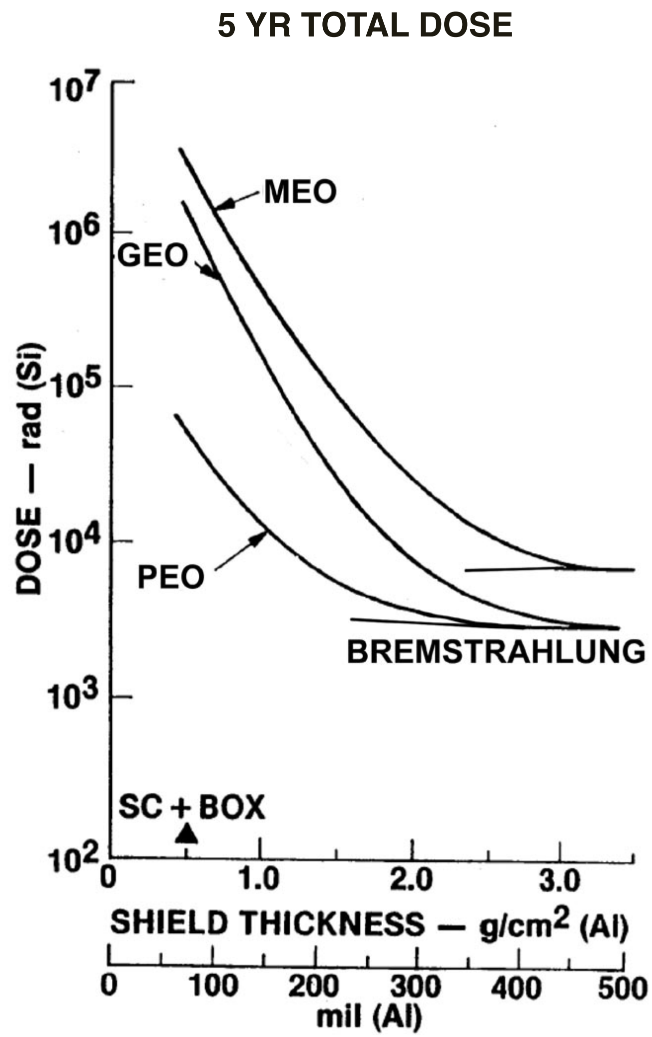
MATERIAL	LIMIT. DOSE (Rads)	MISSION RATING	REF.	STATUS
Metals	10 E 12	1	C	No problem; Damage threshold in excess of 10 E 12 rads
Ceramics	10 E 12	1	C	No problem; Damage threshold in excess of 10 E 12 rads
Carbon/Carbon	10 E 12	1	C	No problem; Damage threshold in excess of 10 E 12 rads
White Paints	10 E 10?	2	D	Use Hughes H-1 paint; very stable (electrons and protons)
Black Paints	10 E 11	2	D	Most acceptable; use QS-1 for additional margin
Composites	10 E 10?	2	A,D	Choice; Cyanate matrix based on RTX366 (250F cure)
Cabling	5 E 6	3	D	RayChem SPEC-44, 55 cables, plus required shielding
Fiber Optics	?	2?	?	Probably OK; data classified
Adhesives	10 E 10	2	A,D	Shielded in use; current adhesives (like EA9394) OK
Seals/Gaskets	5 E 7	3	A,D	Shielded in use; need to verify dose/tolerance
Lubricants	10 E 9	2	A,D	Shielded in use; all OK; Dichronite, dry lubes excellent
Blankets	5 E 9	2	A,D	Kapton should be OK; CP-1 film for additional margin
ESD Coatings	10 E 12	1	?	OK; Indium tin oxide, flight heritage-Voyager/Galileo
Propellants	10 E 8	3	A,D	Shielded in use; testing needed to verify acceptability
AR Coatings	10 E 12	1	D	Silica, tantala; verified in hi-rad environments; OK
Glass	10 E 6	4	A,B,D	Shielding required; testing/flight history required
Silica	1.4 E 7	2	A,B,D	Excellent, rad-hard; flight history Voyager/Galileo

Mission Rating:
1 = Current materials acceptable
2 = Acceptable; requires dose calculations
3 = Acceptable; with dose calculations & test data
4 = Questionable; conclusive proof required
5 = Unacceptable

General References:
A = "Designers Guide to Radiation Effects on Materials for Use on Jupiter Fly-Bys and Orbiter"
F.L.Bouquet, IEEE Transactions, Vol. NS-26, August 1979
B = "A Review of Reliability and Quality Assurance Issues for Space Optics Systems"
V.R.Farmer, Jet Propulsion Laboratory
C = "Radiation Effects on Non-Electronic Materials Handbook", B.P.Dolgin, Jet Propulsion Laboratory
D = JPL / Manufacturer's test data

Radiation Hardening Procedures





RADIATION HARDENING APPROACH

- Define the shielded radiation environment
- Parts parameter data--characterization screening
- Worst-case circuit analysis--conservative design rules
- Shield to provide the part performance requirements
- Employ radiation tolerant circuit designs

Summary

Conclusions

- **WHY DO WE CARE?**
  - ENVIRONMENTAL EFFECTS ARE POTENTIALLY EXPENSIVE PROBLEMS
  - THERE ARE STILL MANY UNKNOWNS
  - PROPER DESIGN WILL LIMIT PROBLEMS

- **WHAT CAN WE DO?**
  - DESIGN: EVALUATE THE MISSION DESIGN USING AN INTEGRATED APPROACH
  - BUILD: REQUIRE ADEQUATE TESTING (RECOMMEND ENGINEERING TEST MODEL!)
  - FLIGHT: DURING FLIGHT, EVALUATE EFFECTIVENESS OF MITIGATION METHODOLOGY
  - POST FLIGHT: USE DATA TO UPDATE MODELS

Integrated Approach to Mission Design

DESIGN PROCEDURES

1) Identify Requirements Based on Trajectory, Instruments, and Unique Mission Constraints

2) Rate the Environments versus the Interactions

3) Identify the Design Trade-Offs for the Most Critical Environment/Interaction Concerns

4) Establish Weight, Cost, Complexity Criteria

5) Optimize Combinations of Design Choices

6) Evaluate Resulting Designs

Space Environments and Interactions References

BASIC CONCEPTS

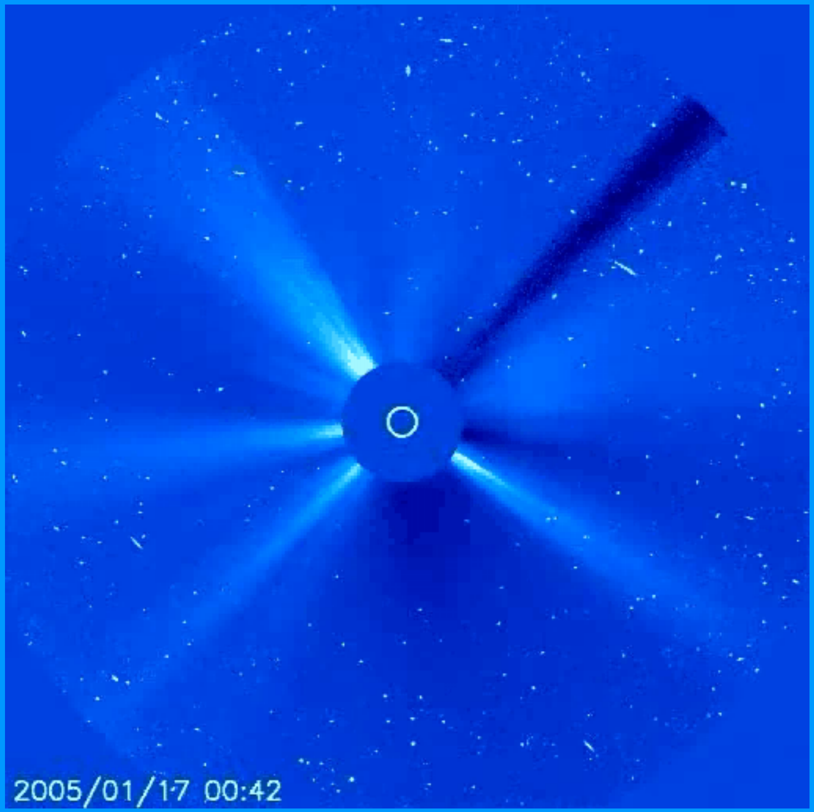
- Haymes, R.C. Introduction to Space Science. New York, NY: John Wiley and Sons, Inc., 1971.
- Garrett, H.B. and C.P. Pike, eds. "Space Systems and Their Interactions with Earth's Space Environment." Prog. Astronaut. Aeronaut. 71 (1980):
- Jursa, A., ed. Handbook of Geophysics and the Space Environment. National Technical Information Services Document, Accession No. ADA 167000, 1985.
- Wertz, J.R. and W.J. Larsen, eds. Space Mission Analysis and Design. Doredecht, The Netherlands: Kluwer Academic Publishers, 1991.
- DeWitt, R.N., D.P. Dutson, and A.K. Hyder, eds. The Behavior of Systems in the Space Environment. Doredecht, The Netherlands: Kluwer Academic Publishers, 1994.
- Tribble, A. The Space Environment: Implications for Spacecraft Design. Princeton, NJ: Princeton University Press, 1995
- Hastings, D., and H.B. Garrett. "Spacecraft-Environment Interactions." Atmospheric and Space Science Series, ed. A.J. Dessler. Cambridge, England: Cambridge University Press, 1996.
- Pisacane, V.L. "The Space Environment and its Effects on Space Systems", AIAA Press, Reston, VA, 2008

USEFUL INTERNET SITES FOR SPACE ENVIRONMENT EFFECTS

http://see.msfc.nasa.gov/	MSFC SEE Homepage
http://crsp3.nrl.navy.mil/	CREME96 Homepage
http://sat-nd.com/#FAILURES	Recent Satellite Outages and Failures
http://standards.nasa.gov/	NASA TECHNICAL STANDARDS PROGRAM
http://engineer.jpl.nasa.gov/standards.html	Space Engineering Standards (JPL)
http://www.swpc.noaa.gov/	Today's Space Weather
http://spaceweather.com/	The NASA Space Weather Bureau
http://www.ngdc.noaa.gov/	National Geophysical Data Center
http://geomag.usgs.gov/	USGS Geomagnetism Program
http://www.ngdc.noaa.gov/geomag/	Geomagnetic Field Models
http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html	International Geomagnetic Reference Field
http://portal.cssdp.ca:8080/ssdp/jsp/logon.jsp	Canadian Space Data Data
http://www.meteorblog.com/	Meteor Showers
http://www.imo.net/index.html	International Meteor Organization Index
http://www.orbitaldebris.jsc.nasa.gov/	Debris Models
http://www.geo.mtu.edu/weather/aurora/	The Aurora
http://www.ngdc.noaa.gov/dmsp/	DMSP Auroral Photos (Latest Aurora)
http://www.ngdc.noaa.gov/stp/GOES/goes.html	GOES Daily Satellite Data (Geosynchronous)
http://nssdc.gsfc.nasa.gov/cd-rom/cd-rom.html	NSSDC CD Catalog of Space Data
http://hubblesite.org/newscenter/	HST Pictures
hhttp://www.nasa.gov/home/index.html	NASA Space Link Educational Data Base
http://www.jpl.nasa.gov/	JPL Homepage
http://www.cmf.nrl.navy.mil/clementine/	NRL Clementine Site
http://umbra.nascom.nasa.gov/spd/	NASA Space Physics--Mission Descriptions
http://www.cambridge.org/catalogue/ catalogue.asp?isbn=9780521607568	My Spacecraft-Environment Interactions Book

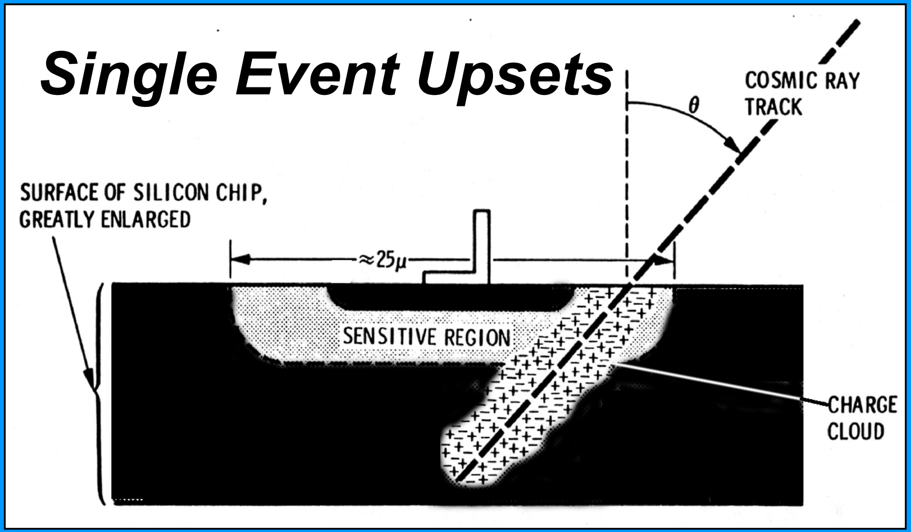
Backup

Jupiter

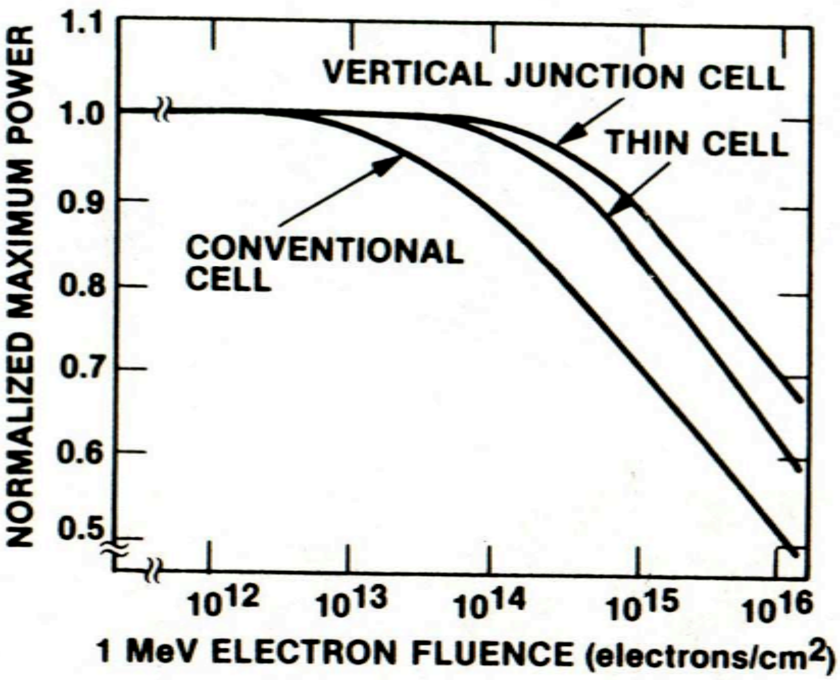


SOLAR PROTON EVENTS:

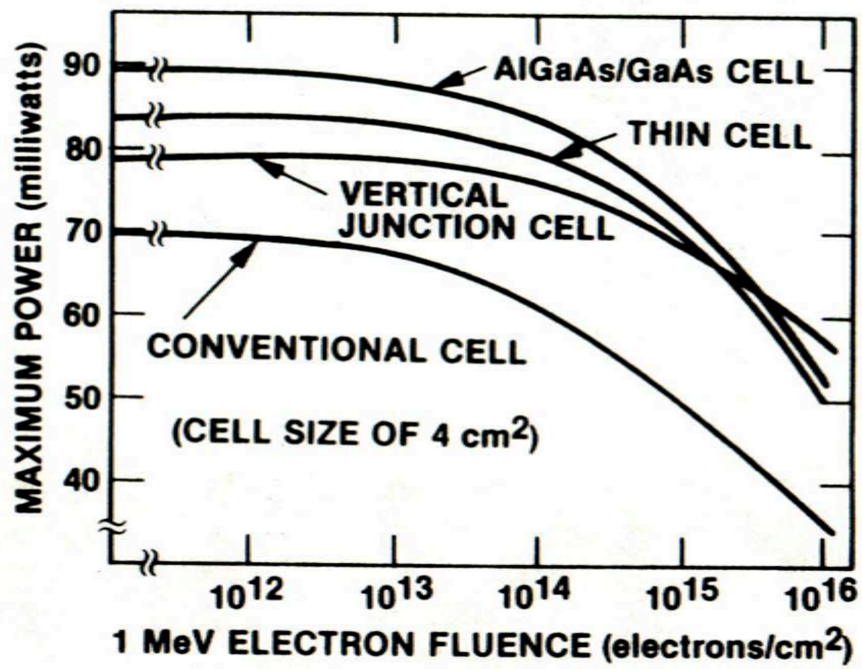
SPACE "RAIN"



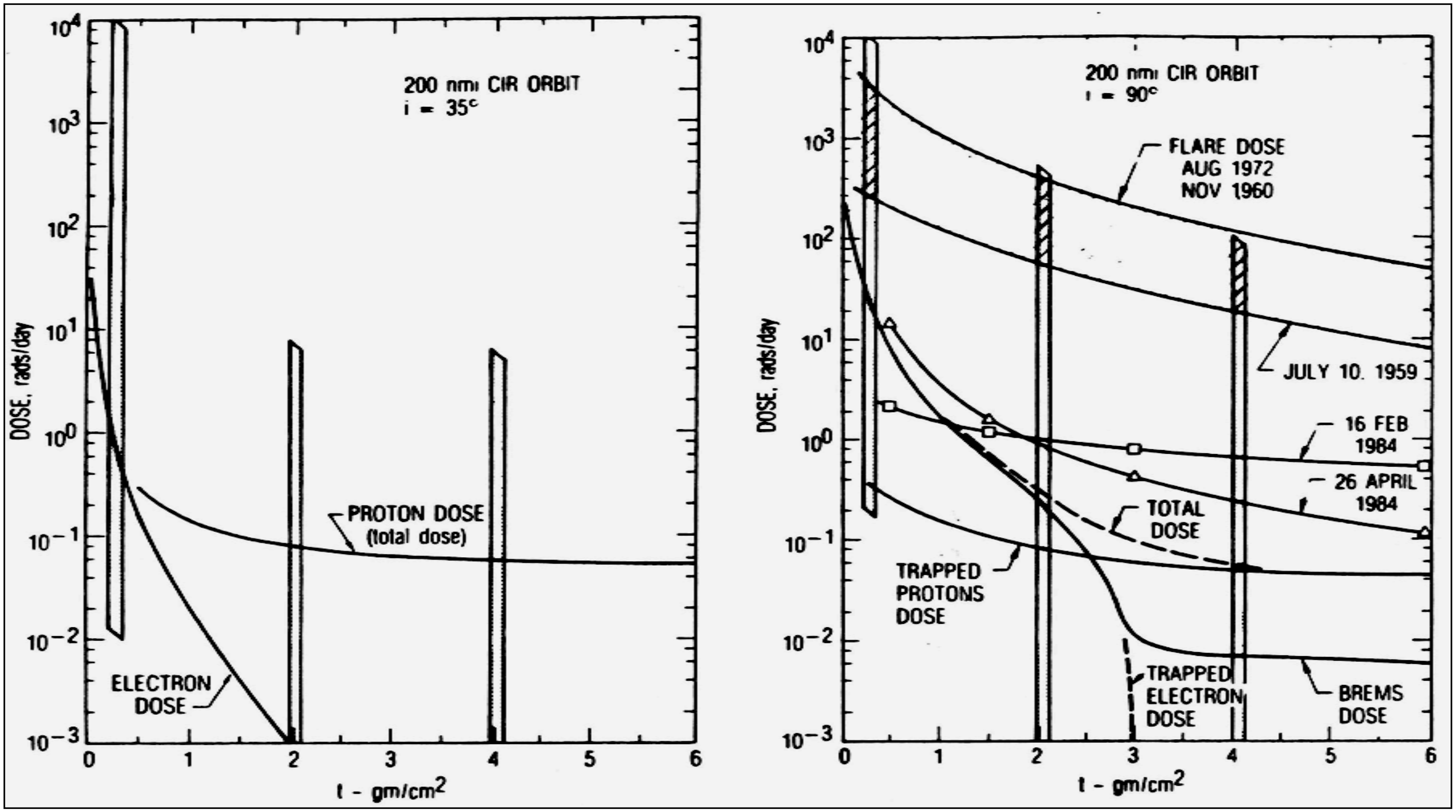
Radiation Effects on Solar Cell Power



SOLAR CELL GEOMETRY EFFECTS vs ELECTRON DAMAGE



COMPARISON OF AlGaAs/GaAs CELLS WITH SILICON CELLS OF VARIOUS GEOMETRIES AFTER ELECTRON IRRADIATION



Dose-Depth Curves for 35° and 90° 200 NM Orbits

Integrated Approach to Mission Design

KEY ENVIRONMENTS VERSUS INTERACTIONS

INTERACTIONS

ENVIRONMENTS	TOTAL IONIZING DOSE	SINGLE EVENT UPSETS	LATCH-UP	SURFACE CHARGING	INTERNAL CHARGING	PLASMA WAKE/SHEATH	POWER LOSS	VxB	SURFACE DAMAGE	CONTAMINATION	GLOW	PARTICLE IMPACTS	TORQUES	THERMAL
NEUTRAL ATMOSPHERE									X	x	X		X	x
E,B FIELDS				x		x	x	X					X	
EM FIELDS						x								X
SOLAR WIND PLASMA				x									X	
IONOSPHERE PLASMA				x		X	X	x						
AURORA PLASMA				X										
TRAPPED RADIATION	X	X	x		X		X							
GALACTIC COSMIC RAYS		X	x											
SOLAR PROTON EVENTS	X	X	X				x							
METEOROIDS							x					X	X	
DEBRIS							x					X	X	

*Legend: **X** = Major Effect x = Observable Effect x = Minor Effect

(Note: assessment very dependent on spacecraft design)

Integrated Approach to Mission Design

DESIGN OPTIONS VERSUS INTERACTIONS

INTERACTIONS

DESIGN OPTIONS	TOTAL IONIZING DOSE	SINGLE EVENT UPSETS	LATCH-UP	SURFACE CHARGING	INTERNAL CHARGING	PLASMA WAKE/SHEATH	POWER LOSS	VxB	SURFACE DAMAGE	CONTAMINATION	GLOW	PARTICLE IMPACTS	TORQUES	THERMAL
SHIELDING	X	X	x	X	X		X			X		X		X
POSITIONING	X	x	x	X	x	X	X	X	X	X	X	X	X	X
MATERIAL PROPERTIES				X	X	x	X		X	X			X	X
EDAC SOFTWARE	x	X	X	x	x									
REDUNDANCY	x	X	X									x		
CIRCUIT DESIGN	X	X	X	X	X	x	X	x						x
MARGIN/HARDNESS	X	X	X	x	x				x			X		X
GROUNDING				X	X			X		x				
TRAJECTORY	X	x	x	X	X	x	x	X	X		X	X	X	x
OPERATIONAL PROCEDURES	x	x	x	x	x					x	X		X	
CONSTRUCTIONS METHODS				X	X	x	x		x	X	x			

*Legend: **X** = Major Effect x = Observable Effect x = Minor Effect

(Note: Assessment very dependent on spacecraft design)

Integrated Approach to Mission Design

DESIGN OPTIONS VERSUS MISSION DESIGN FACTORS

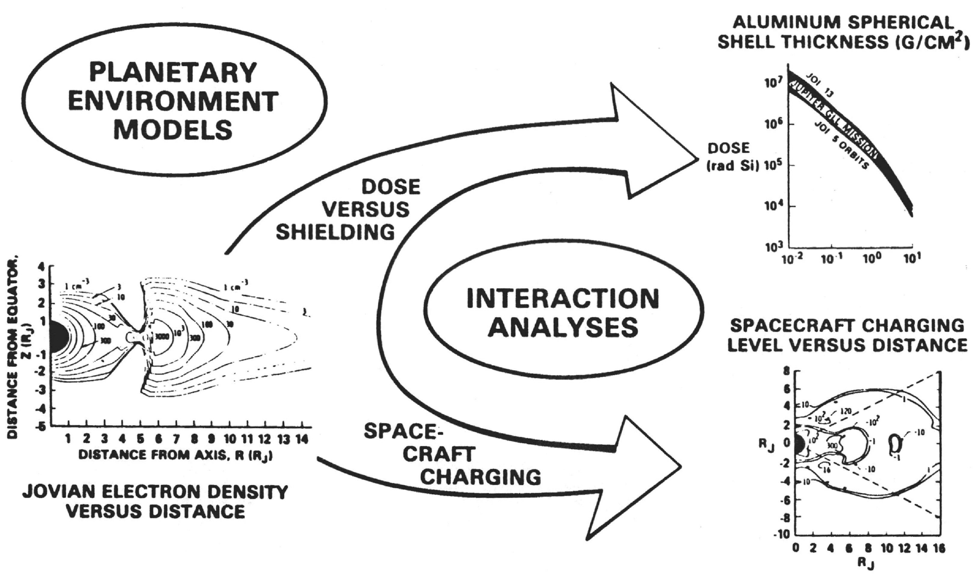
DESIGN OPTIONS	COST	WEIGHT	POWER	COMPLEXITY	RELIABILITY	AVAILABILITY	USABILITY	SPECIAL ISSUES
SHIELDING	**X**	**X**	x	**X**	x		**X**	**X**
POSITIONING	x	$\scriptstyle x$	$\scriptstyle x$	**X**	$\scriptstyle x$	x	**X**	**X**
MATERIAL PROPERTIES	**X**	$\scriptstyle x$		**X**	x		$\scriptstyle x$	**X**
EDAC SOFTWARE	**X**			**X**	**X**	x	**X**	
REDUNDANCY	**X**	**X**		**X**	**X**	x	x	
CIRCUIT DESIGN	x	x	**X**	**X**	x	**X**	x	**X**
MARGIN/HARDNESS	**X**		x	x	**X**	**X**	**X**	x
GROUNDING	$\scriptstyle x$		x	x	x			**X**
TRAJECTORY	**X**		$\scriptstyle x$	x	x	x		**X**
OPERATIONAL PROCEDURES	$\scriptstyle x$		x	$\scriptstyle x$	x	**X**	$\scriptstyle x$	x
CONSTRUCTION METHODS	$\scriptstyle x$	x	x	x	x			**X**

*Legend: **X** = Major Effect x = Observable Effect $\scriptstyle x$ = Minor Effect

(Note: Assessment very dependent on spacecraft design)

Environmental Requirements Procedural Flow

- THE FIRST STEP IS TO DEFINE THE ENVIRONMENT(S) THAT THE SPACECRAFT CAN BE EXPECTED TO ENCOUNTER.
- STEP TWO IS TO ANALYZE POTENTIAL ENVIRONMENTAL INTERACTIONS THAT COULD BE OF CONCERN
- THE THIRD STEP IS TO CARRY OUT APPROPRIATE STEPS TO MITIGATE THE ADVERSE INTERACTIONS
- THE SPACECRAFT DESIGN IS EVALUATED THROUGH TESTING TO VERIFY THAT IT CAN FUNCTION UNDER THE PRESCRIBED RANGE OF ENVIRONMENTAL CONDITIONS
- IN-FLIGHT DATA FROM THE ACTUAL SPACECRAFT IS ANALYZED TO DETERMINE HOW WELL THE DESIGN METHODS WORKED
- FINALLY, THE INFORMATION LEARNED FROM THE FLIGHT IS USED TO UPDATE AND DEVELOP BETTER MODELS FOR FUTURE DESIGNERS



Estimated Plasma Parameters/Potentials in the Solar System

REGION	ALTITUDE	N_0, cm^{-3}	IONS	CHARACTERISTIC ENERGY, eV		λ_D, m		V, km/s	J_{PH}, nA cm^{-2}	POTENTIAL, † V					
										SUNLIGHT			ECLIPSE		
				I^+	E^-	I^+	E^-			1-D	RAM	3-D	1-D	RAM	3-D
VENUS	200 km	10^5	O^+, O_2^+	0.05	0.3	0.005	0.01	8	8	-1.2	-1.0‡	-0.83	-1.8	-1.2	-0.88
	1500 km	10^2	O^+	0.2	1	0.33	0.74	8	8	6.0	6.0‡	2.4	-5.6	-4.4‡	-2.9
EARTH	150 km	10^5D*	O^+, O_2^+, NO^+	0.1	0.2	0.007	0.01	8	2	-1.1	-0.7‡	-0.55			
		10^3N*	NO^+	0.05	0.1	0.05	0.07	8	2				-0.58	-0.33‡	-0.37
	1000 km	10^4D	O^+	0.3	0.4	0.04	0.05	8	2	-1.3	-1.2‡	-1.2			
		10^4N	H^+	0.2	0.2	0.03	0.03	8	2				-0.75	-0.73‡	-0.52
	3.5 R_E	10^3	H^+	1	1	0.23	0.23	3.7	2	-1.6‡	-1.6	-1.4	-3.8‡	-5.2	-2.5
GEOSYNCHRONOUS	5.62 R_E	2	H^+	5000	2500	370	260	3	2	2.0	1.9	2.0‡	-8500	-23000	-8500‡
HIGH LATITUDE		0.1	H^+	200	200	330	330	800	2	15.	15.‡	15.	-750	-490‡	-500
JUPITER															
COLD TORUS	3.5-5.5 R_J	50-1000	S^+, O^+, O^{++}	0.5	0.5	0.74	0.74	44	0.08	-0.75	-0.59‡	-0.72	-2.3	-1.2‡	-1.6
				2	1	0.33	0.23	69	0.08	-3.8	-2.2‡	-3.1	-4.2	-2.3‡	-3.3
HOT TORUS	6.0-8.0 R_J	1000-100	S^+, O^{++}	40	10	1.5	0.74	75	0.08	-37	-34‡	-33	-39	-34‡	-33
				80	20	6.6	3.3	100	0.08	-65	-60‡	-60	-78	-70‡	-65
PLASMA SHEET	8.0-15 R_J	12	H^+, S^{++}	50	50	15	15	150	0.08	-110	-110	-94‡	-190	-170	-130‡
OUTER MAGNETOSPHERE		0.01	H^+	1000	1000	2300	2300	250	0.08	9.6	9.5	9.5‡	-3800	-4400	-2500‡
SOLAR WIND	0.3 AU	50	H^+	40	65	6.6	8.5	500	20	4.6	4.9‡	4.4	-260	-150‡	-160
	1.0 AU	2	H^+	10	50	17	37	450	2	7.8	8.0	7.3‡	-230	-120	-110‡
	5.2 AU	0.2	H^+	1	10	17	53	400	0.08	7.4	8.0	6.0‡	-50	-18	-21‡

MOST VALUES ARE ROUGH ESTIMATES (SEE APPENDIX B)
* D MEANS DAY, AND N NIGHT
† SEE APPENDIX B FOR DESCRIPTION OF COMPUTATION AND CAPTIONS
‡ "PREFERRED" ESTIMATES

Radiation Definitions

FUNDAMENTAL UNITS OF ENERGY:

- ERG: (CGS SYSTEM) 1 ERG = 1 $G\text{-}CM^{2}\text{-}S^{-2}$
- JOULE: (MKS SYSTEM) 1 J = 1 $KG\text{-}M^{2}\text{-}S^{-2}$
- ELECTRON VOLT (EV) 1 EV = 1.602×10^{-12} ERG = 1.602×10^{-19} J

FUNDAMENTAL UNITS OF ENERGY ABSORPTION (DOSAGE):

- RADS*: (CGS SYSTEM) 1 RAD (SI) =100 ERG/G (SI)
- GRAY.: (MKS SYSTEM) 1 GY (GRAY) = 1 JOULE/KG
  1 GY = 100 RAD = 10^{4} ERG/G

FUNDAMENTAL UNIT OF INTENSITY OR FLUX:

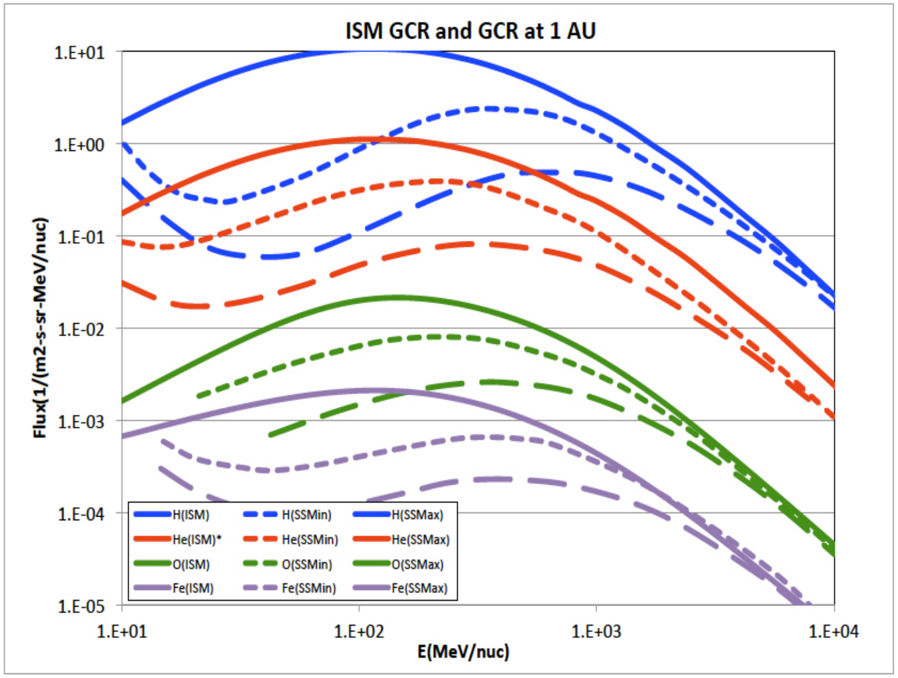
- FLUX: NUMBER PER UNIT TIME OF ENERGY E PER UNIT ENERGY INTERVAL dE IN SOLID ANGLE ($d\Omega = \cos\theta \, d\theta \, d\phi$) IN DIRECTION θ, ϕ INCIDENT ON UNIT SURFACE AREA (dA) PERPENDICULAR TO DIRECTION OF OBSERVATION.

- PROTONS OR ELECTRONS: $PARTICLES\text{-}CM^{-2}\text{-}S^{-1}\text{-}SR^{-1}\text{-}KEV^{-1}$
- HEAVY IONS: $PARTICLES\text{-}M^{-2}\text{-}S^{-1}\text{-}SR^{-1}\text{-}MEV^{-1}\text{-}\mu^{-1}$
  (μ ="NUCLEON")

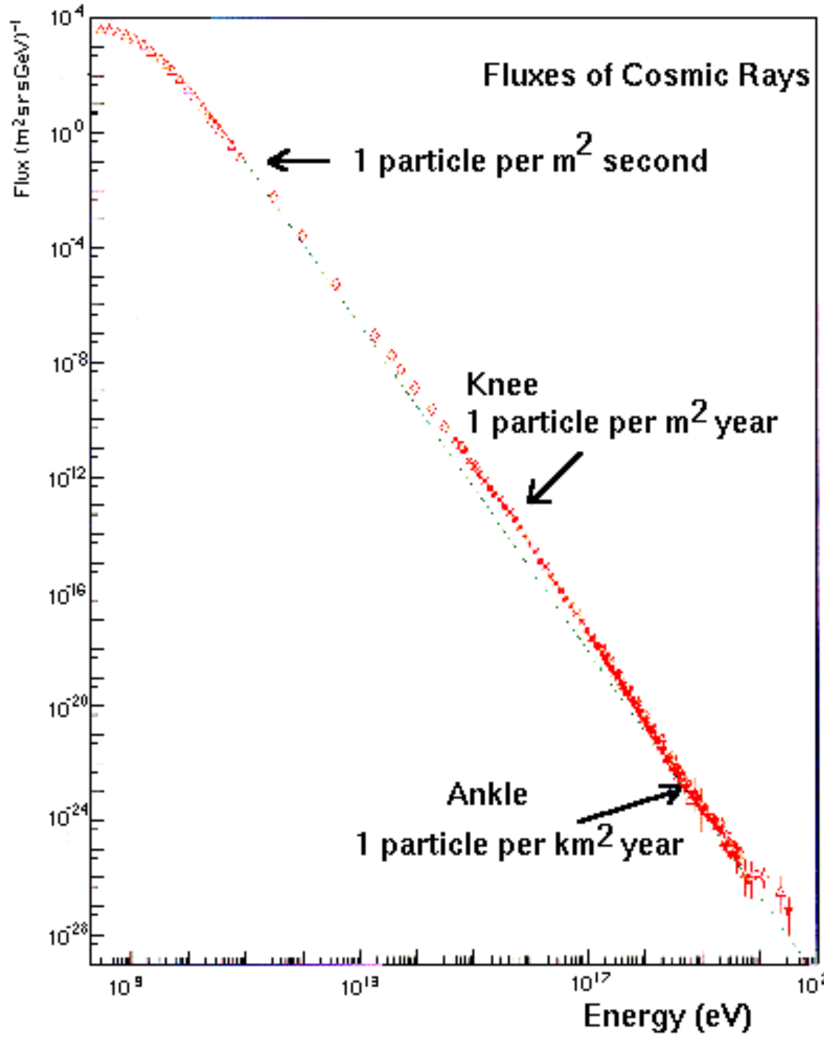
RAD: "RADIATION ABSORBED DOSE"

Galactic Cosmic Rays

Cosmic Ray Nuclear Species Spectra at 1 AU

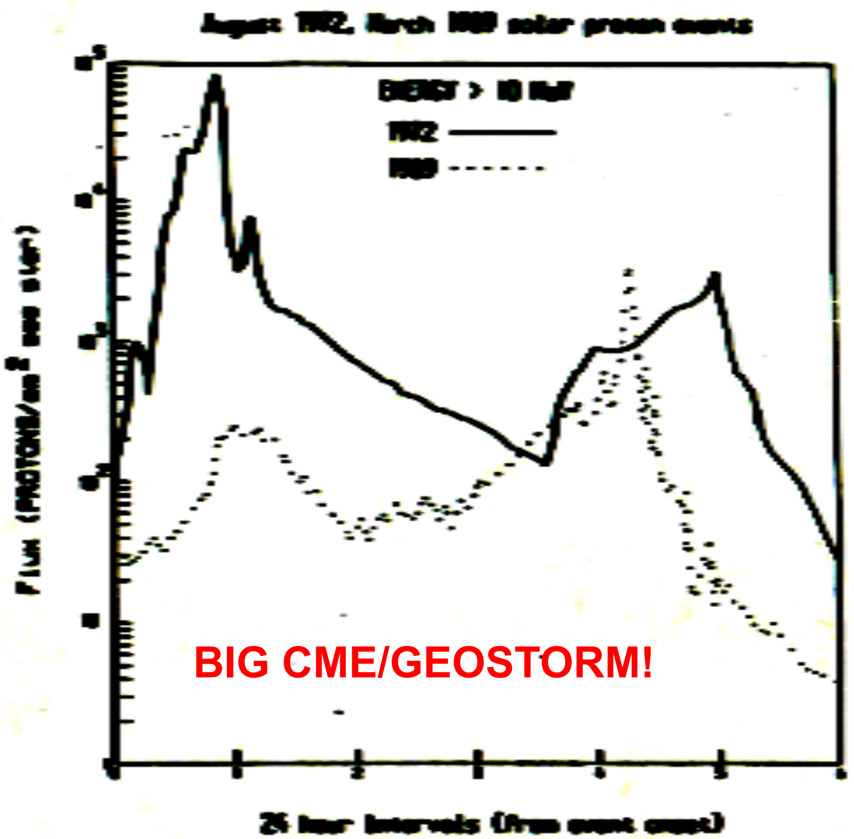


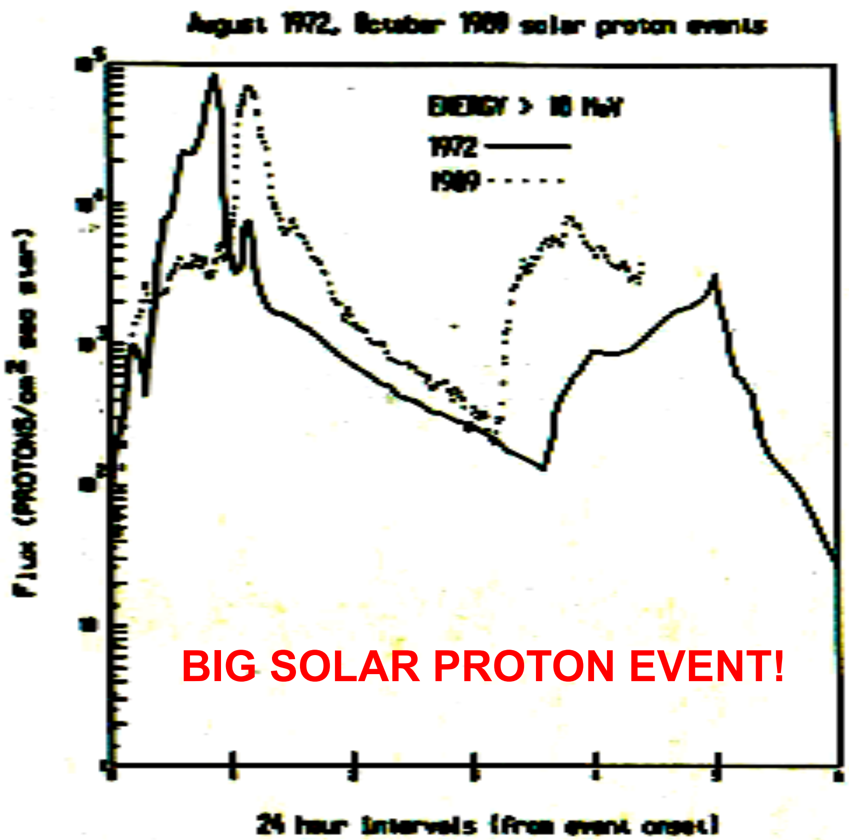
GCR ions at 1 AU for SSMin and SSMax and in Interstellar Space (R. Mewaldt and others).



Solar Proton Events and CMEs

March–October 1989 Solar Proton Events Compared with August 1972 Event for E>10 MEV





SPE and CME Effects on Spacecraft Systems

OCTOBER 1989 STORM EFFECTS ON SPACECRAFT (PRELIMINARY)

- 6% AVERAGE LOSS IN SOLAR ARRAY OUTPUT ON AF GEOSYNCHRONOUS SPACECRAFT DURING OCTOBER EVENT
- 0.6 AMP DROP IN GOES-7 SOLAR ARRAY OUTPUT (SIMILAR DROP ON GOES-5 AND -6)
- 7 SEU'S OBSERVED ON GOES-5 AND -6
- 6% DROP IN MAGELLAN SOLAR ARRAY OUTPUT DURING OCTOBER EVENT
- SEVERE PROBLEMS WITH MAGELLAN STAR SCANNER
- DMSP MICROWAVE TRANSMISSIONS LOST
- 50 SEU RAM HITS ON TDRS-A ON 19-20 OCTOBER; 2 SEU'S ON TDRS-C; 4 SEU'S ON TDRS-D
- INTELSAT 6 "PITCH GLITCHES"
- 8 SEU'S ON PIONEER VENUS
- INSAT 1B ATTITUDE CONTROL LOSS ON OCTOBER 20 (ATTRIBUTED TO SPACECRAFT CHARGING)

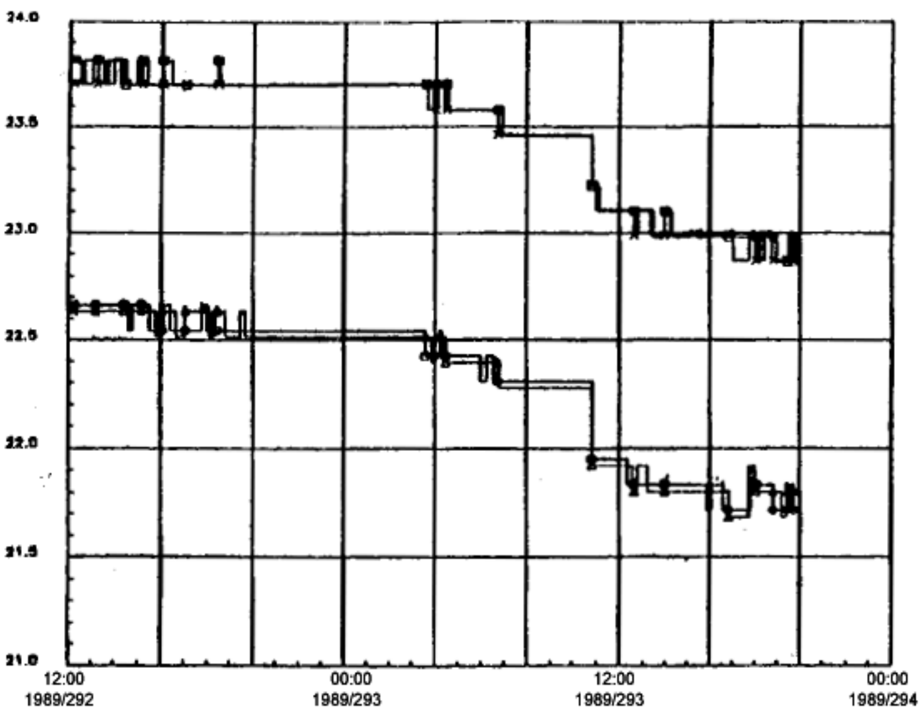
MARCH 1989 STORM EFFECTS ON SPACECRAFT

- GOES-7 COMMUNICATIONS CIRCUIT ANOMALY ON 12TH; IMAGERY LOSS ON 13TH
- JAPANESE COMMUNICATIONS SATELLITE CS-3B ANOMALY ON 17TH; PERMANENT LOSS OF HALF OF DUAL REDUNDANT COMMAND CIRCUI
- JAPANESE GEOSTATIONARY SATELLITE GMS-3 SUFFERED SEVERE SCINTILLATIONS DURING 1200-1430 UT ON 23 MARCH. DATA TRANSMISSIONS LOST FOR HOUR ON 23 MARCH.
- UNCONFIRMED SEU HITS ON SHUTTLE DISCOVERY DURING LAUNCH
- UNCONFIRMED SEU HITS ON TDRS D DURING INJECTION
- 7 COMMERCIAL GEOSYNCHRONOUS SPACECRAFT HAD ORBITAL ATTITUDE ANOMALIES--177 THRUSTER FIRINGS REQUIRED TO CORRECT
- INTELSAT ANOMALIES REPORTED ON 18 AND 20 MARCH
- TDRS CPE ANOMALY ON 18 MARCH
- MARECS-1 (177°) HAD SEVERAL SWITCHING EVENTS ON MARCH 3, 17

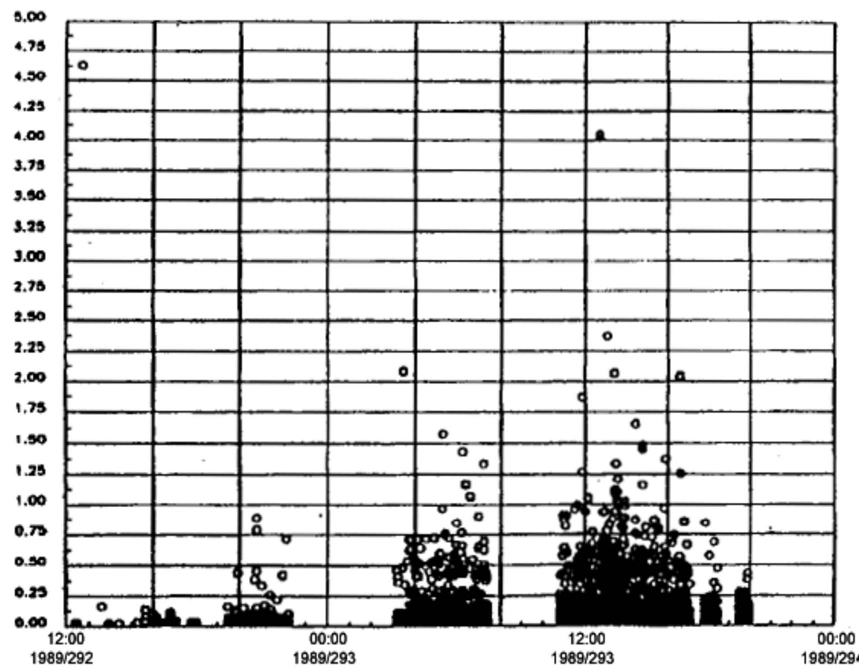
Data Courtesy Joe Allen

1989 Solar Proton Event Effects on Magellan

SOLAR ARRAY CURRENT

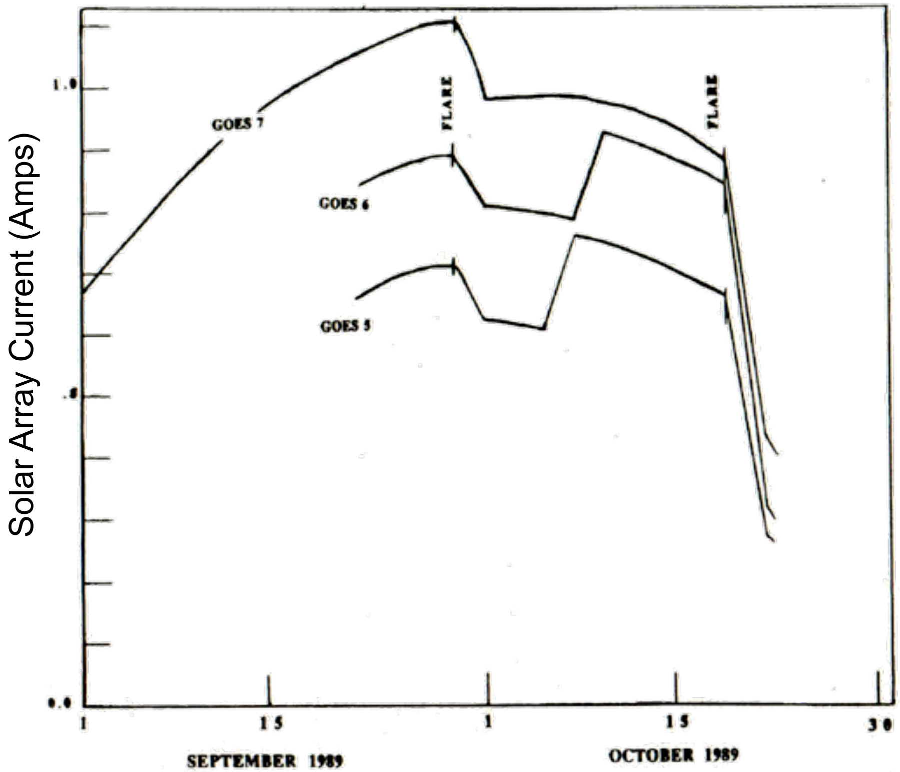


STAR SCANNER VOLTAGE

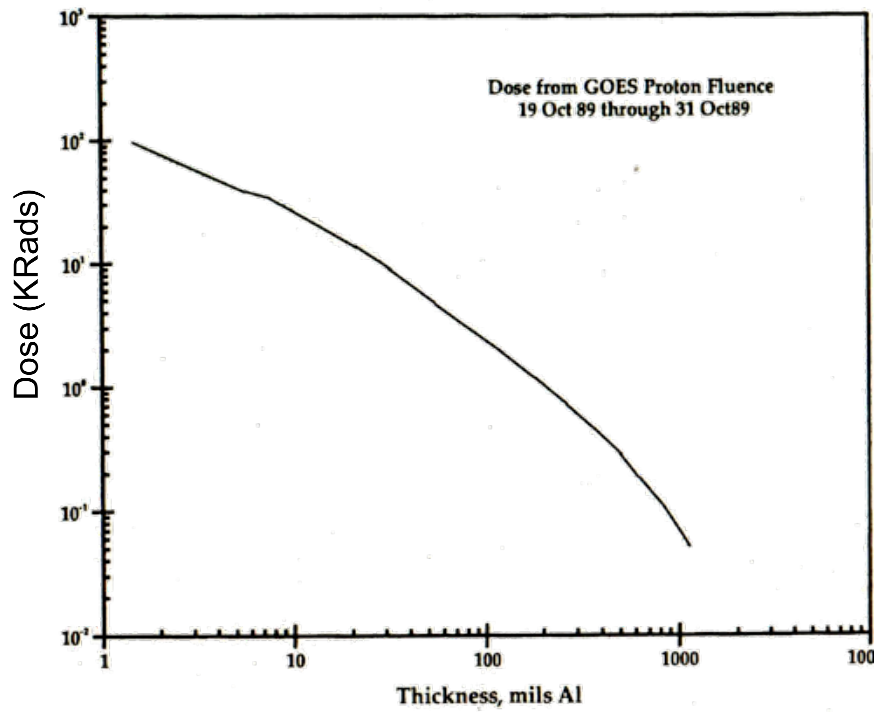


1989 Solar Proton Event Effect on Geosynchronous Orbit

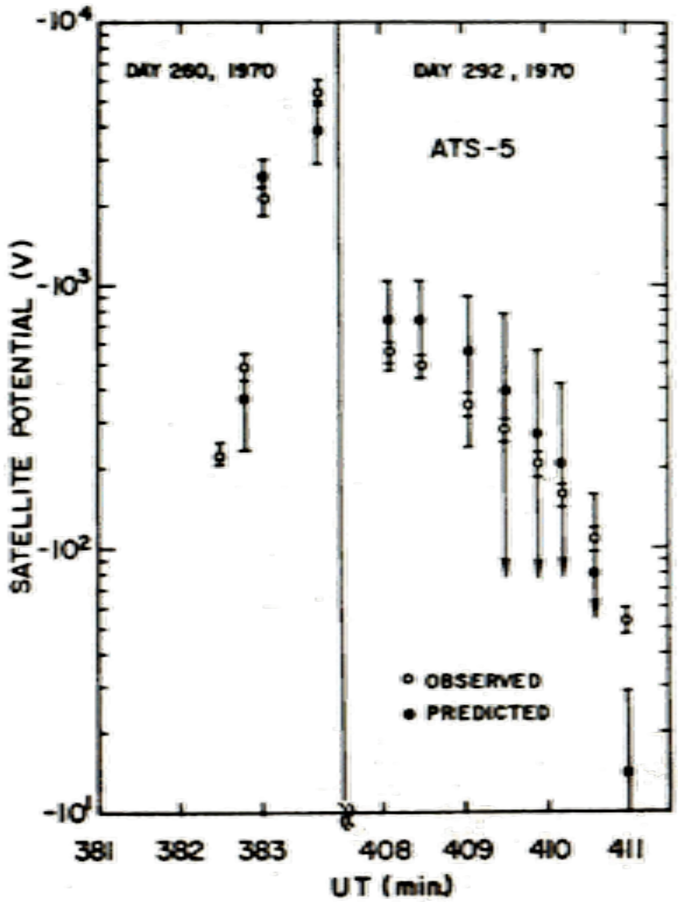
GOES 5, 6, AND 7 SOLAR ARRAY CURRENT VARIATIONS

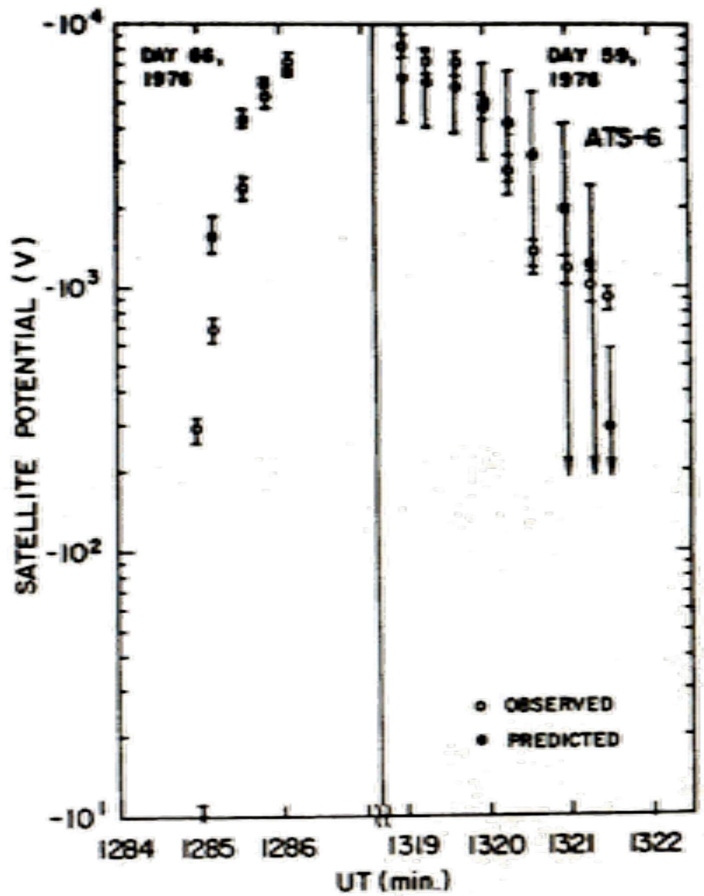


OCTOBER 1989 GOES PROTON DOSE

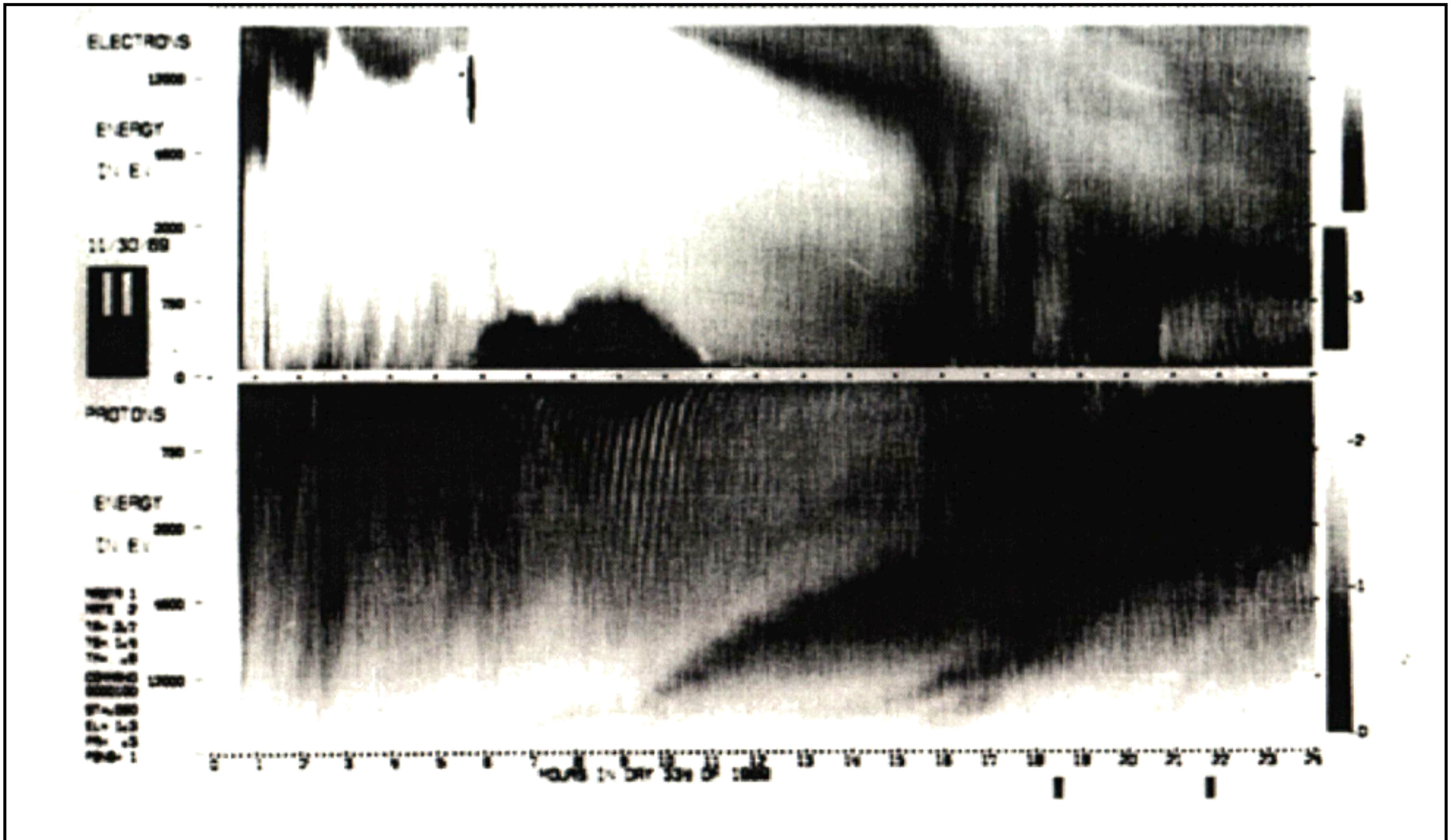


OBSERVED AND PREDICTED POTENTIALS DURING ECLIPSE PASSAGE AT GEOSYNCHRONOUS

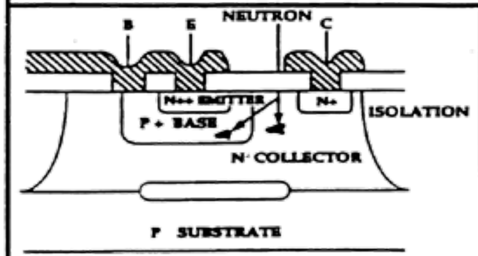
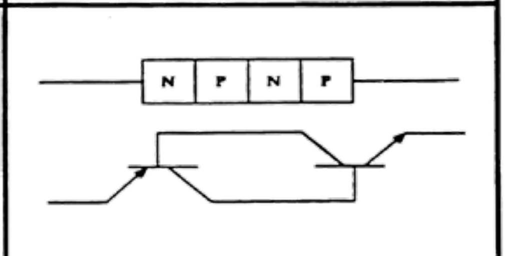




Differential Charging on ATS-5

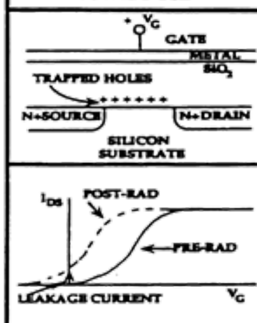
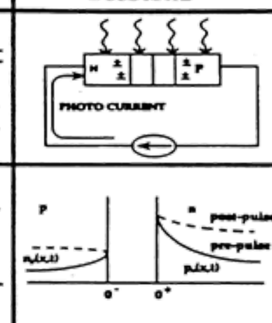
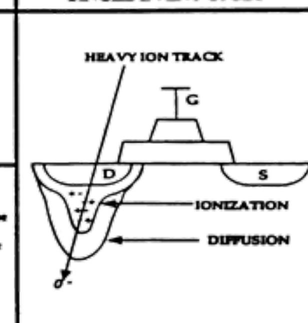


RADIATION EFFECTS ON MICRO-ELECTRONICS

NEUTRON	LATCHUP
	
- CREATES CRYSTAL DISLOCATION DAMAGE IN SEMICONDUCTOR LATTICE - RESULTS IN LEAKAGE CURRENTS, RECOMBINATION, DEGRADED CIRCUIT PERFORMANCE - MINORITY CARRIER DEVICES (I.E., BIPOLAR) ARE MORE SUSCEPTIBLE TO NEUTRON IRRADIATION THAN MOS DEVICES	- HIGH CURRENT CONDITION - ACTIVATION OF A PARASITIC SILICON-CONTROLLED RECTIFIER - DOSE RATE AND SEU INDUCED - TRANSISTOR MUST BE POWERED OFF IMMEDIATELY OR DEVICE BURNOUT OCCURS - ISOLATED TECHNOLOGIES IMMUNE

Effects:

- ***Neutron Effects***
- ***Latchup***
- ***Total Dose***
- ***Dose Rate***
- ***Single Event Upset***

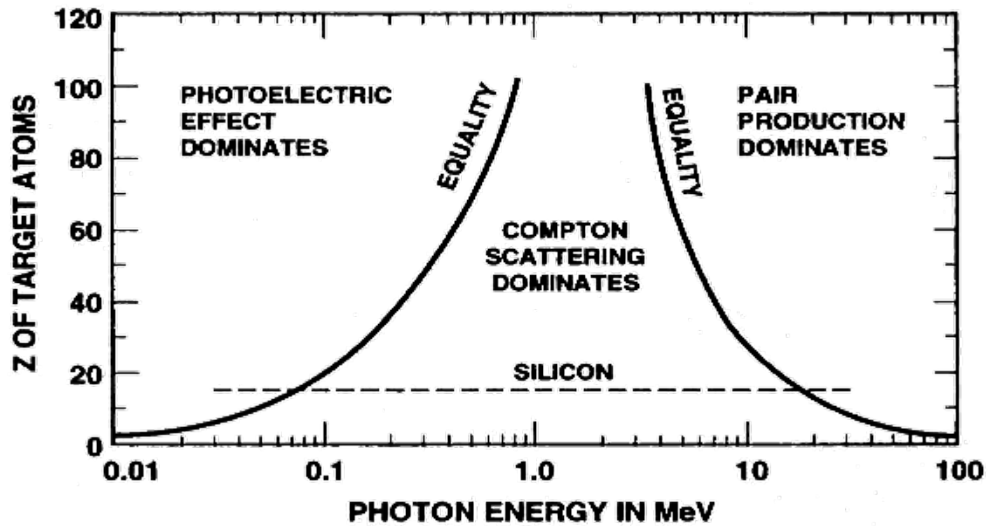
TOTAL DOSE	DOSE RATE	SINGLE EVENT UPSET
		
- CHARGE BUILDUP IN INSULATOR - TRAPPED CHARGE CREATES THRESHOLD VOLTAGE SHIFTS AND LEAKAGE CURRENTS - AT EXTREME, DEVICES REMAIN ALWAYS ON OR ALWAYS OFF	- ELECTRON-HOLE PAIR GENERATION - LARGE JUNCTION CURRENTS - DEVICE CAN UPSET OR BURN OUT - DEVICE SURVIVABILITY REQUIRES MAINTAINING FUNCTIONALITY	- HIGH ENERGY, HEAVY IONS DEPOSIT SUFFICIENT CHARGE ALTERING STORED INFORMATION - HIGH ENERGY PROTONS CREATE NUCLEAR REACTION CAUSING UPSET - HIGH ALTITUDE AND INCLINED SATELLITES VULNERABLE

Radiation Effects on Devices

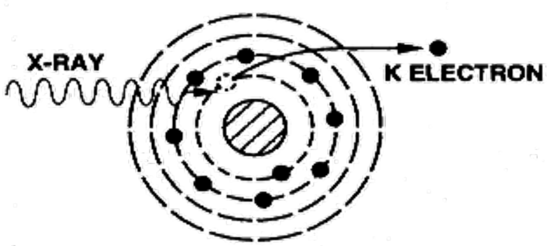
Type of Radiation Effect	Effect on Devices
• **Total Ionizing Dose (TID) – protons, electrons, gamma rays**	Both gradual, parametric degradation and sudden functional failure – cumulative effect
– Enhanced low dose rate effect	Severe Radiation Hardening Assurance problem in linear bipolar devices
• **Single Event Effects (SEE)**	
– protons, heavy ions	Variety of single particle effects
– Single Event Upset (SEU)	Soft failures – change in logic state
– Single Event Latchup (SEL)	Functional and catastrophic failure
– Single Event Burnout (SEB)	Catastrophic failure in power transistors
– Gate Rupture (SEGR)	"Hard SEU"
– Single Event Functionality Interrupt (SEFI)	Recoverable functional failure; change in operating mode
– Single Event Dielectric Rupture (SEDR)	"Hard" SEUs; similar to SEGR, FPGA antifuse shorting
• **Displacement damage effects** – protons, neutrons	Bulk lattice damage – "billiard ball" collisions Analog devices, solar cells, optocouplers
• **Single particle "microdose"** – heavy ions	TID failure of a single transistor – "weak" bits
• **Single particle-induced transients in linear/ analog parts**	Large transients that can upset digital circuits

Photon Interactions with Matter

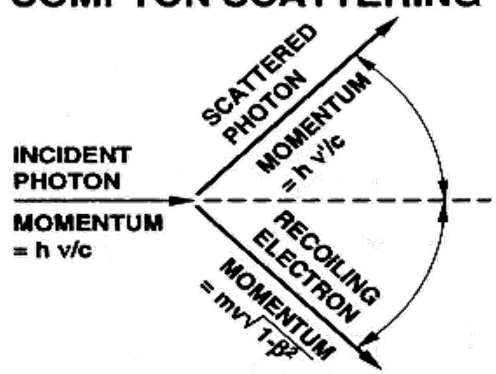
RANGE OF IMPORTANCE



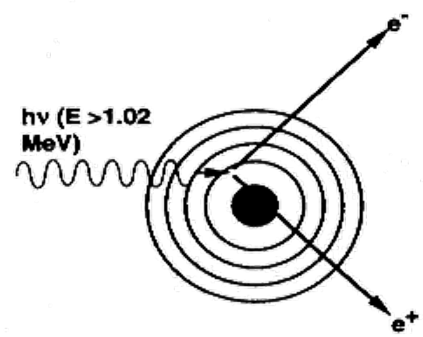
PHOTOELECTRIC



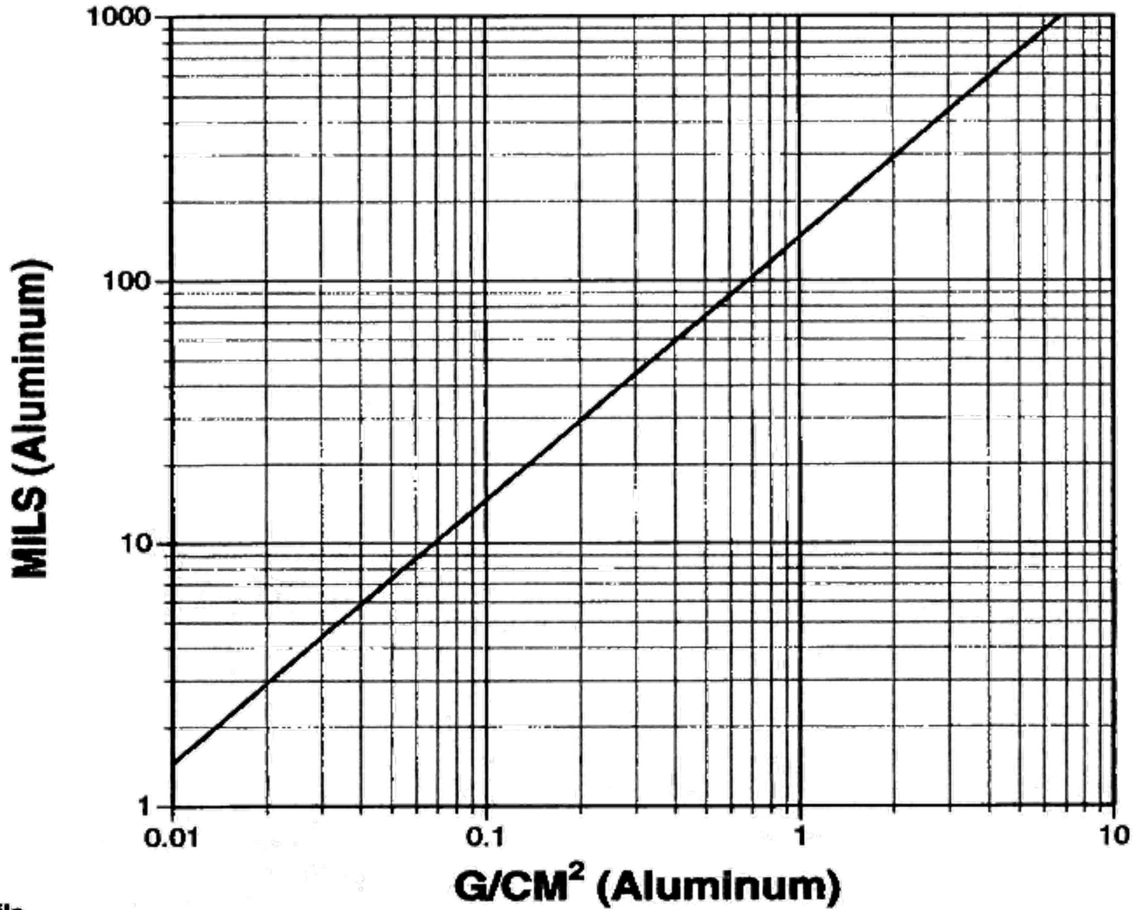
COMPTON SCATTERING



PAIR PRODUCTION



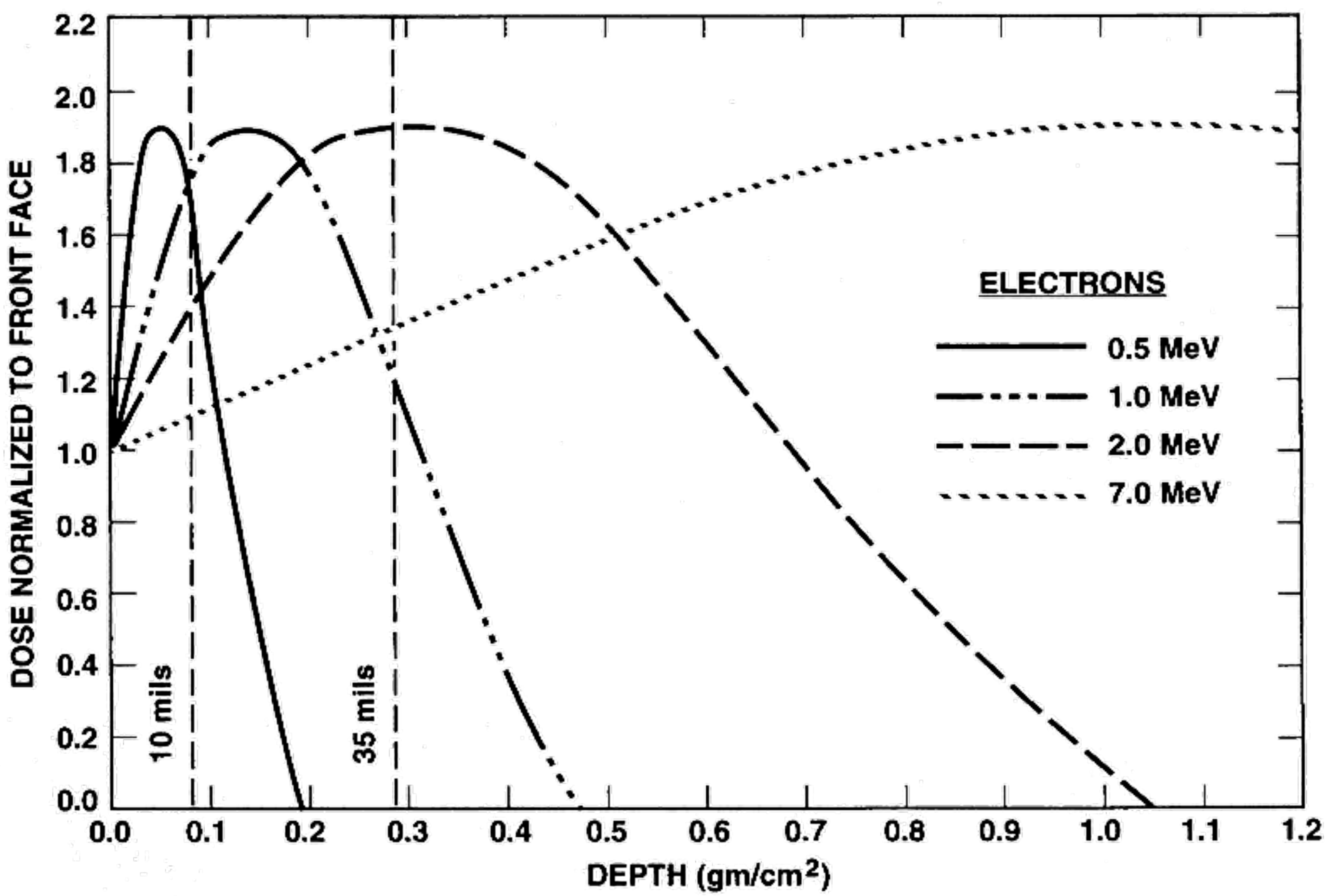
MILS TO G/CM^2 CONVERSION FOR ALUMINUM (ρ = 2.7 G/CM^3)



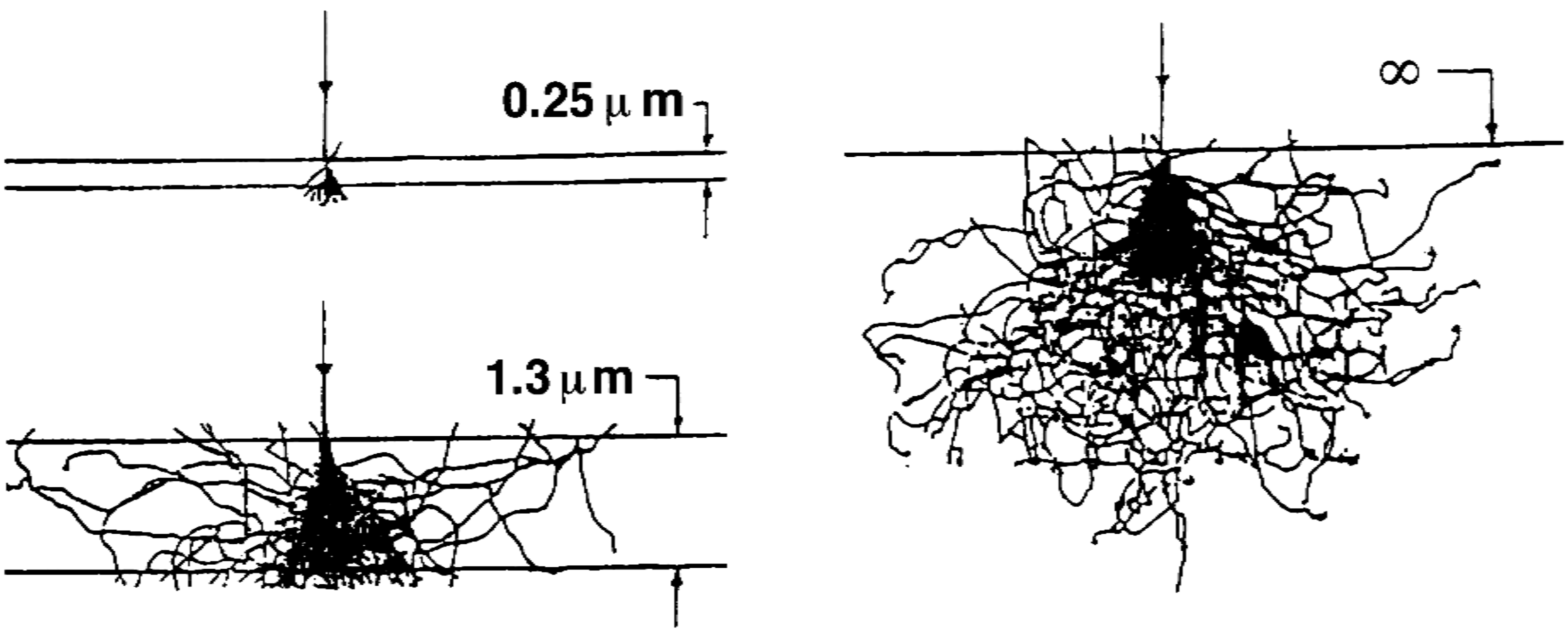
1 g/cm^2 = 145.8 mils
100 mils = .686 g/cm^2
1 mm = 39.3 mils

CHARGED PARTICLE INTERACTIONS (Cont'd)

ELECTRON DOSE vs DEPTH FOR CaFMg

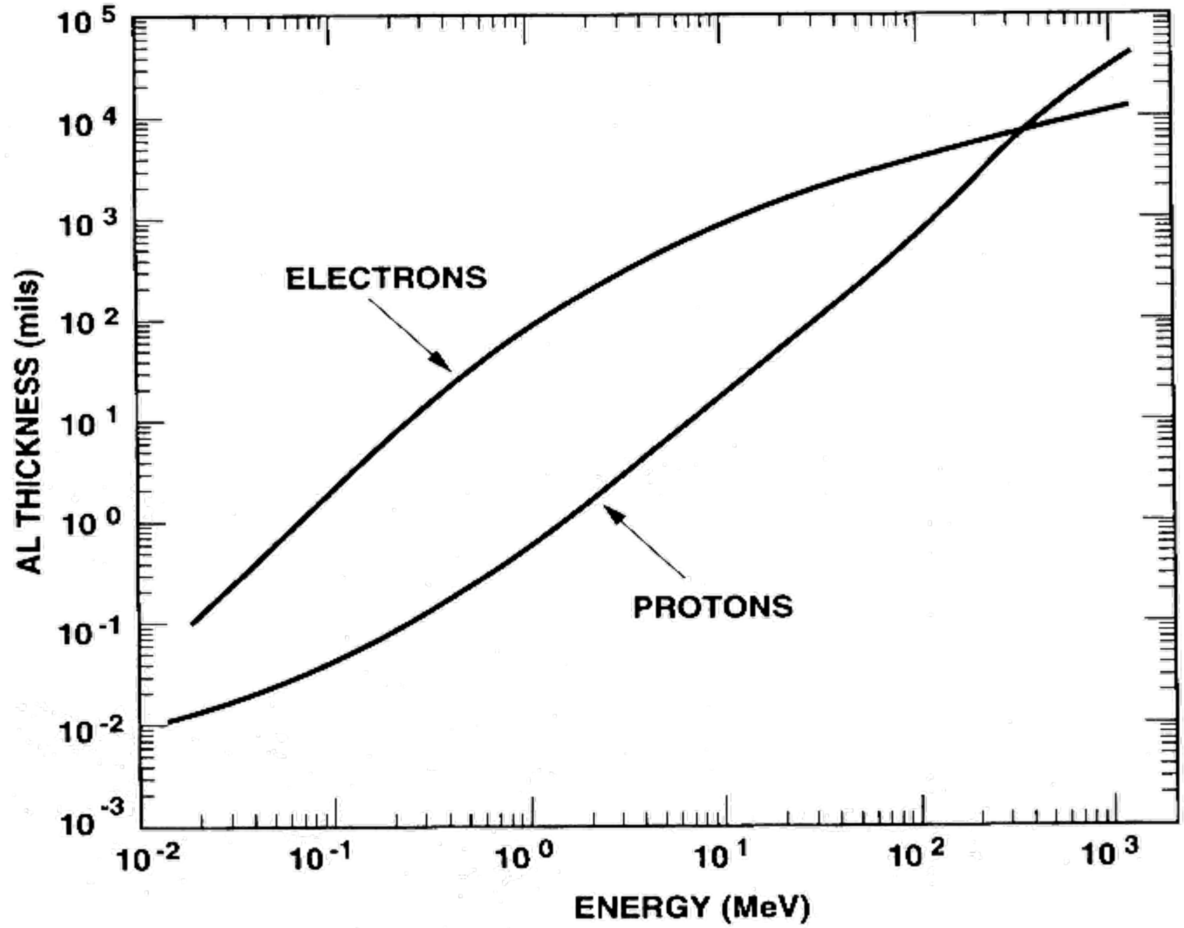


Radiation Transport: Electron Monte Carlo Simulations



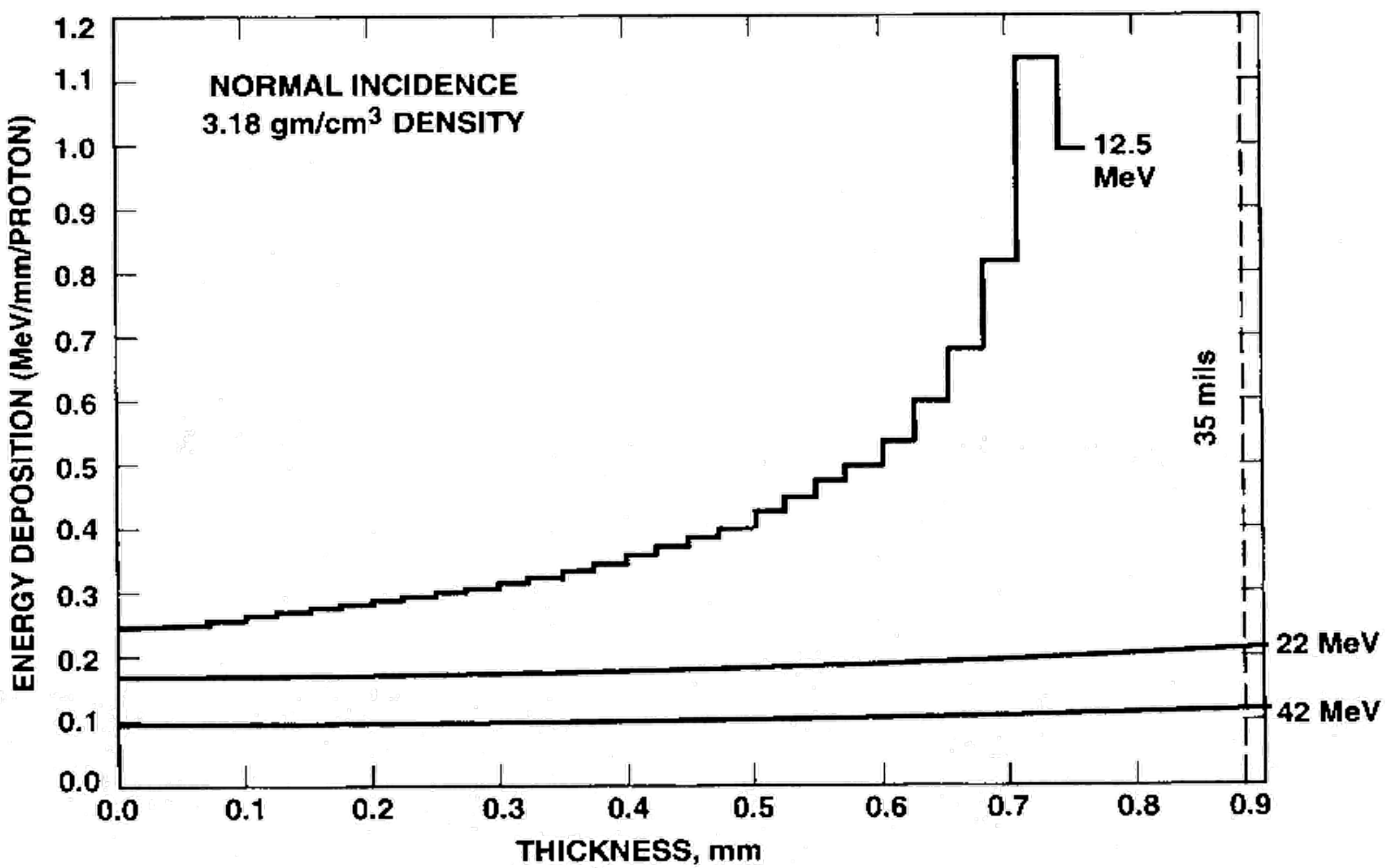
CHARGED PARTICLE INTERACTIONS

PROTON/ELECTRON ENERGY vs PENETRATION DEPTH FOR AL

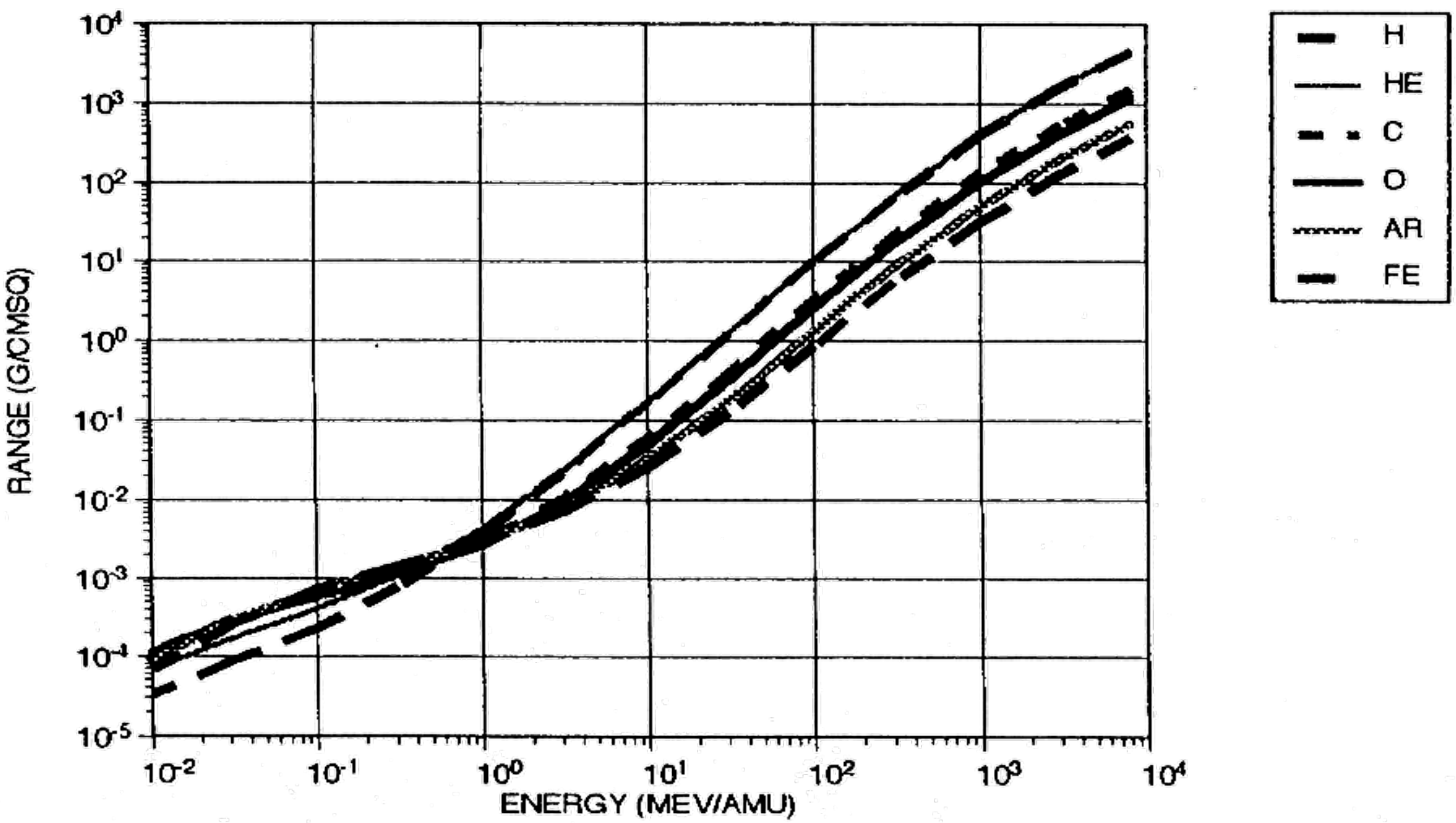


CHARGED PARTICLE INTERACTIONS (Cont'd)

PROTON DOSE vs DEPTH FOR CaF_2

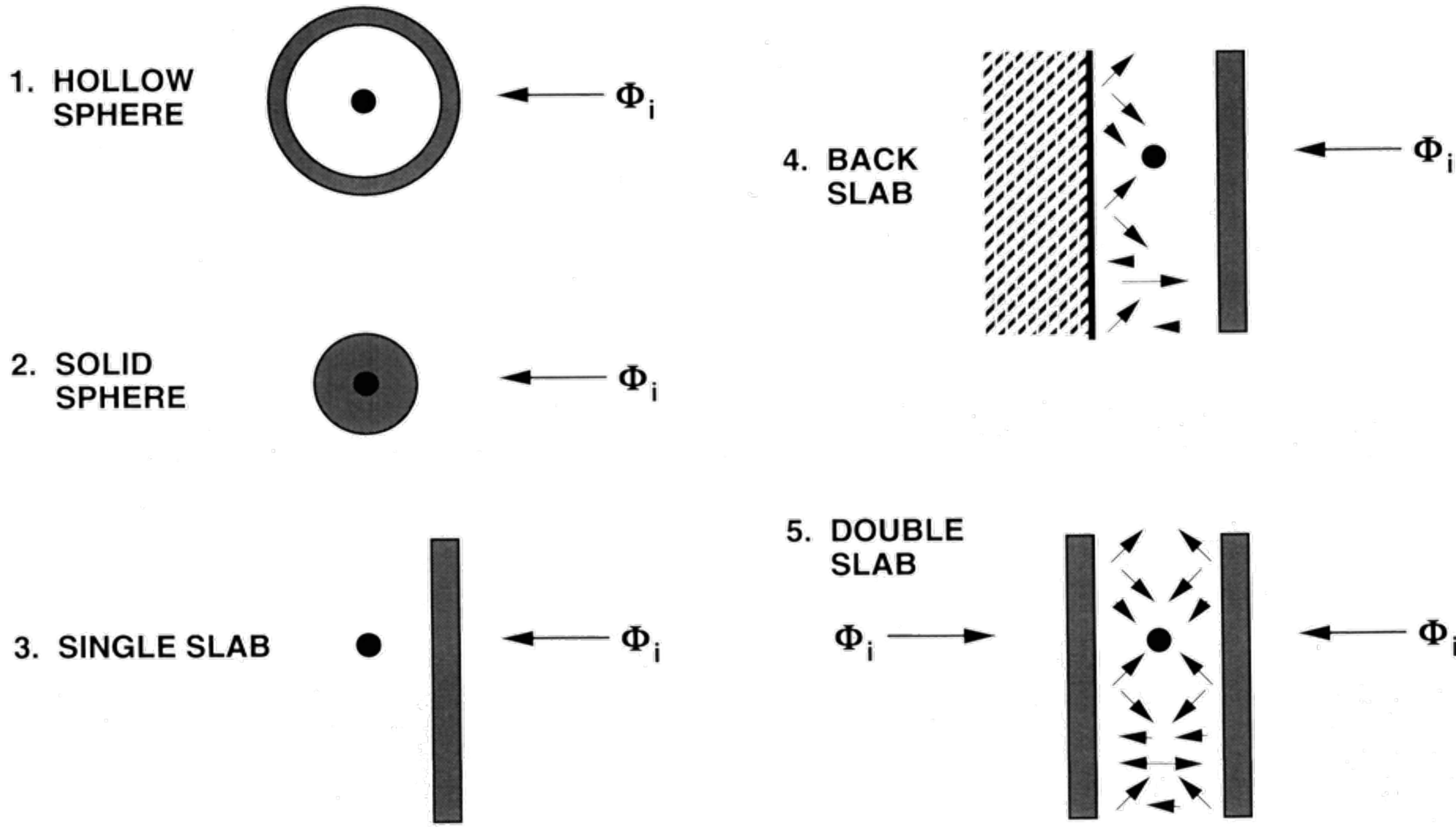


RANGE OF IONS IN ALUMINUM



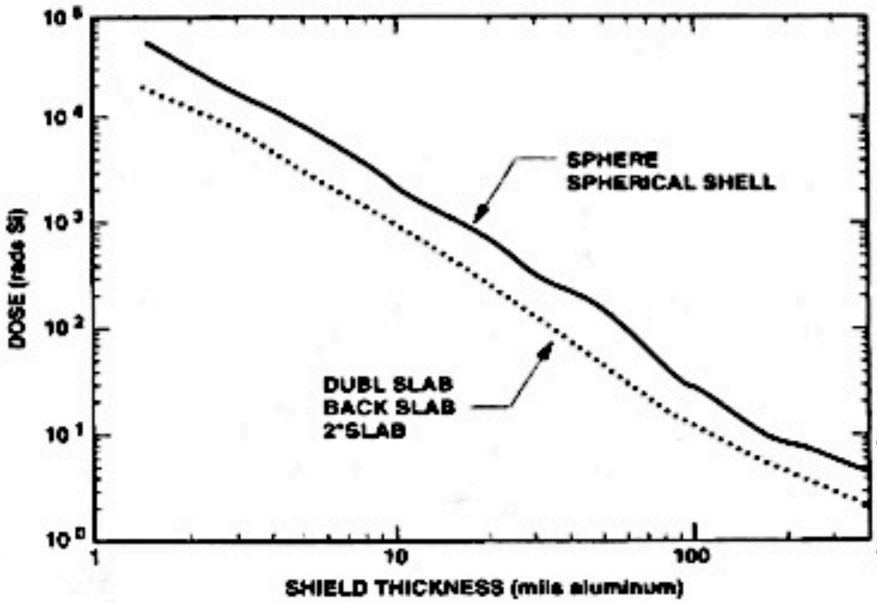
Ion range versus energy in Al[32] for H, He, C, O, Ar, and Fe. The range is in units of g-cm^2 and the energy in MeV/µ.

GEOMETRIC EFFECTS ON SHIELDING
GEOMETRIC CONFIGURATIONS

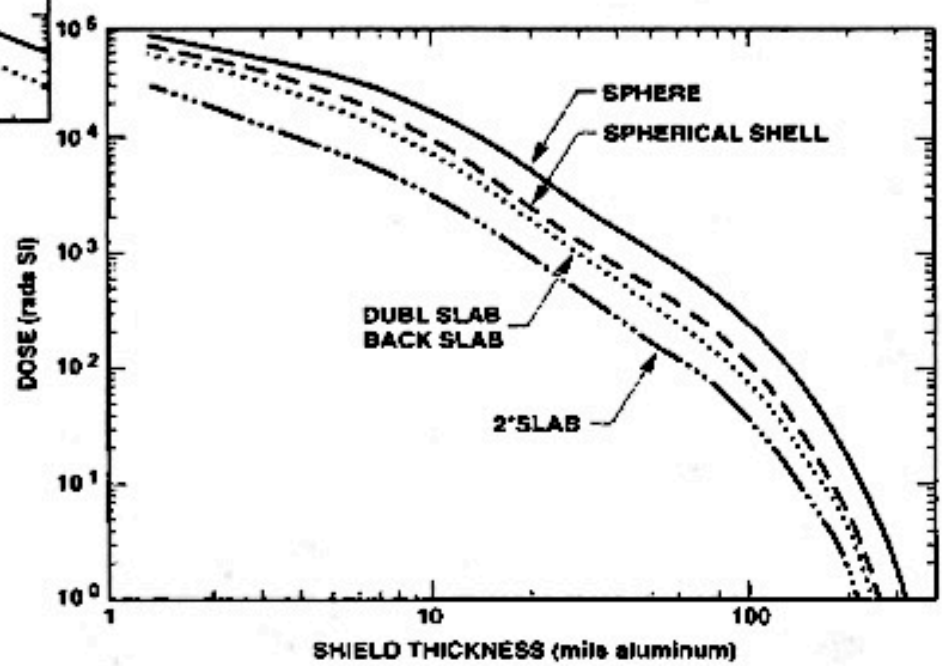


Geometric Effects on Shielding

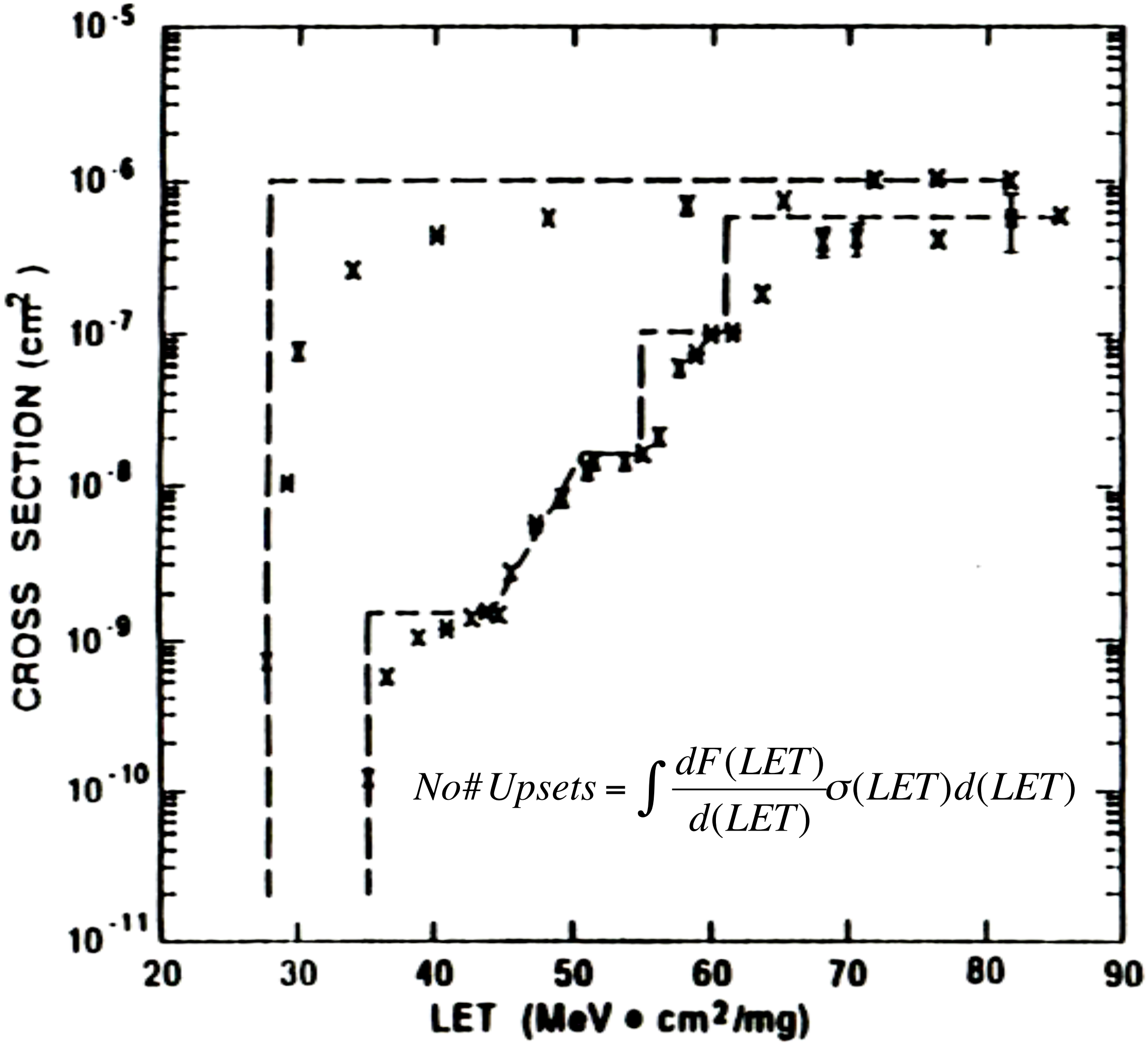
RADIATION DOSE FROM TRAPPED PROTONS



RADIATION DOSE FROM TRAPPED ELECTRONS



Examples of Single Event Upset Cross Sections

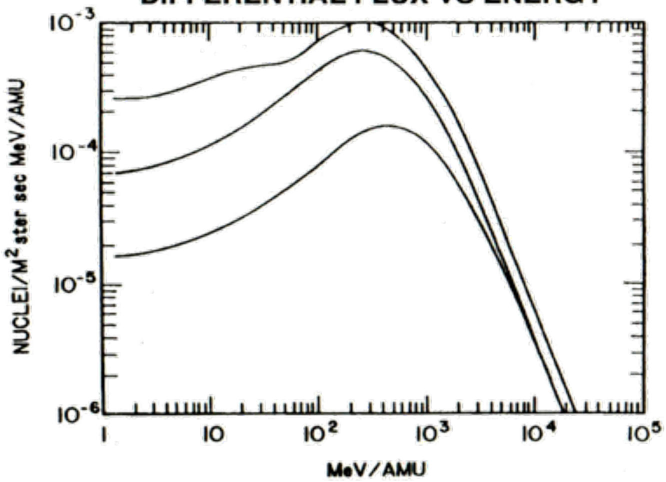


$$No\#\,Upsets = \int \frac{dF(LET)}{d(LET)} \sigma(LET)\, d(LET)$$

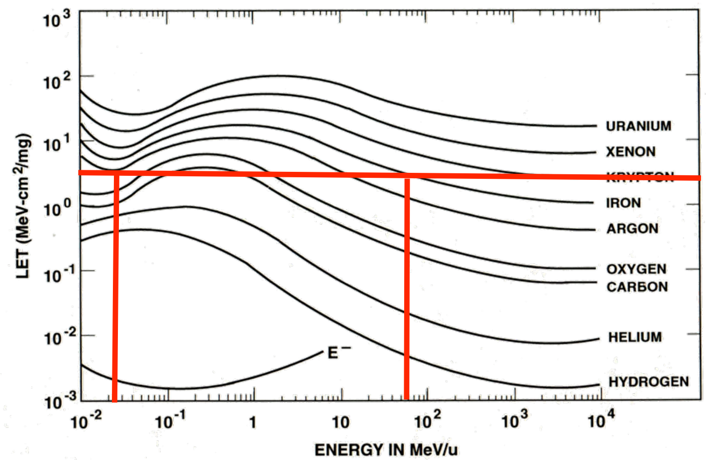
TRANSFORMING DIFFERENTIAL FLUX VS ENERGY TO INTEGRAL FLUX VS LET

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

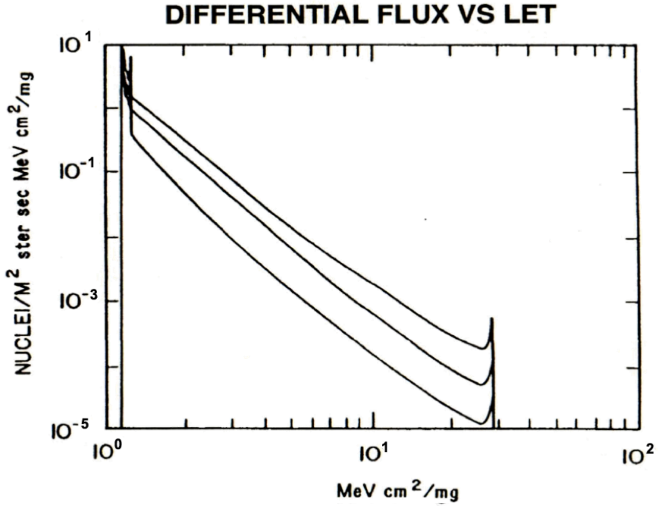
DIFFERENTIAL FLUX VS ENERGY

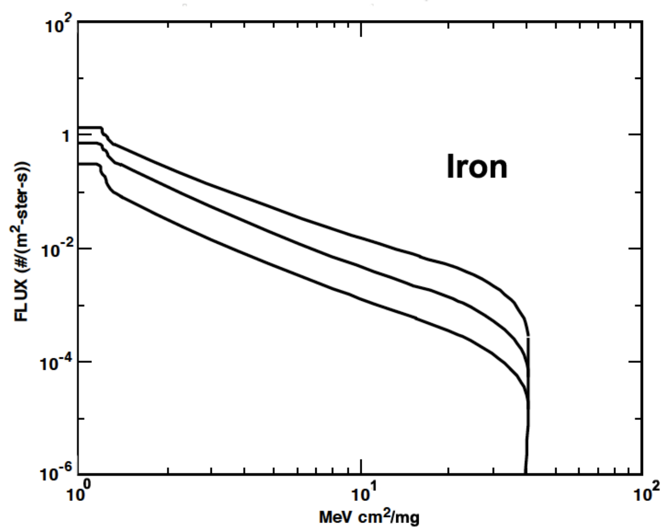


STOPPING POWERS IN SILICON

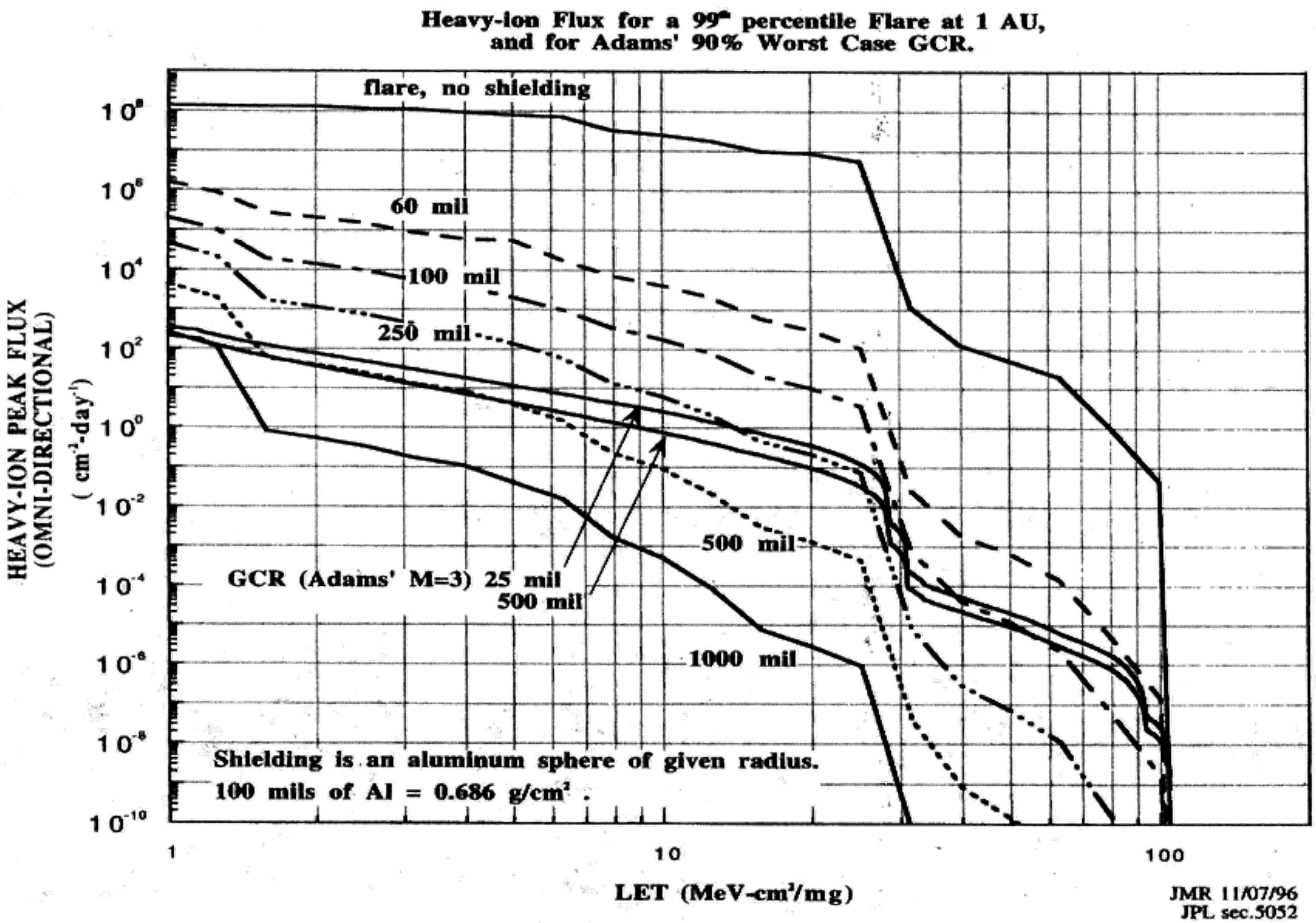


DIFFERENTIAL FLUX VS LET



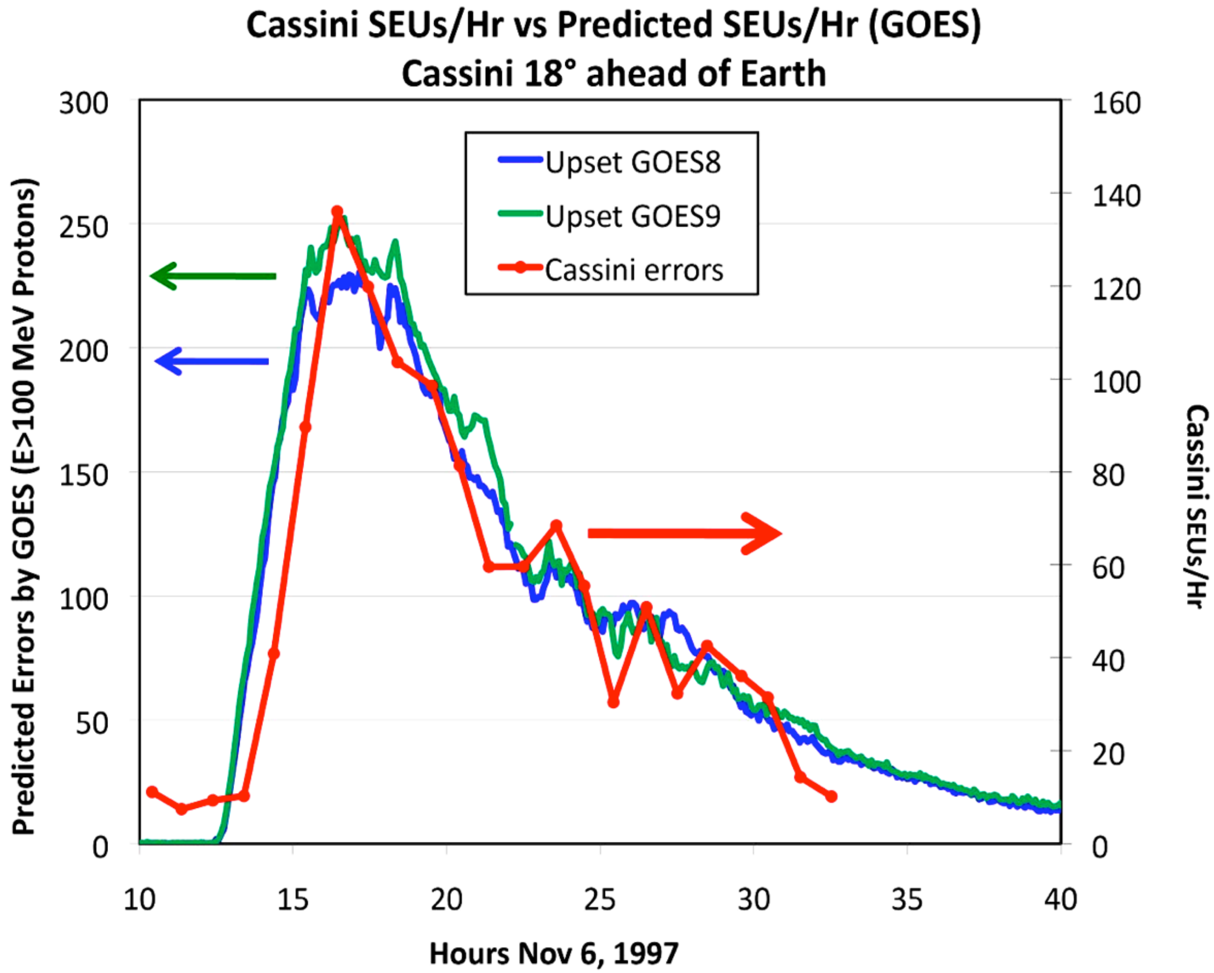


SPE VS GCR RADIATION ENVIRONMENTS



Solar Proton Event (SPE) Effects on Cassini

Space Weather Impacts on Spacecraft and Mitigation Strategies



Lessons Learned: Real Time SPE Observations can Predict Effects on Ops (Cassini Solid State Recorder Upsets)

Simulated Galileo AACS "Power on Reset" Anomalies

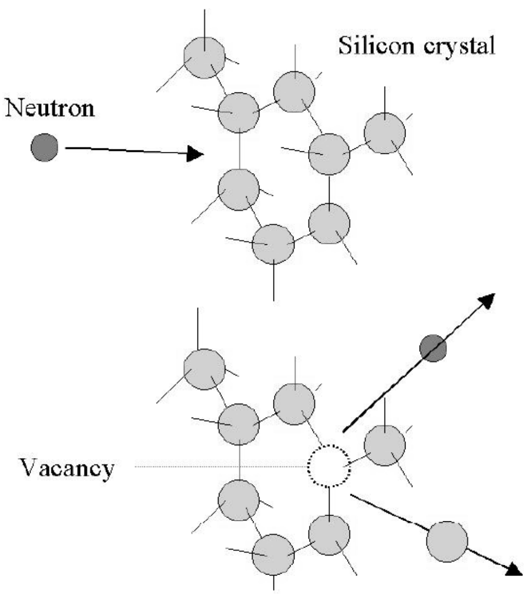
Anomalous Solar Flare--Box Shield
(For Units containing: 54LS373, 25LS374, 54S374, 2914)

SEU Risk Summary for AACS

Category:	Miss	No	Rpt	Ace	POR	ACE Effect Obs (Rpt+Ace+POR)
Total Flip Rate: (Flips/sec)	.03307	.00486	.00105	.00015	.00042	.00162
Time/Event: (days)	.00035	.00238	.01097	.07885	.02736	.00714
% Occurence:	83.612	12.289	2.6665	.37112	1.0619	4.0995
P>=1 Disturbance in 100 Days:	1	1	1	1	1	1

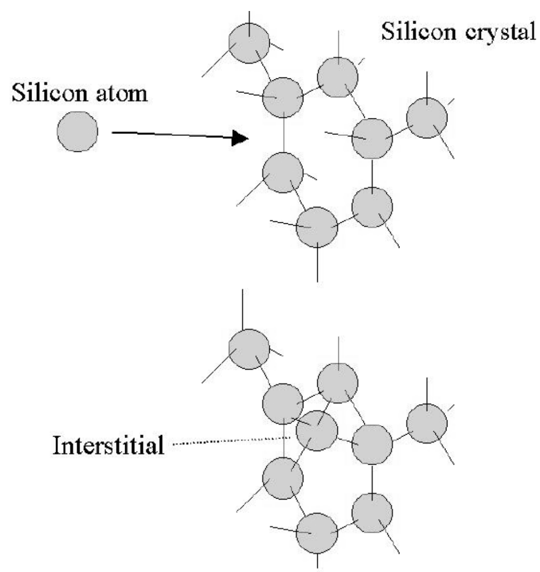
WHAT IS DISPLACEMENT DAMAGE DOSE (DDD)?

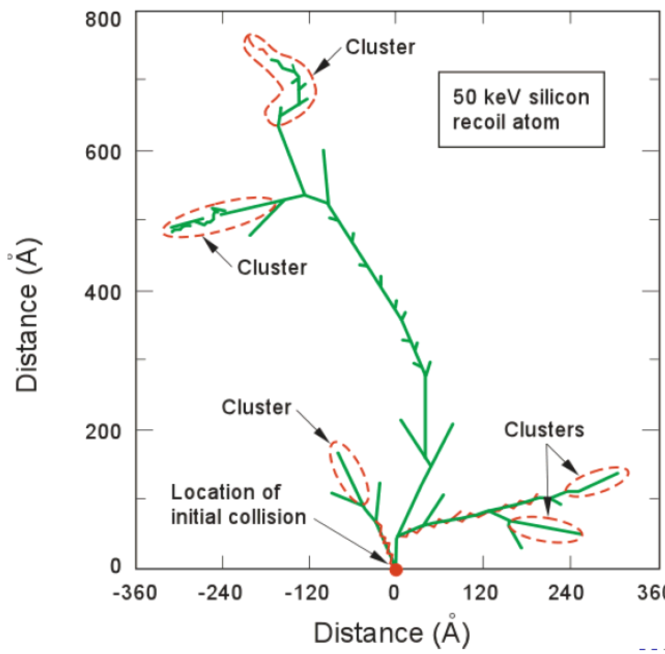
Physical process of DDD: **Displacement => Generates Vacancies => Device Property Degradation**



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

Interstitial formation due to Silicon rearrangement after scattering



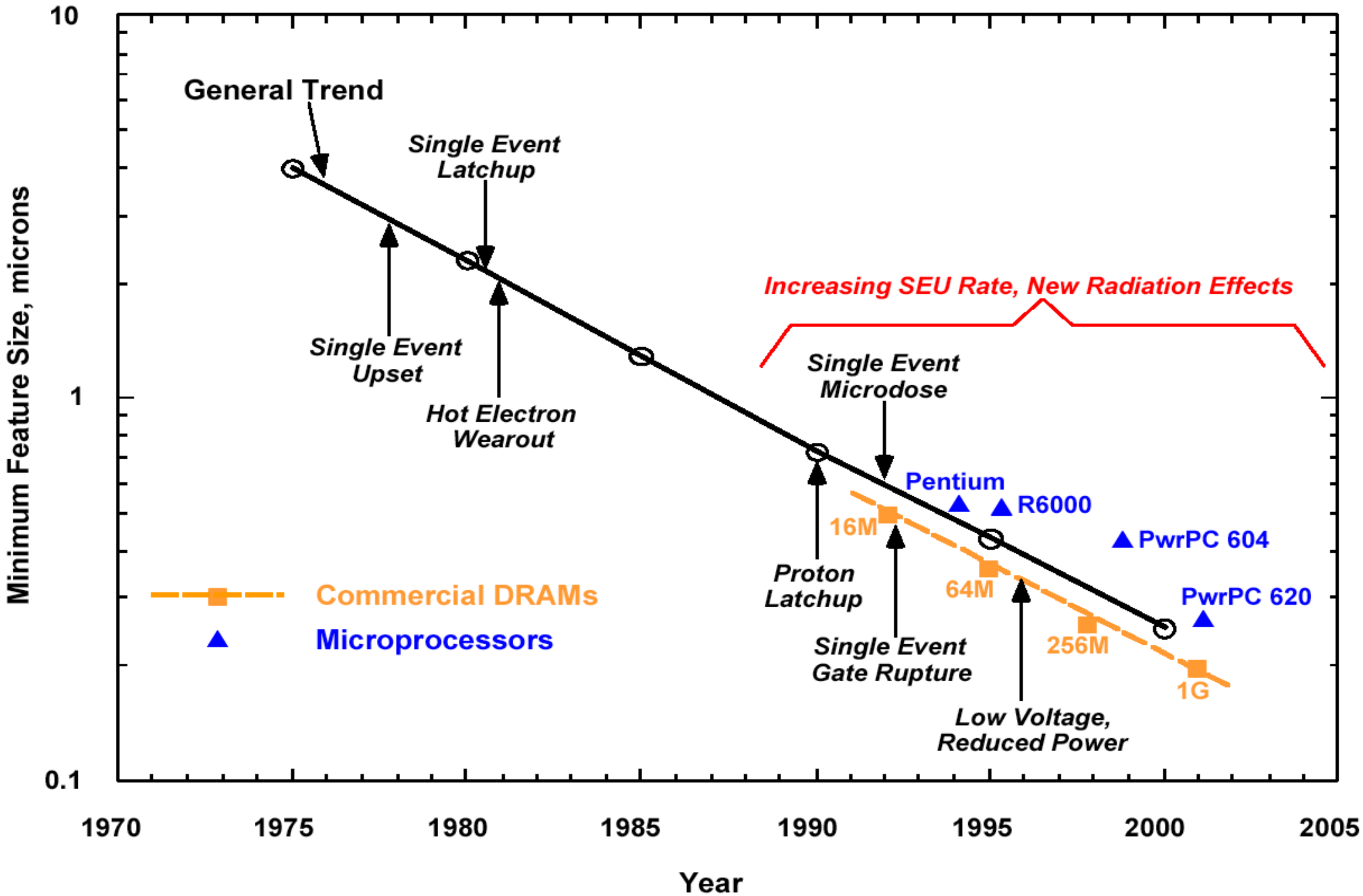


Cascade damage in a silicon lattice

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

Feature Size/Radiation Effects Trends in Microelectronics



Note increasing radiation vulnerability with decreasing feature size

Things That Can Go Bump in the Night ...

"AND WHAT, OH WISE ONE, SHOULD WE DO ... ?"

CONCENTRATE ON EARLY DETECTION, PREVENTION, AND MITIGATION

- **TEST, TEST, TEST, TEST, TEST, TEST,....................**
- **TRUST BUT....INSPECT AND VERIFY—IN PERSON IS BEST!!!**
- **UTILIZE YOUR MISSION ASSURANCE, RELIABILITY, SAFETY, AND QUALITY ASSURANCE PERSONNEL**

AND FINALLY:

- **GARLIC CLOVES SHOULD BE INCLUDED ON ALL INTERPLANETARY SPACECRAFT (JUST IN CASE)**