Spacecraft Environmental Interactions: Putting It Together

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Putting it Together

- **CHARGING**
  - **Surface Charging**
  - **IESD**
  - **Mitigation Techniques**
- **RADIATION**

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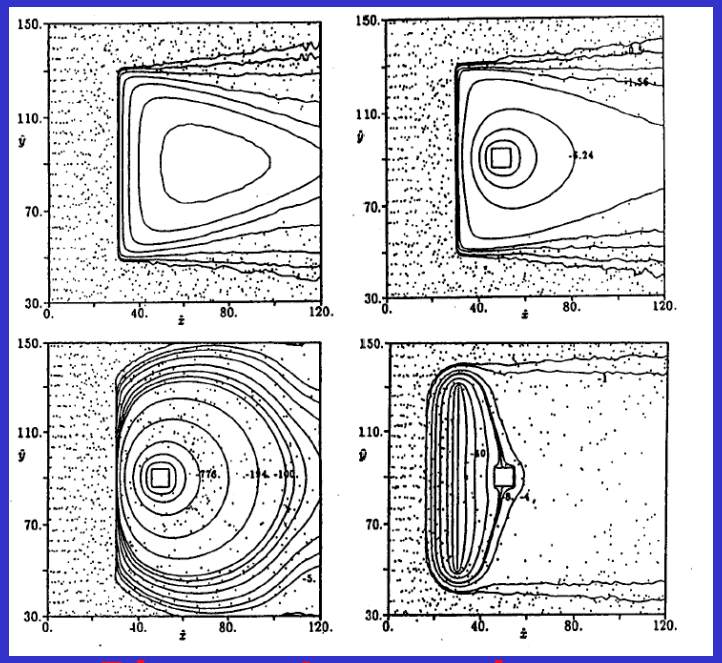
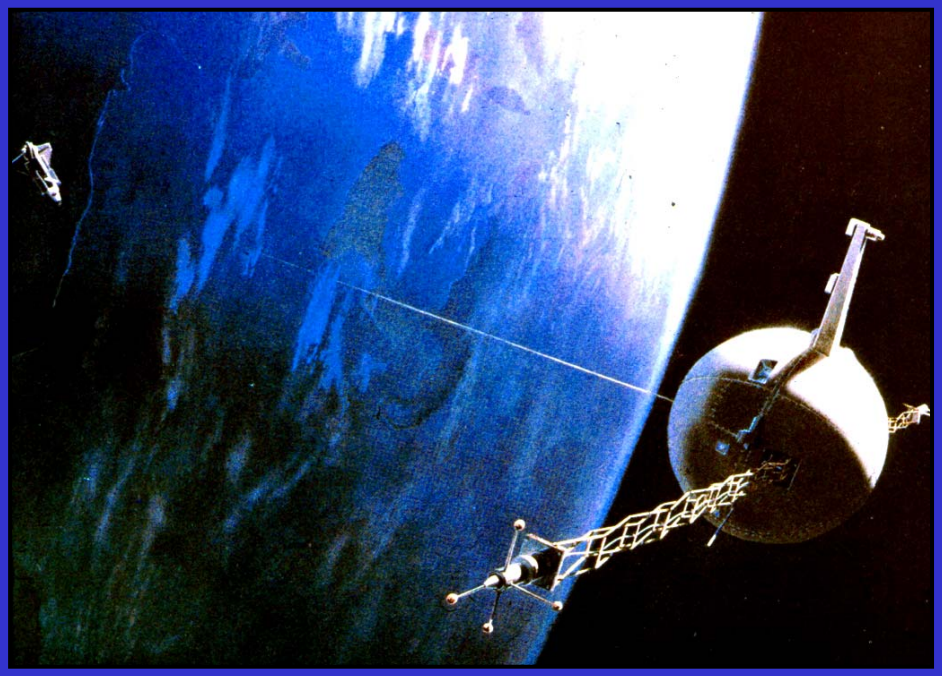
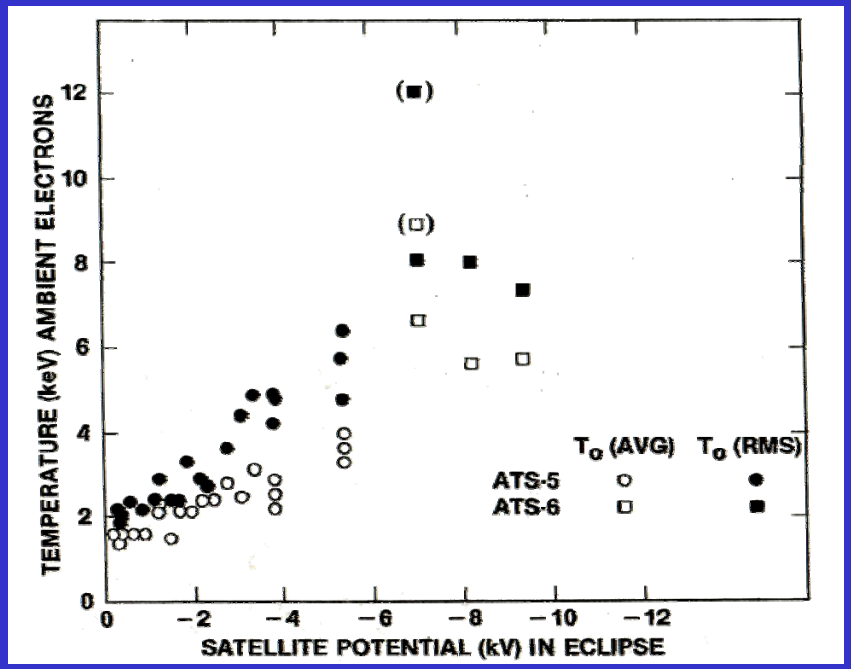
CHARGING EFFECTS



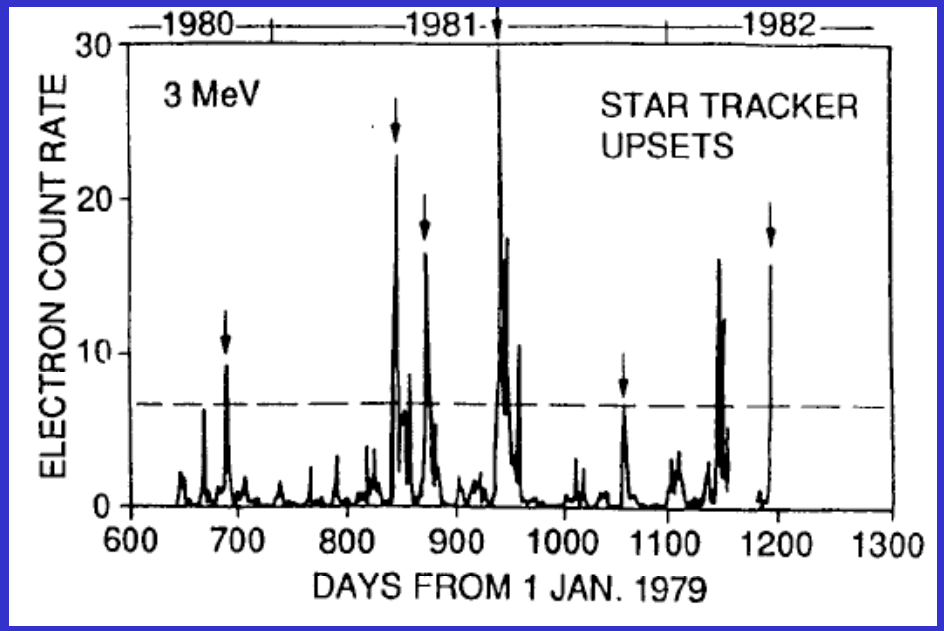
Plasma Interactions



VxB



Surface Charging



Internal Charging

Surface Charging

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Spacecraft Charging AT High Altitudes

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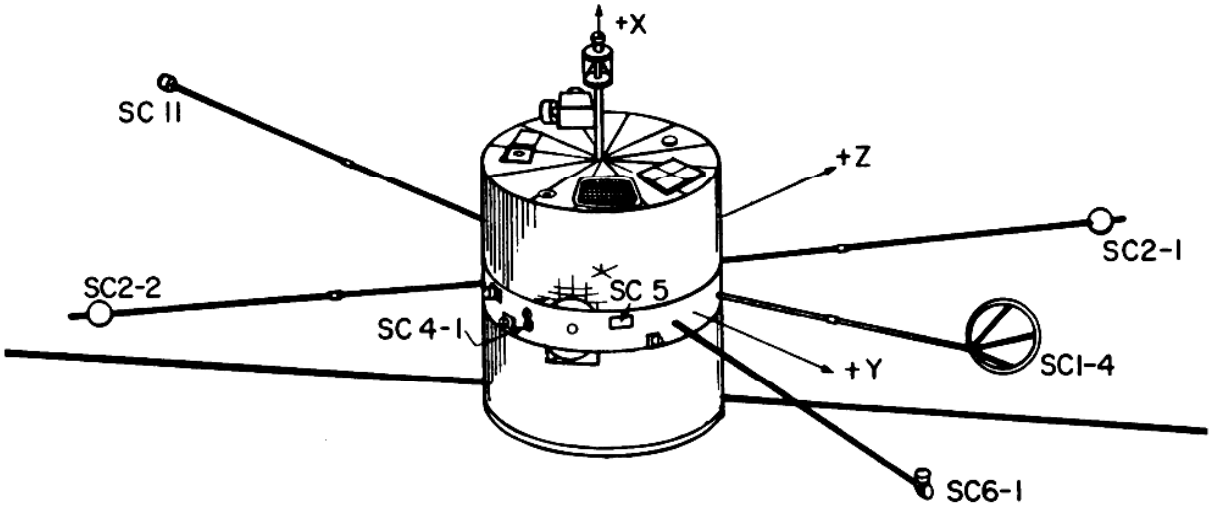
Charging Milestone: The P78-2 SCATHA Mission



P78-2

- DEFINE THE AMBIENT ENVIRONMENT
- MEASURE THE SATELLITE SHEATH AND POTENTIAL
- STUDY ARCING
- VALIDATE CHARGING CODES
- TEST CHARGE CONTROL TECHNIQUES

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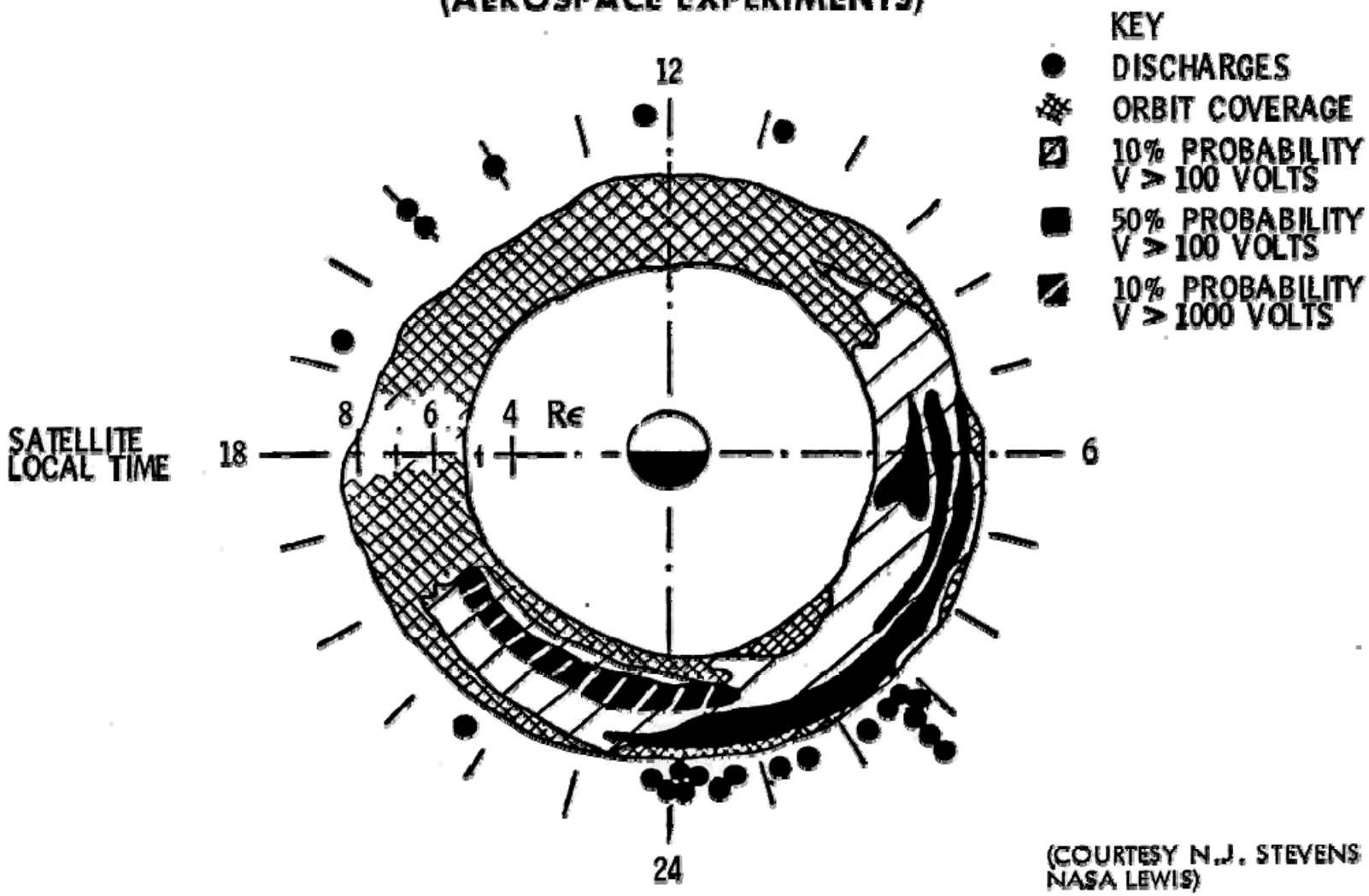
SUMMARY OF SCATHA CHARGING/DISCHARGING DATA
(AEROSPACE EXPERIMENTS)



(COURTESY N.J. STEVENS NASA LEWIS)

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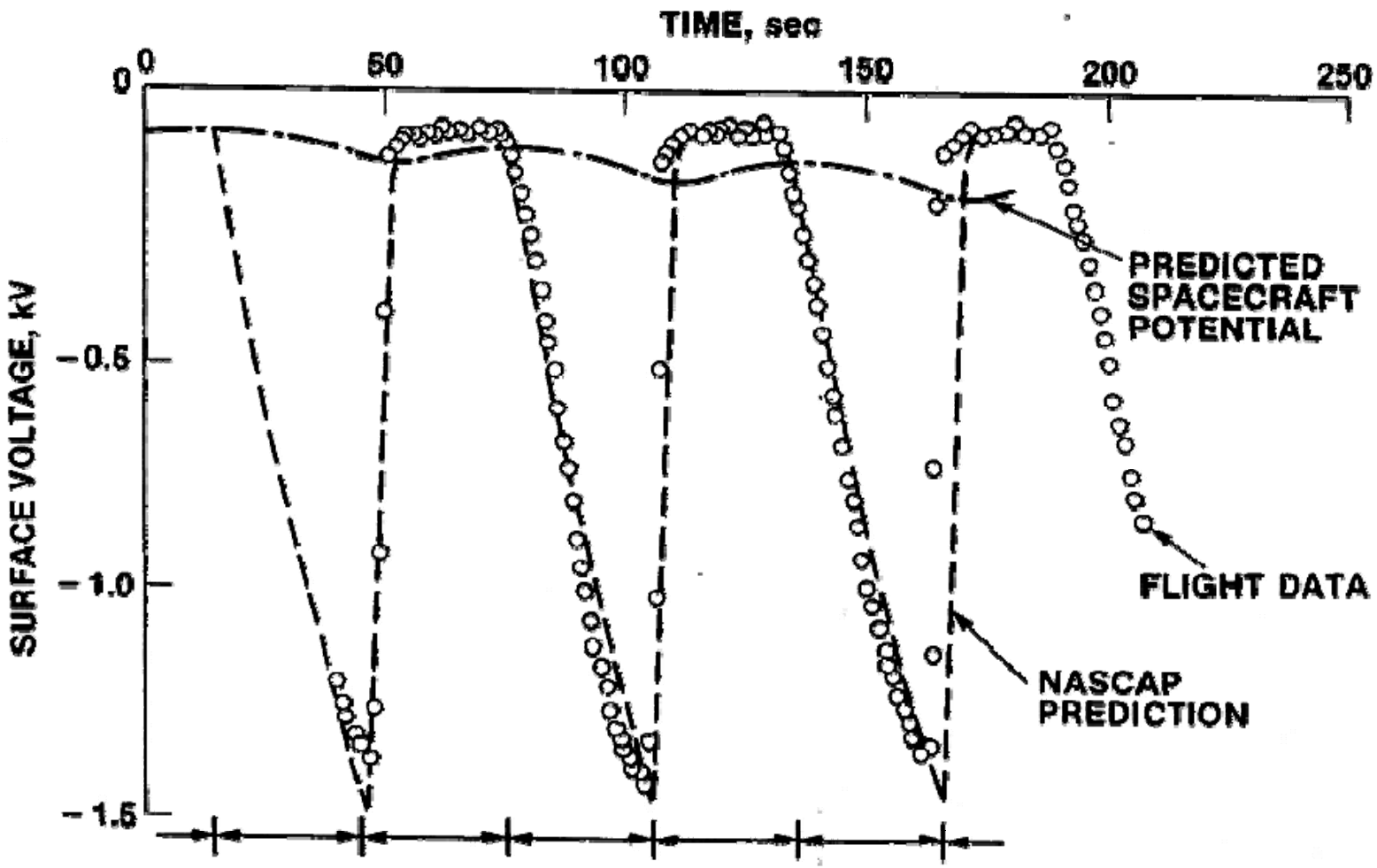
SCATHA KAPTON POTENTIALS VERSUS NASCAP PREDICTIONS



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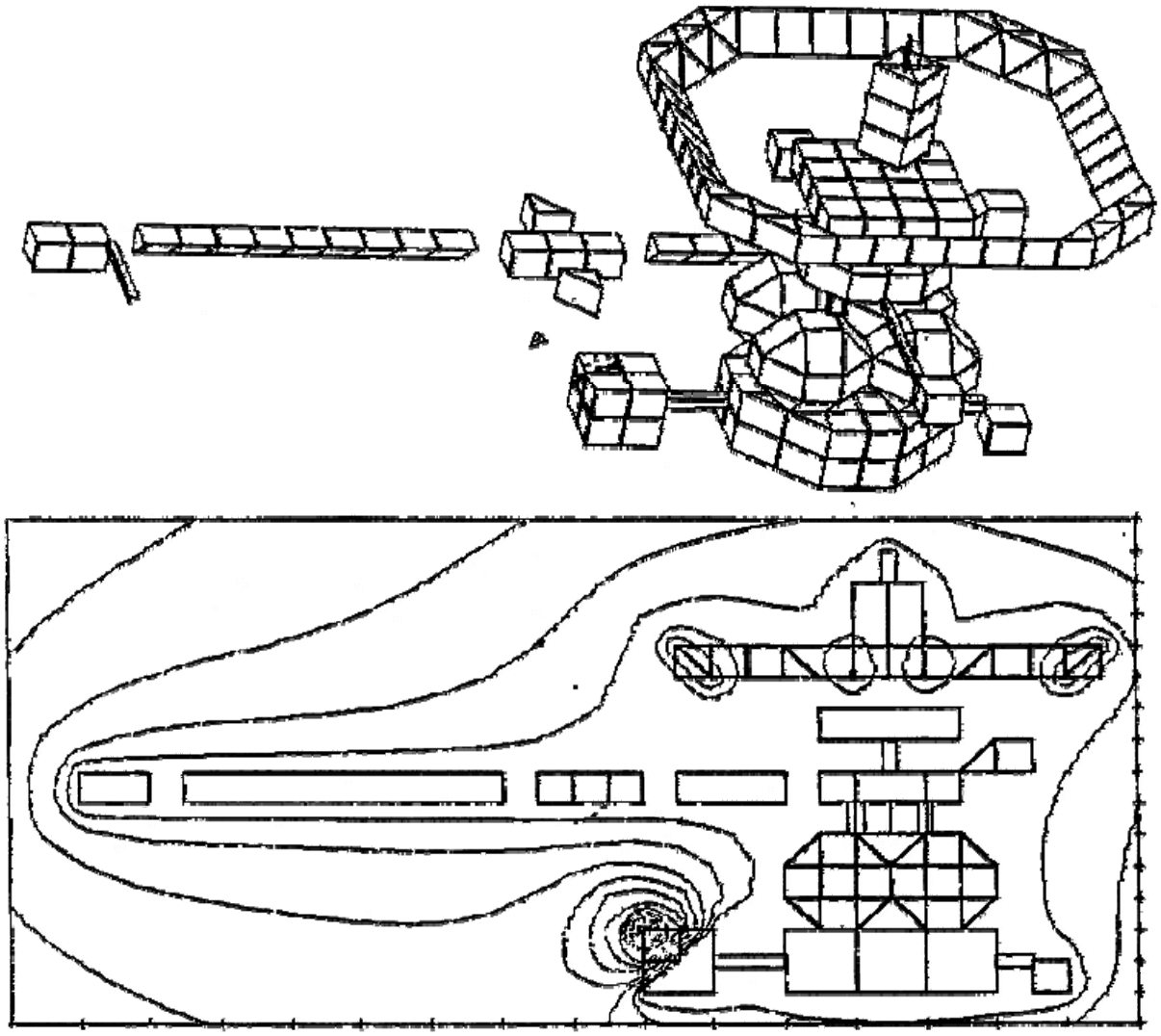
NASCAP MODELS OF GALILEO



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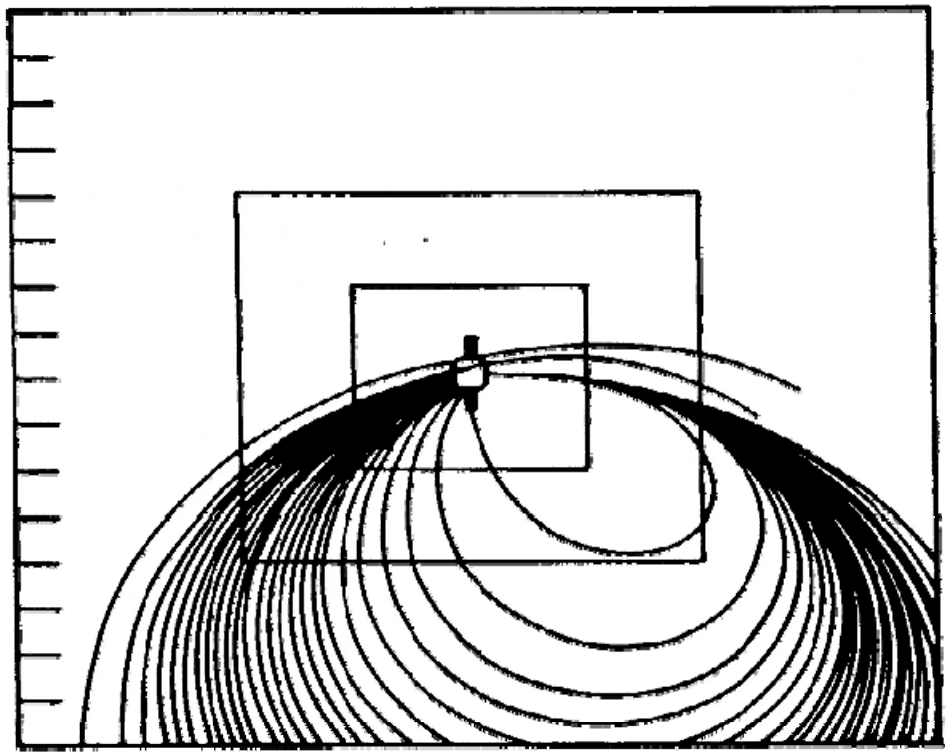
Particle Trajectories from an Electron Emitter as Computed by the NASCAP Code (Rubin et al. (1980)) in the Presence of a Magnetic Field



CONDUCTING OBJECT POTENTIAL = +0.96 keV
UNIFORM MAGNETIC FIELD = 0.1 GAUSS ALONG -X AXIS
MEAN BEAM ENERGY = 1.1 keV
BEAM ENERGY SPREAD = 0.1 keV (25 energies)
BEAM ANGULAR SPREAD = 0^0
ELECTRON EMISSION CURRENT = 1 ma

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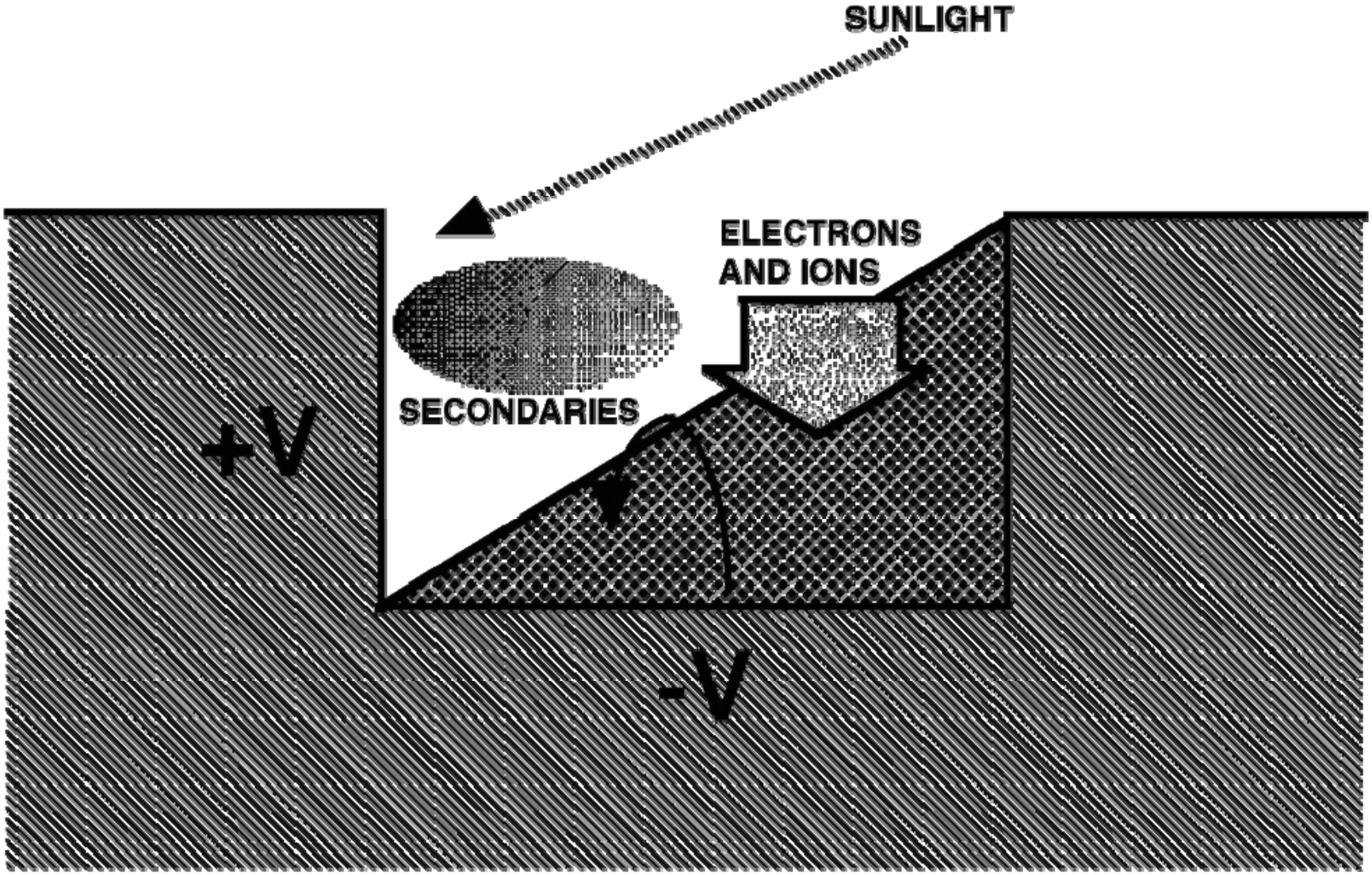
SURFACE CHARGING IN CAVITIES



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Estimated Plasma Parameters/Potentials in the Solar System

REGION	ALTITUDE	N_o, 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	-6500‡
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	9.5	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	6.0	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

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Jovian Surface Potentials-A Simple Estimate

Assumed simple current balance for spherical Aluminum probe in shadow:

$$I_E(V) - [I_I(V) + I_{SE}(V) + I_{SI}(V) + I_{BSE}(V)] = I_T \sim 0$$

SURFACE CHARGING CONCERNS!!

RJ	ALAT	No Aurora		A Max		A κ +I/1	A κ +I/10	A κ +I/100		Diffuse WC	Diffuse WC/10	Diffuse WC/100
15	0	-8		-2212		-1934	-3984	-4834		-1318	-24	-9
25	0	-24		-		-	-	-		-4658	-1567	-81

Estimates of potentials in jovian magnetosphere for: "A Max"--Ajello Maxwellian; "A κ"--Ajello Kappa ("+I/1, +I/10, +I/100"=> 100%, 10%, 1% of ion plasma currents); "Diffuse WC"--diffuse fluxes varied from 100 ergs/cm^2-s to 1 erg/cm^2-s (tabulated as "WC", "WC/10", and "WC/100").

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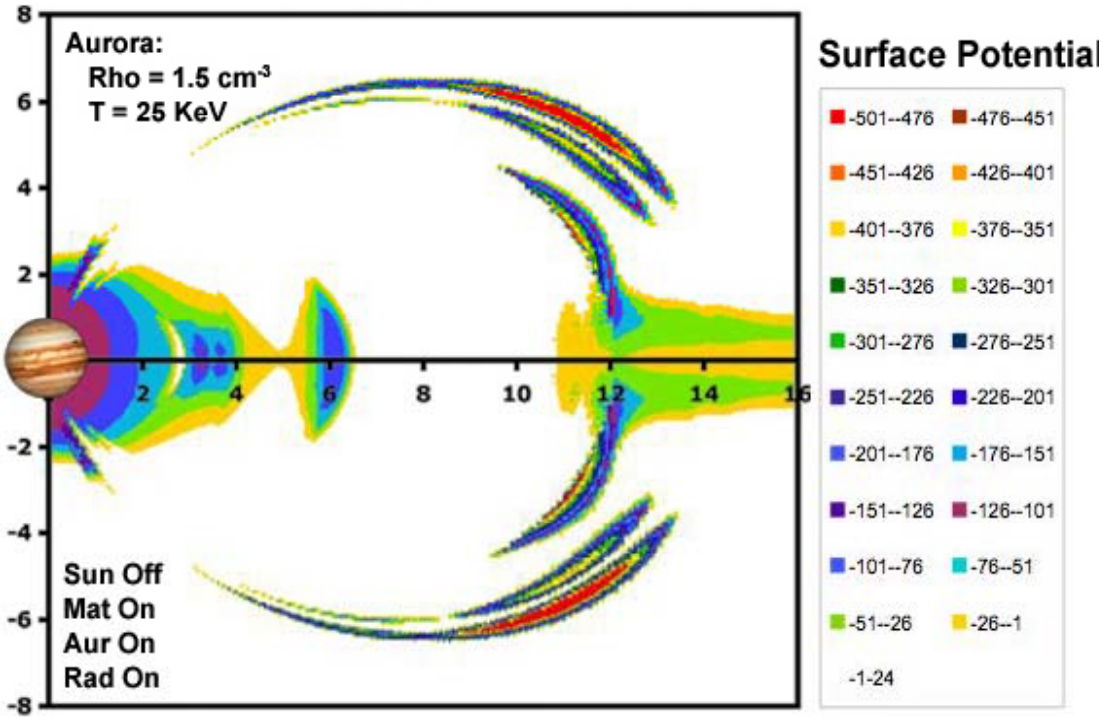
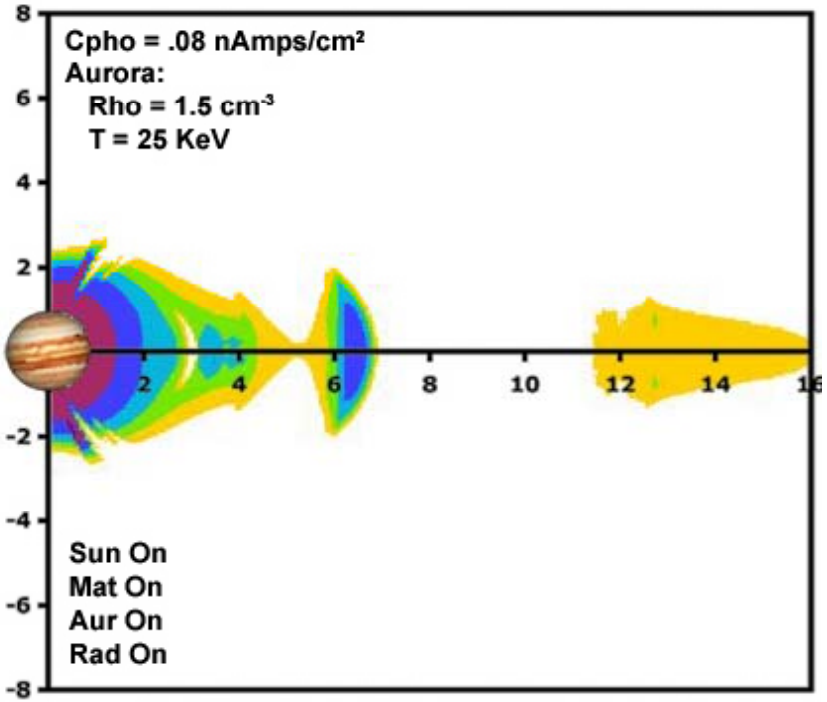
ESTIMATED JOVIAN CHARGING ENVIRONMENT



Dark Side



Sunlit Side

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Auroral Charging at Jupiter:

WE FIND:

- At base of auroral field lines, "Worst Case" auroral zone fluxes ***may*** cause charging (***-2-5 kV***) in the 15-25 Rj equatorial region on shadowed surfaces.

THIS IMPLIES:

- Equatorward extension of aurora will be of concern to missions passing through the 15-25 Rj equatorial region--again, however, these levels are well within levels we protect geosynchronous spacecraft against.
- ***Surface charging will not be of concern at Jupiter if standard mitigation procedures are followed!***

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IESD

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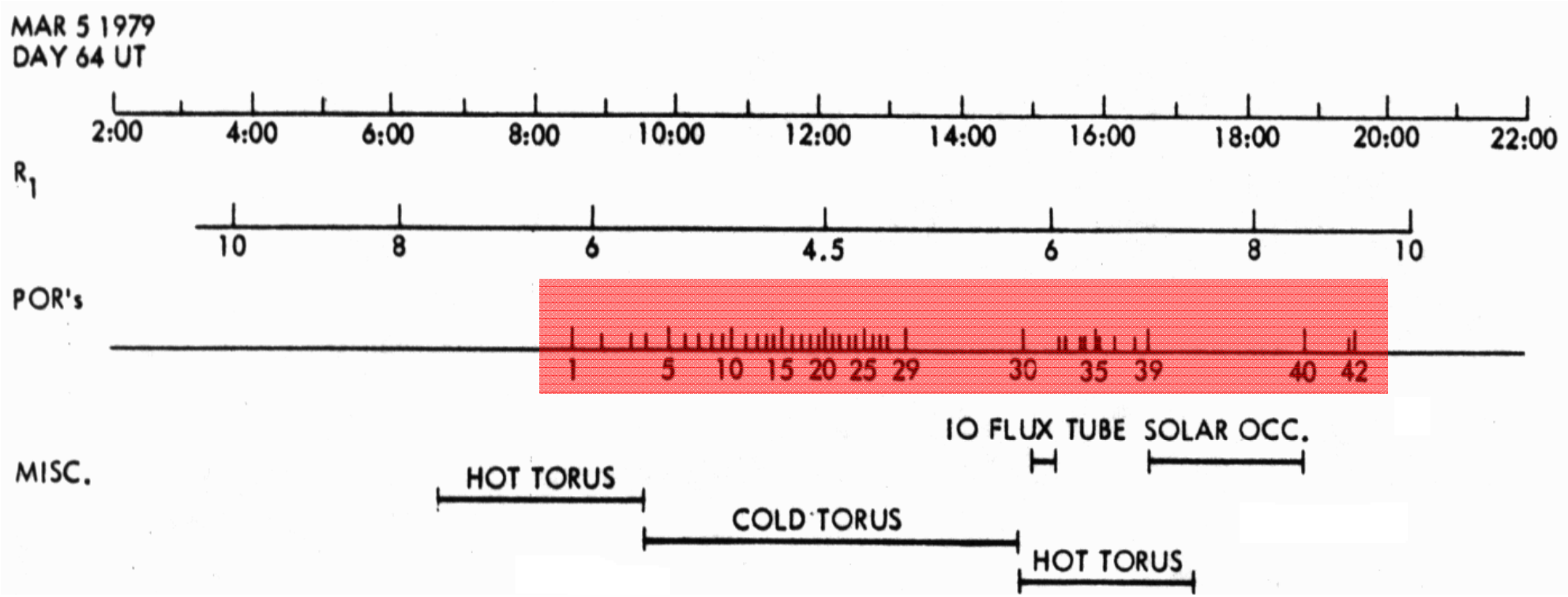
Occurrence Frequency Of Voyager 1 PORs



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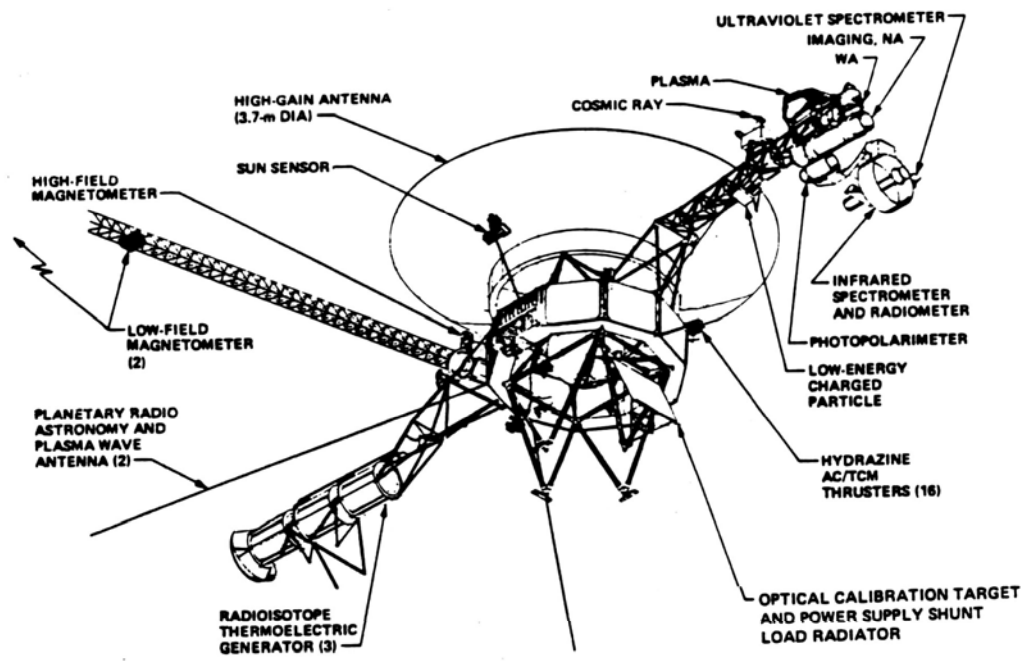
Location of Voyager Dielectric Surfaces (Possible Sources of ESD)

External Dielectrics	Application
Kapton Thermal Blankets	Several
Teflon Thermal Blankets	Numerous
External Cabling Jacketing Teflon	Numerous Especially Magnetometer Boom cable
Other Dielectrics	
Sunshades - Kapton with VDA	Numerous small segments
White Paint (PV-100)	Over Th. Blanket apertures
White Paint (PV-100)	High Gain Antenna (HGA)
Black Paint	Thermal Control on S/C Bus.
Optics	Antenna Support Structure Science Instruments and Star Tracker
Connector Socket Rubber Matrix	Separation Connectors
RTG Oxide Coating	Thermal Radiator
Teflon/Silver Radiator	IRIS Instrument Detector Heat Sink
Brewster Plate	PPS Calibration Target
Kapton Tape	Edge of HGA
Kapton Tape	Misc. Locations
Radome	RF Feed Horn Cover
Misc.	Cable Clamps, Brackets
Fiberglass Struts	Magnetometer Boom
Fiberglass Struts	Science Instrument Supports
Dacron Cloth Tape	Magnetometer Boom Extension Restraint



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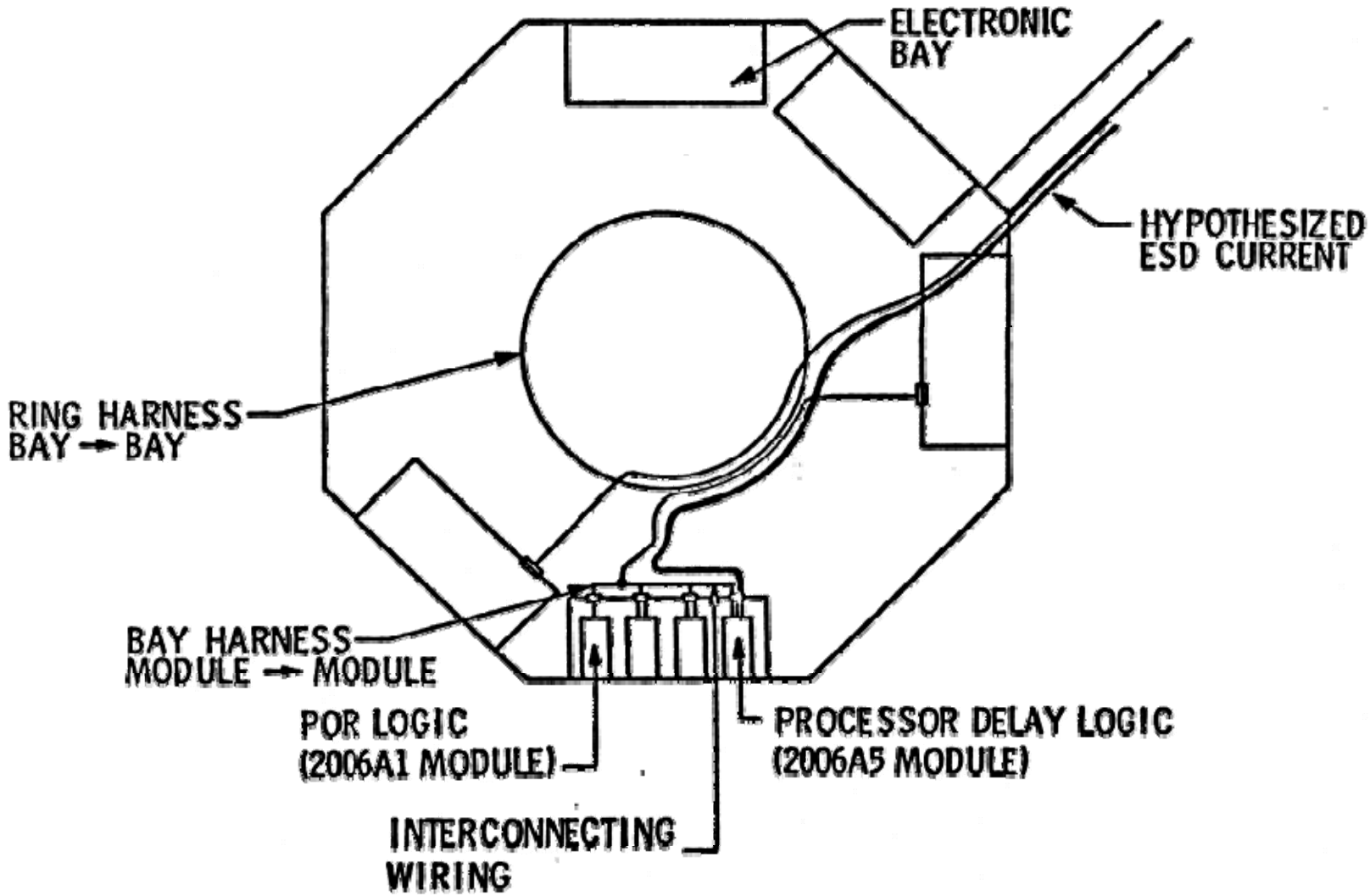
Proposed "Power on Reset" Upset Mechanisms on Voyager



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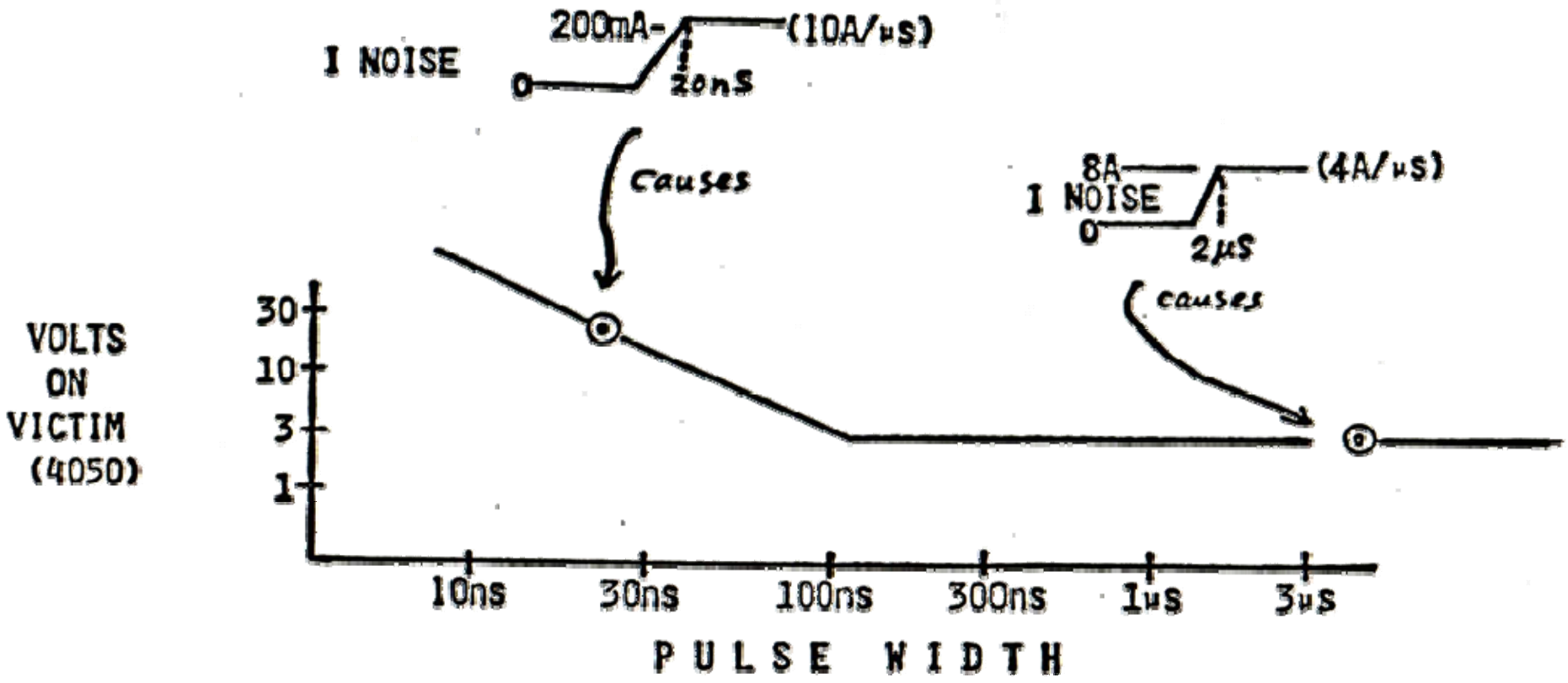
GROUND TEST RESULTS FOR VOYAGER PORs



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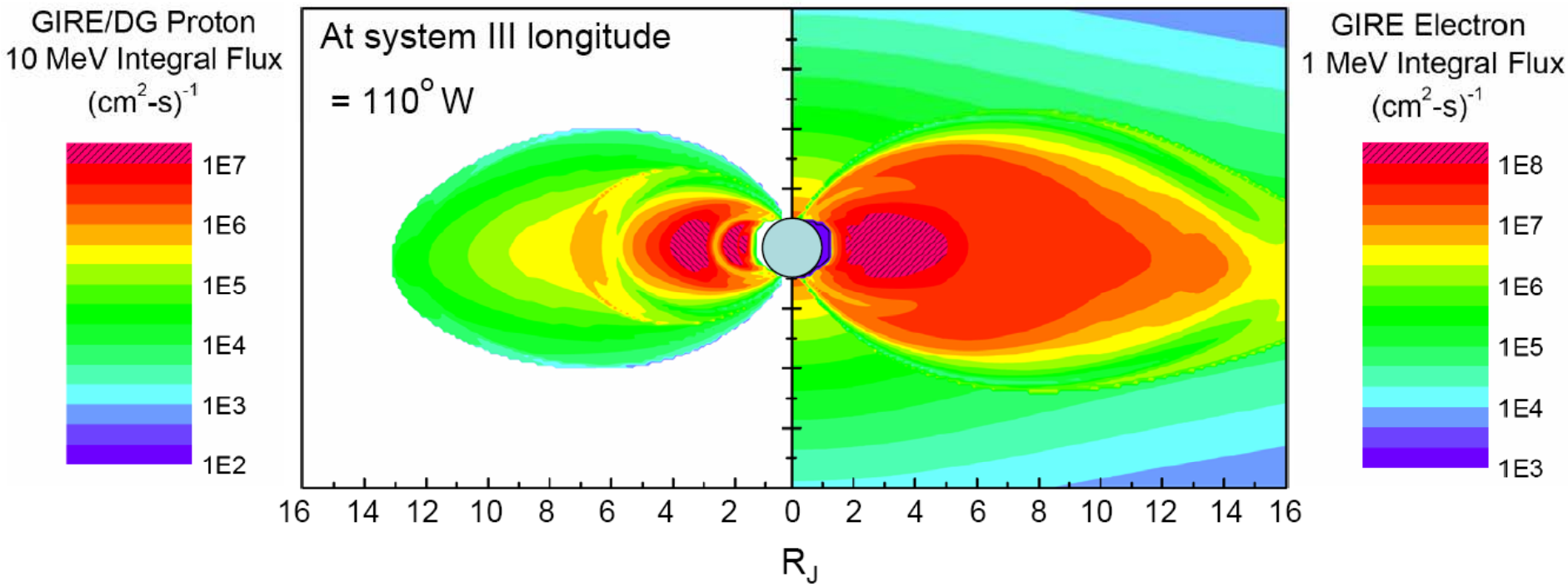
Jovian-Trapped Radiation Models



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.

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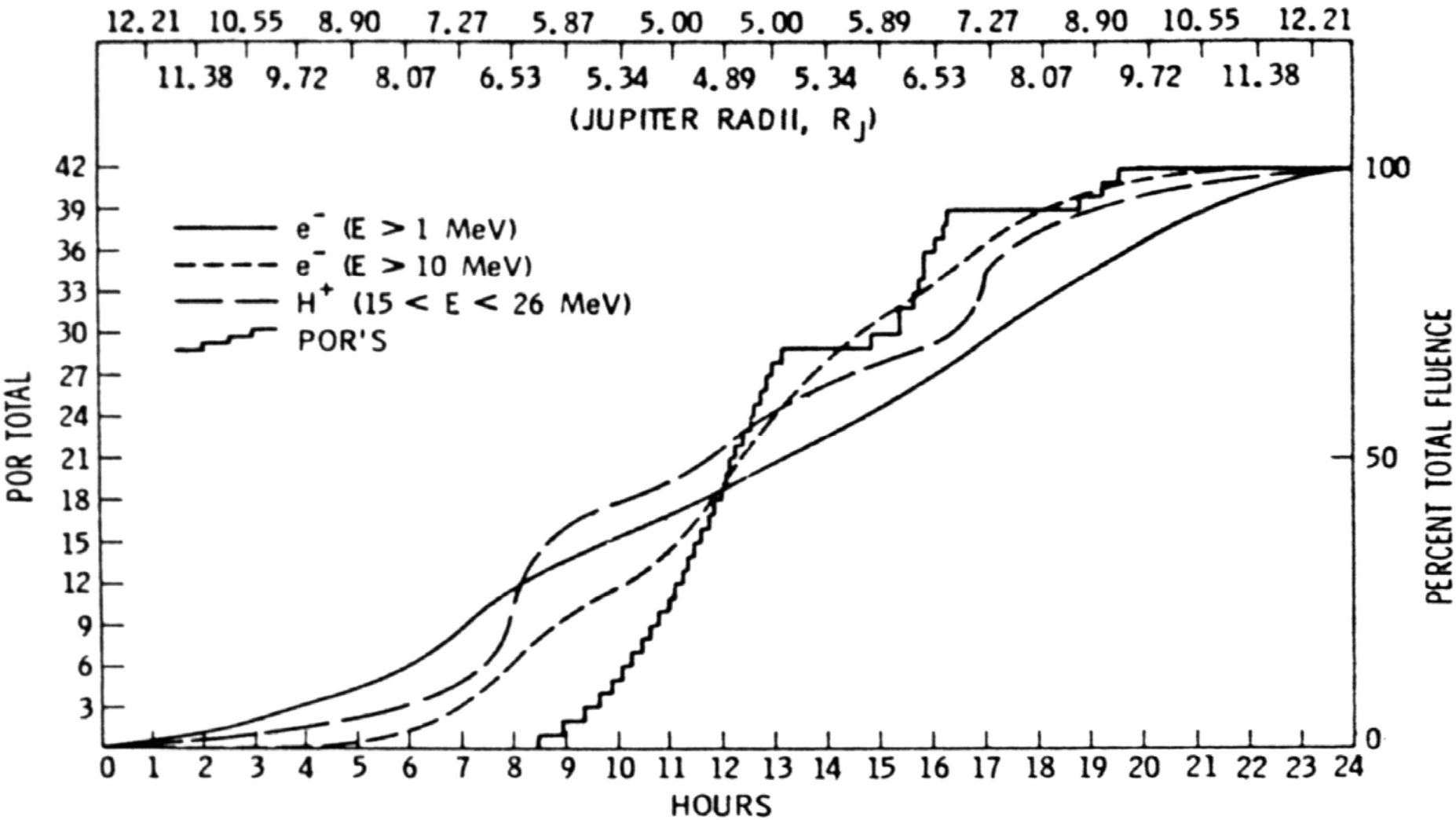
Correlation of Voyager POR's with Jovian High Energy Electron Fluence



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POR "Back of the Envelope" Calculation

1.) 42 Events in ≈12 Hr ⇒ $\tau \approx 10^{8}$ s

2.) At 4.5 R_J; Assuming for E>40 KeV:

$\Delta J = 2\times10^{7}$ el-cm^{-2}-s^{-1}

For 25 mil Teflon/50 mil Al

3.) Therefore the available charge is:

$Q(TOT) \approx \Delta J \cdot \tau =$

2×10^{10} el-cm^{-2}-event^{-1}

4.) For 1 event (experiment):

$\Delta\tau \approx 20$ nsec

$I \approx 200$ mA

⇒ $Q_e = 4\times10^{-9}$ C

As $1q = 1.6\times10^{-19}$ C:

$Q \approx 2.5\times10^{10}$ el-event^{-1}

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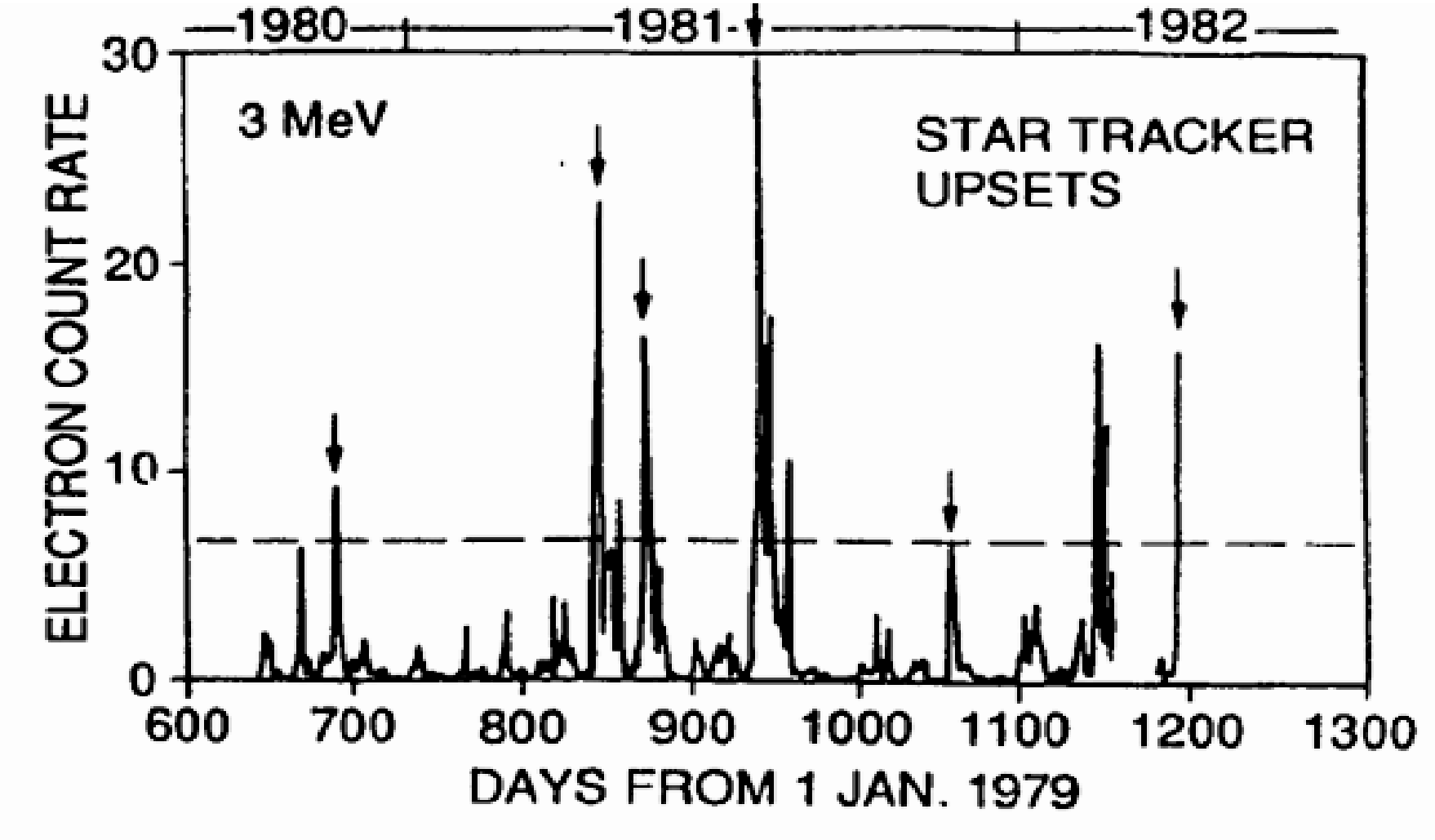
Internal Charging DSP Star Tracker Anomalies Compared With GOES E>2 Electron Fluxes



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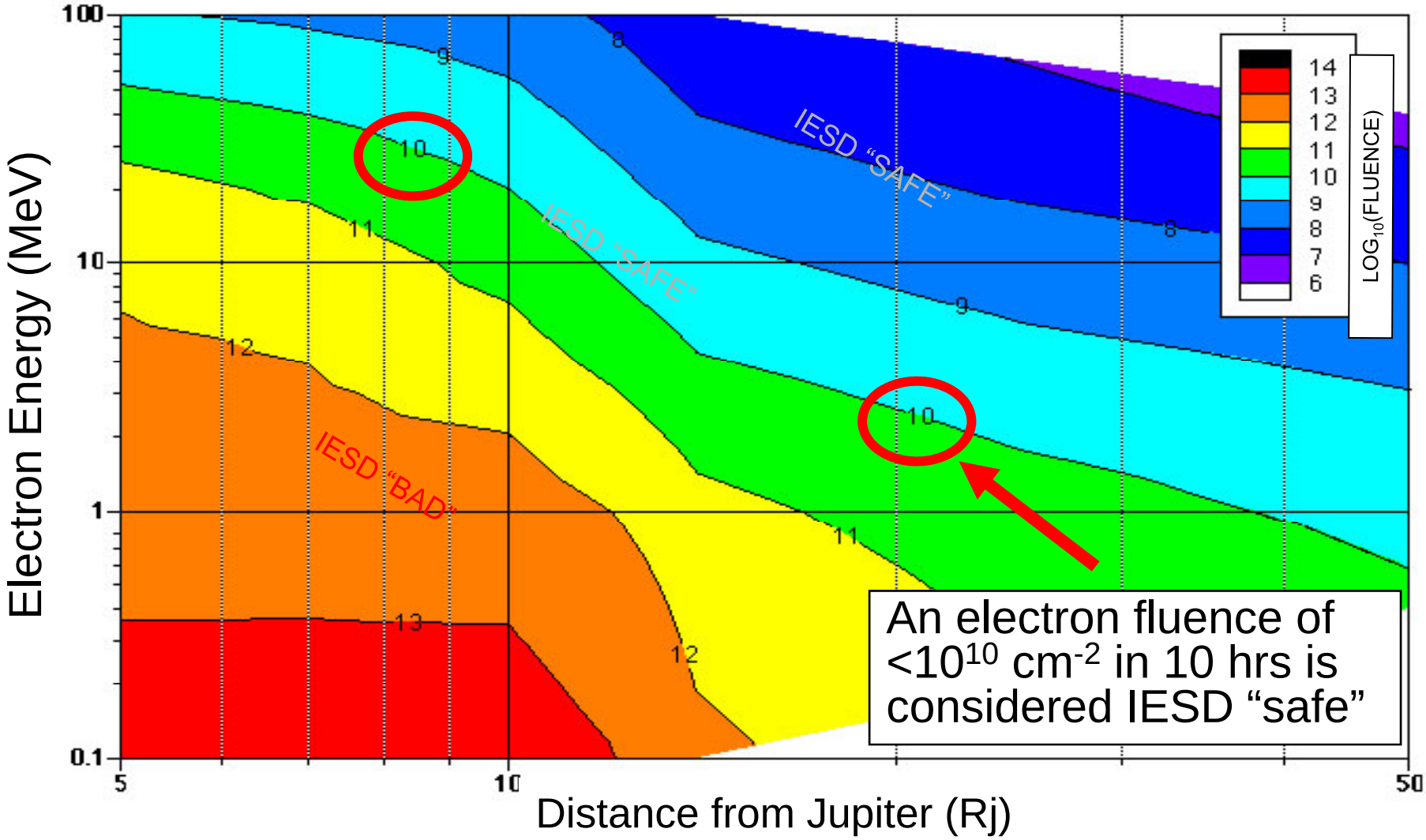
IESD REGIONS FOR JOVIAN FLYBYS



Contour plot of *total electron fluence* (Log) versus flyby perijove distance and energy (note: all flybys are assumed to be in the jovian equatorial plane). Units are (cm^{-2}).

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MITIGATION TECHNIQUES FOR CHARGING

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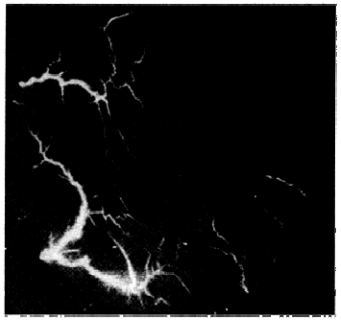
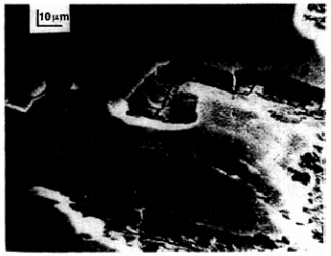
Testing for Spacecraft Charging Effects

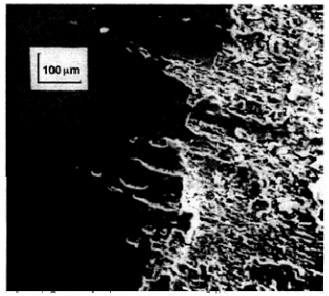
SURFACE DISCHARGE EFFECTS (K.G. BALMAIN, 1980)



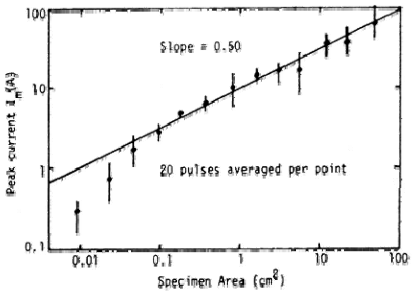
ARC DISCHARGE ON MYLAR (area=48 cm^2)



MAGNIFIED VIEW OF ELECTRON MICROSCOPE IMAGE

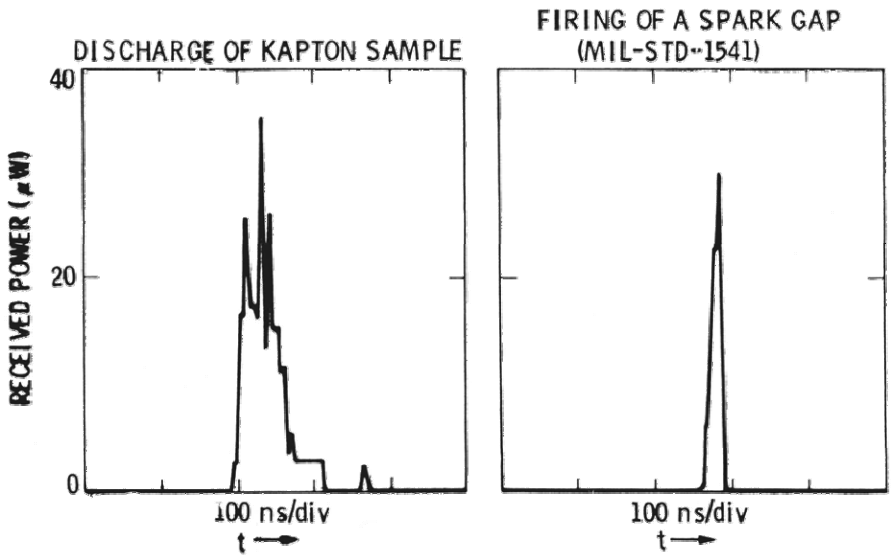


ELECTRON MICROSCOPE IMAGE OF ARC DAMAGE



PEAK ARC CURRENT VS AREA (CURRENT~LENGTH)

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



f = 2000 MHz
BW = 400 MHz

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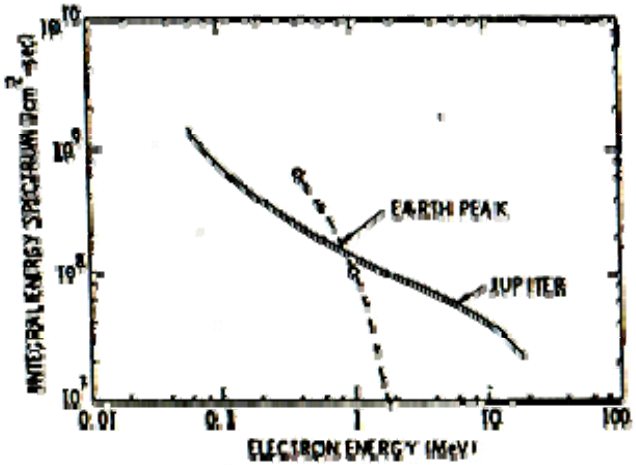
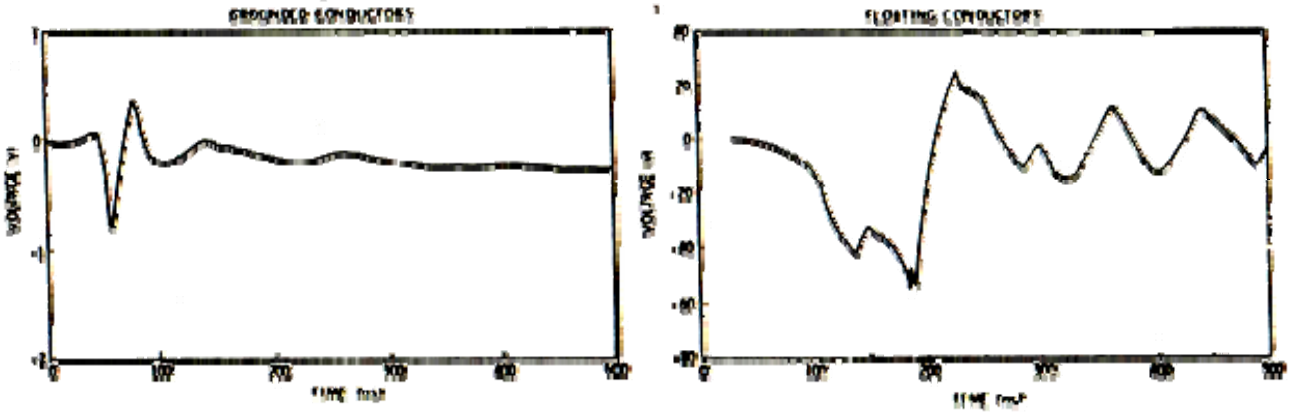
GALILEO IESD GUIDELINES

- 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

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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	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

FROM "MITIGATING IN-SPACE CHARGING EFFECTS—A GUIDELINE", NASA HANDBOOK 4002A

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*GSFC denotes Goddard Space Flight Center

Design Guidelines for Assessing and Controlling Surface Charging Effects

GENERAL DESIGN GUIDELINES:

- Ground all conductive spacecraft elements (including lids, traces, spot shields, etc.
- Use conductive surface materials
- Shield all circuitry (Faraday Cage Concept)
- Filter circuits near ESD sources
- Develop, document and follow procedures
- Test spacecraft systems and circuits for sensitivity to arc discharges
- Follow “Mitigating In-Space Charging Effects—A Guideline”, NASA Handbook 4002A

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Lessons Learned from Juno IESD

- Do not assume too much heritage from other programs (e.g., Mars)
- Develop requirement early
  - Plan adequate test and analysis program early in the project
  - Test as many items as possible to avoid unnecessarily conservative design requirements
- Ground metals to the extent possible
- Full surface coverage for external cables is important to limit discharge “magnitude”, more important than shield thickness
- Thick shield thickness is better for minimizing the charge deposition rate, thus discharging rate
- Select the “right” electron energy and flux for beam tests that simulate actual flight conditions

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Radiation

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Radiation Effects on Devices

Type of Radiation Effect	Effect on Devices
• **Total Ionizing Dose (TID) – protons, electrons, gamma rays**	
– Enhanced low dose rate effect	Both gradual, parametric degradation and sudden functional failure – cumulative 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

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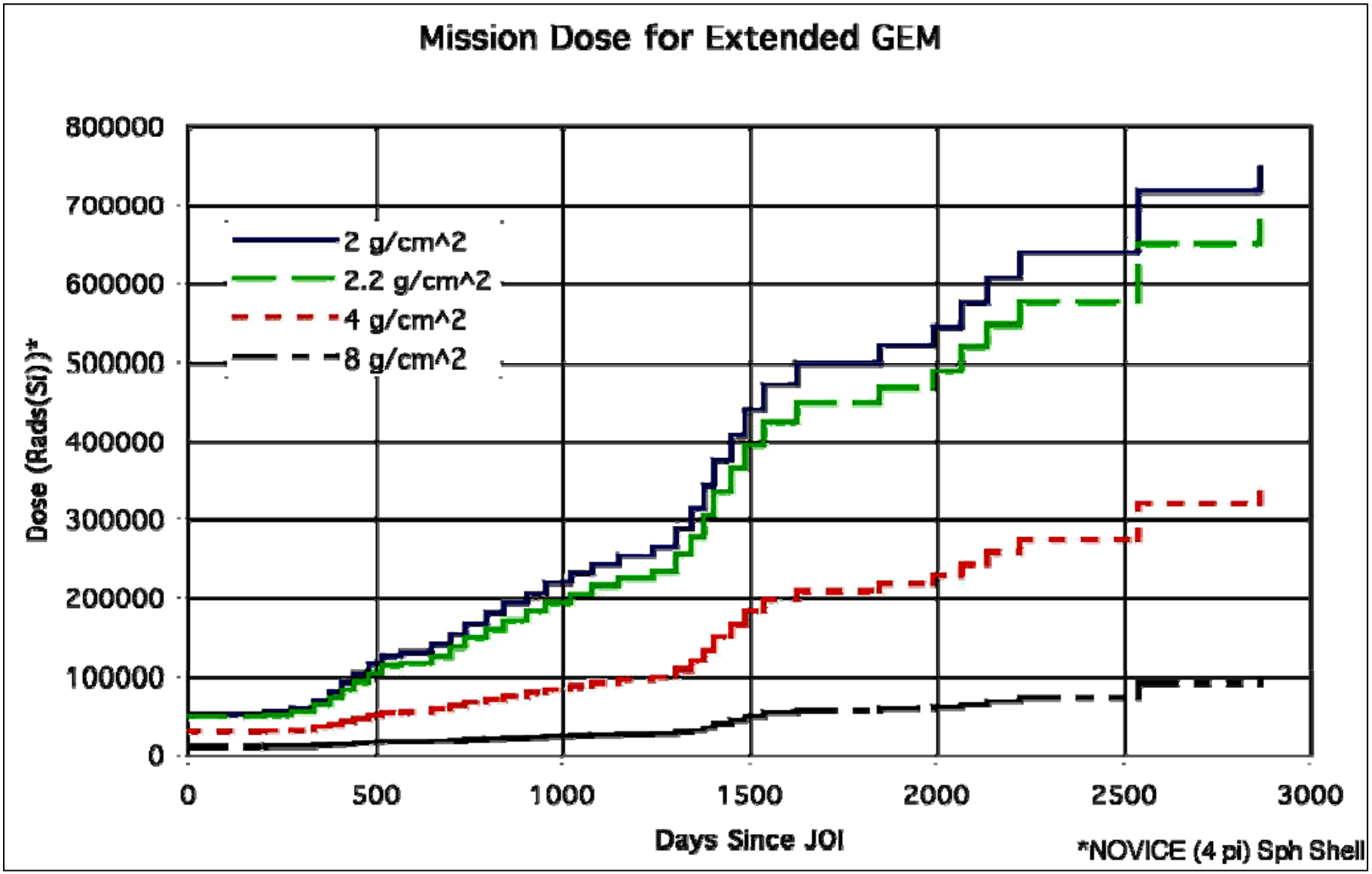
Divine Model Galileo Mission Dose Estimates



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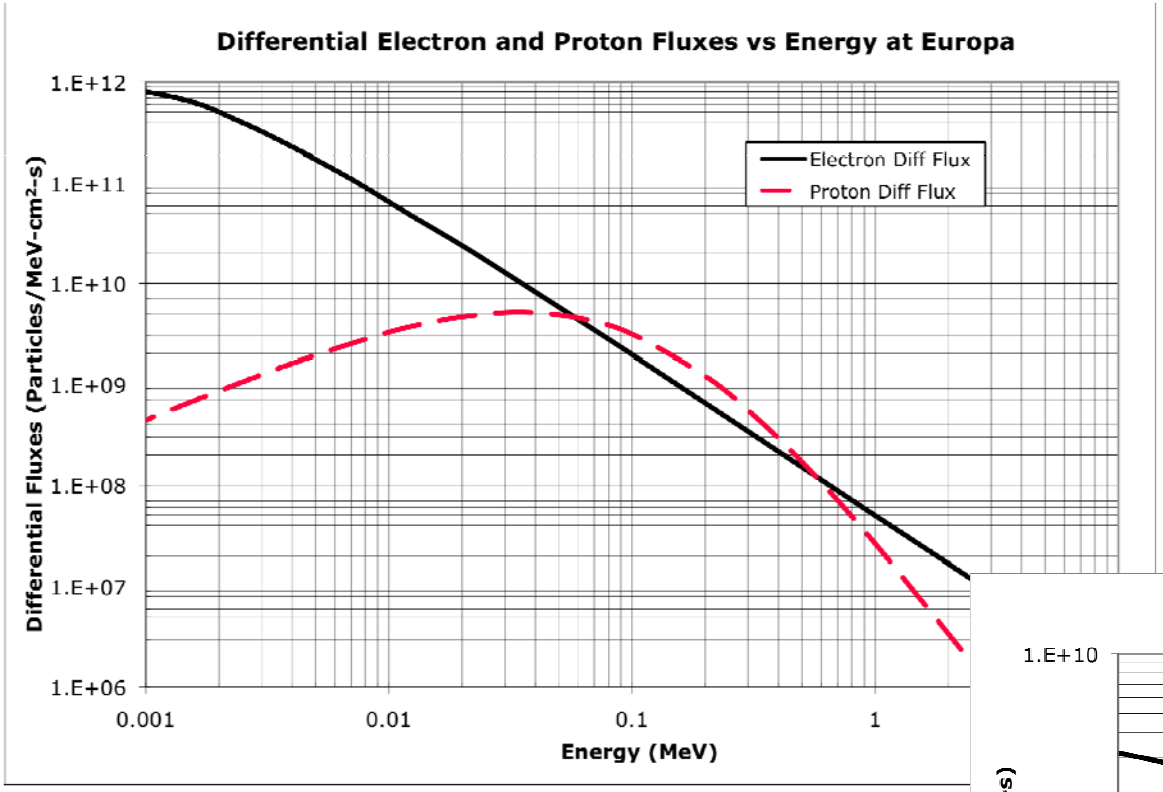
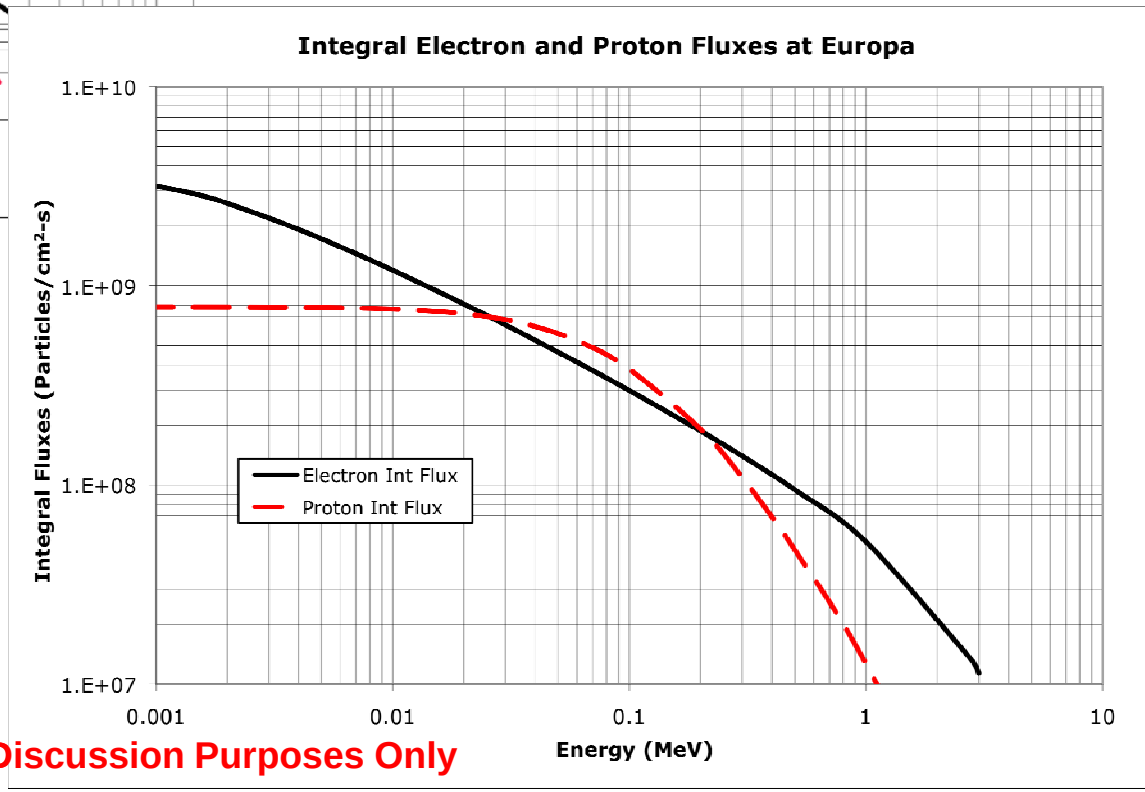


Divine-Garrett Model Electron and Ion Fluxes at Europa



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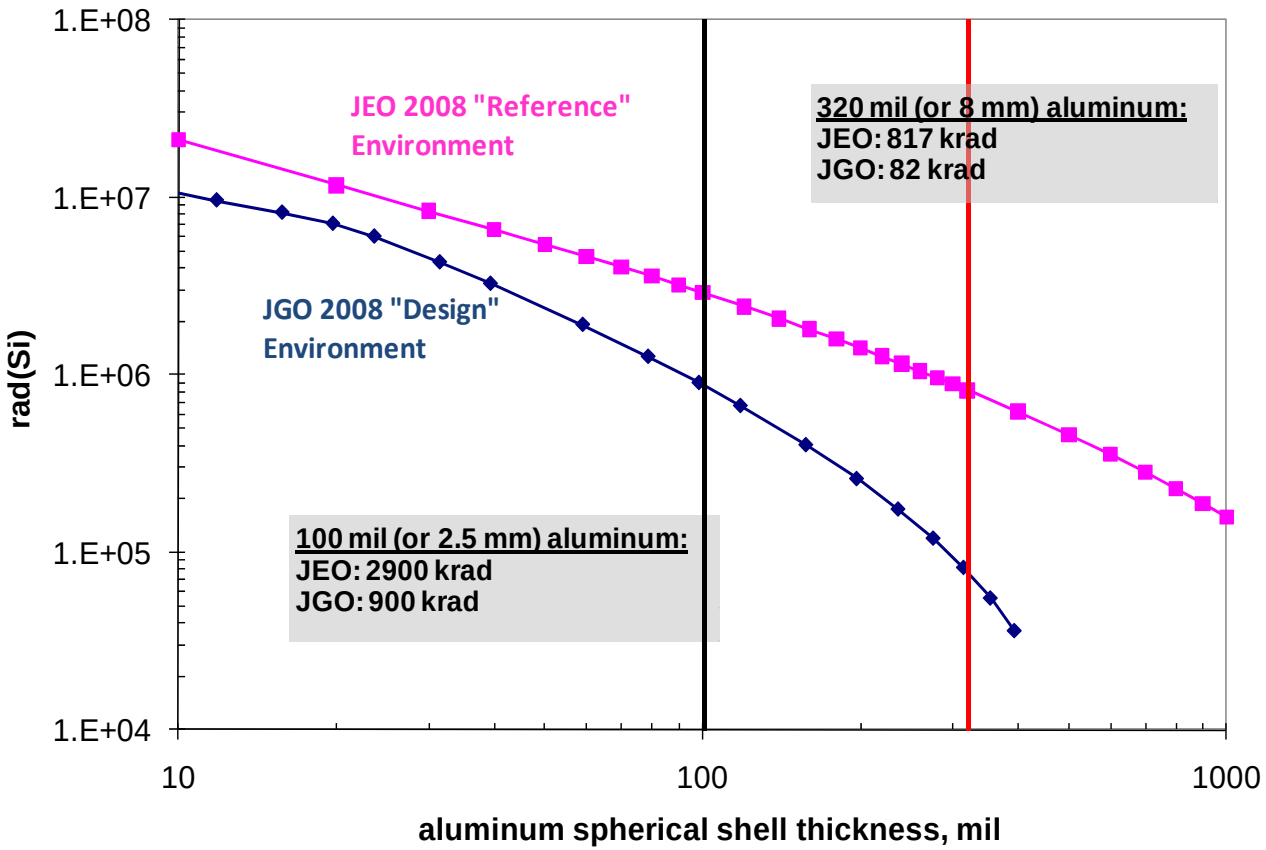
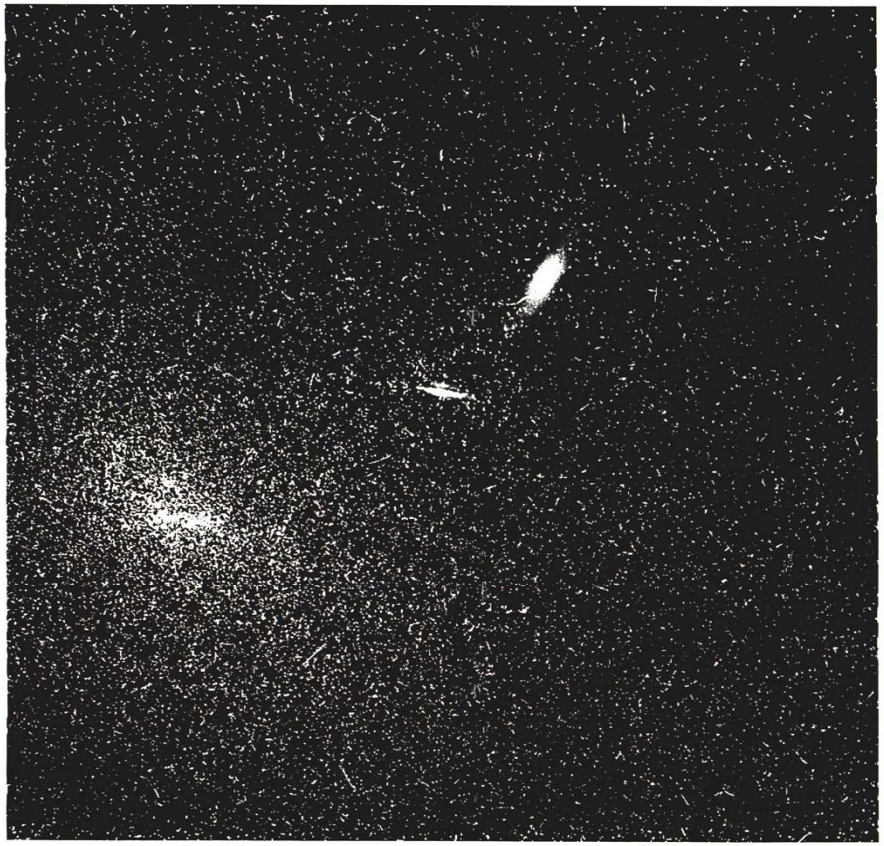
Dose-Depth Curves for JEO and JGO



A dose-depth curve provides the TID level at the center of a "spherical shell" spacecraft for various aluminum thicknesses.

Wide-field Planetary Camera CCD

Proton Events In South Atlantic Anomaly



Wide-field Planetary Camera CCD

Galactic Cosmic Ray Secondaries

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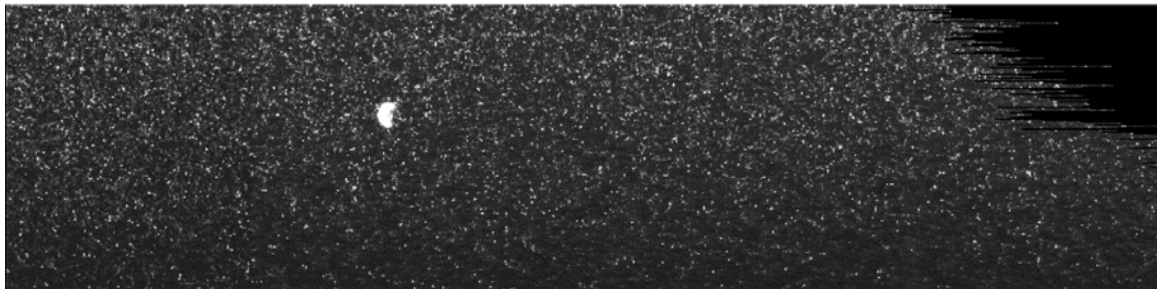
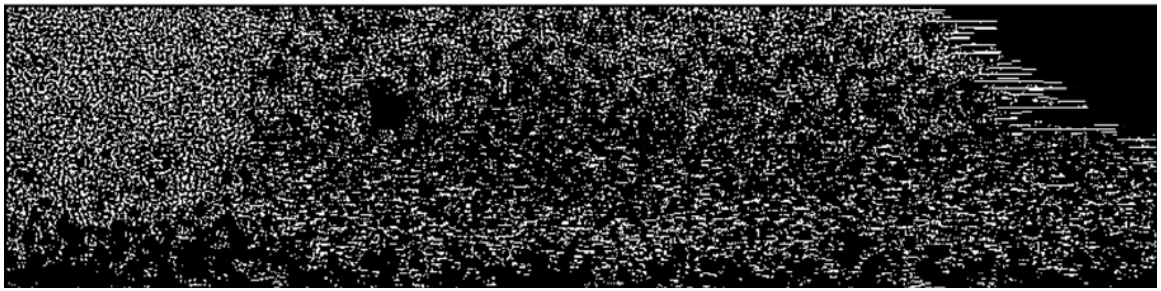
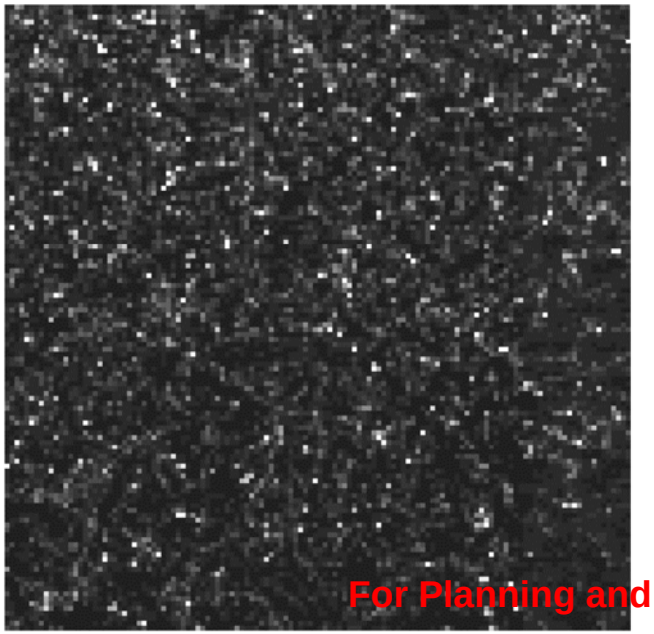
Example of Galileo SEU trails near Europa







CCD IONIZATION TRAILS:

-Radiation exposure 1.7 s for bottom; 7.5 s for top. Pixels are 15x15x10 um.

-Top is raw image stretched to show hits.

-Second is difference between raw image and median filtered image to emphasize hits.

-CCD protected by 1 cm of tantalum. Hits are probably from secondaries generated in tantalum.

-Taken ~10,000 km from Europa (white spot in first picture).

-Last picture is blow up to show upsets.

Courtesy Alan Delamere, Ball Aerospace, Ken Klaasen, JPL

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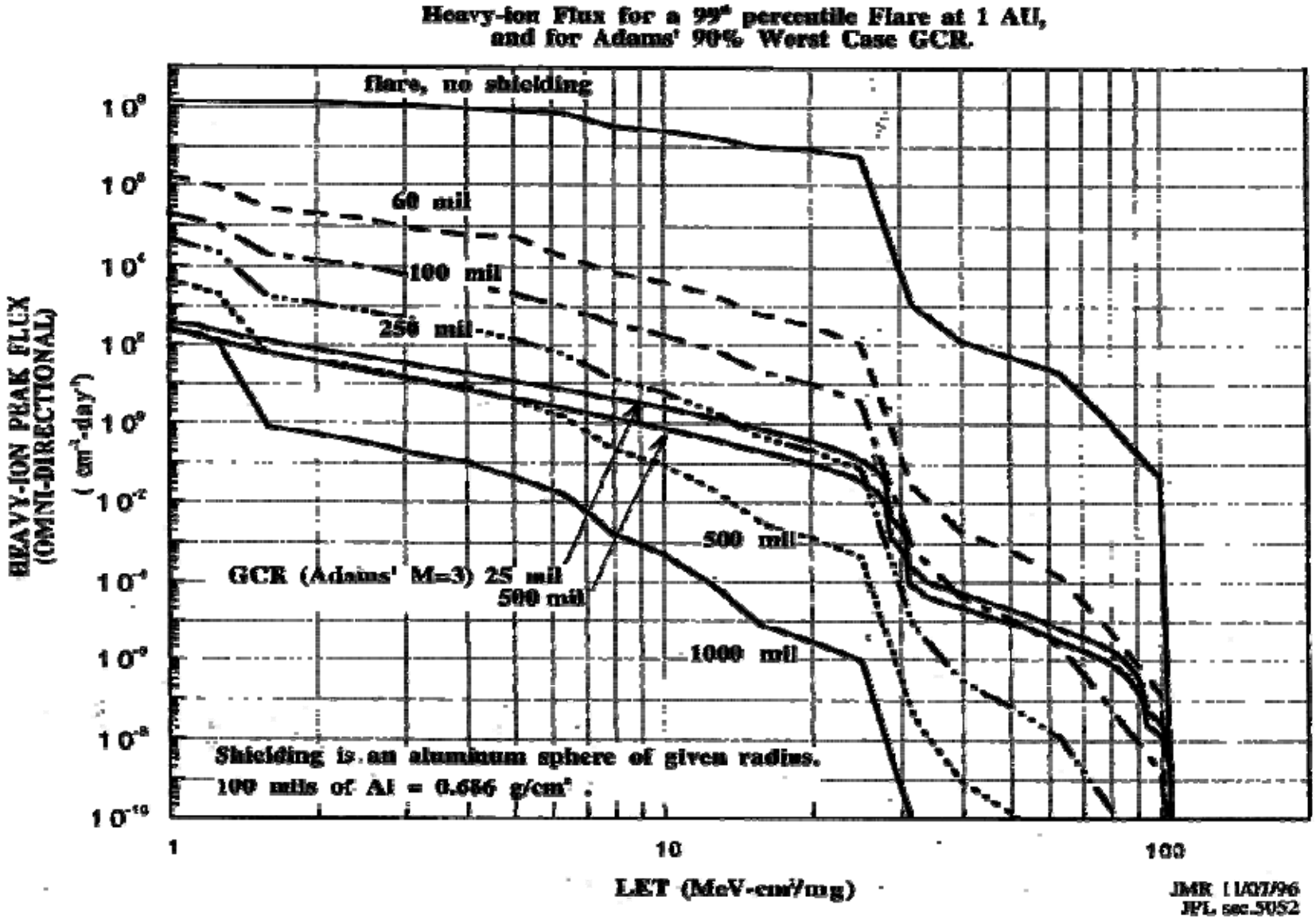
HEAVY-ION HEINRICH FLUX AT 1 AU



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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	.02756	.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

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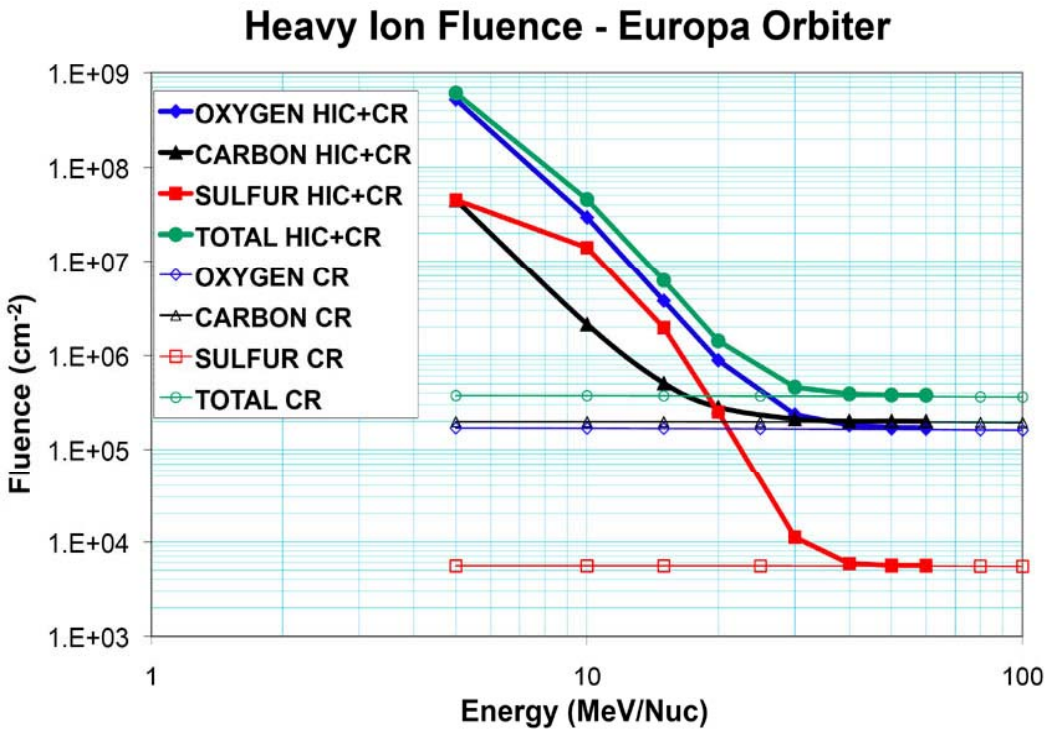
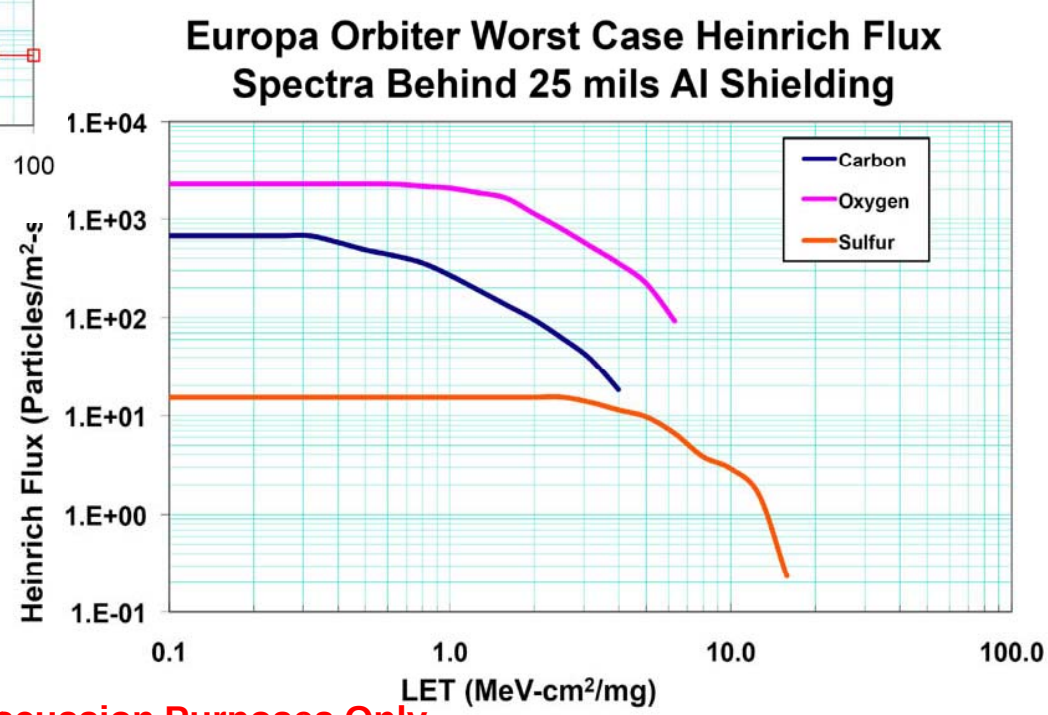
HIC Predictions



Europa Orbiter Mission Fluences "EO9935"

Worst Case Europa Orbiter Heinrich Flux vs LET (25 mils Al Shielding)



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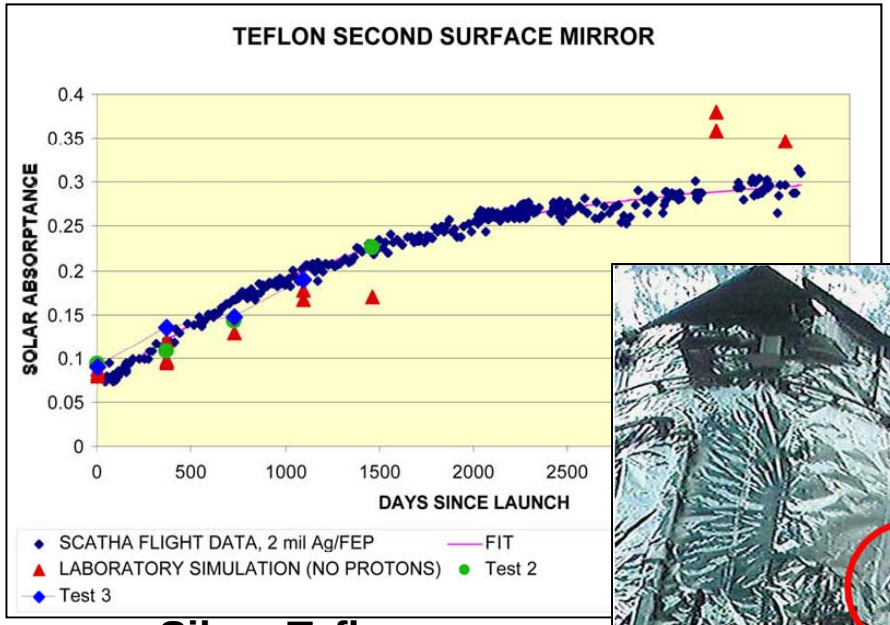
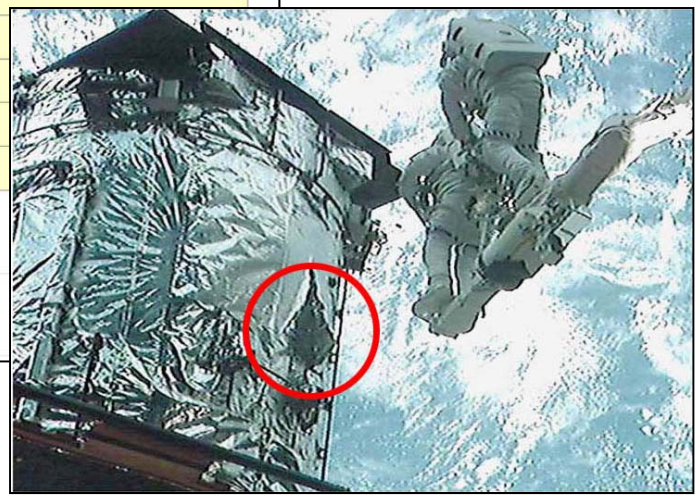
Radiation Effects on Materials



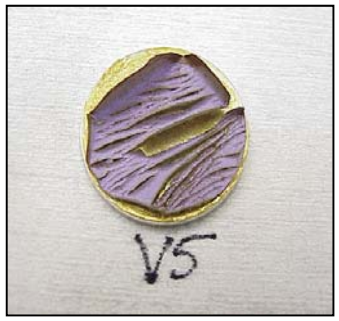
Silver Teflon: Flight Data

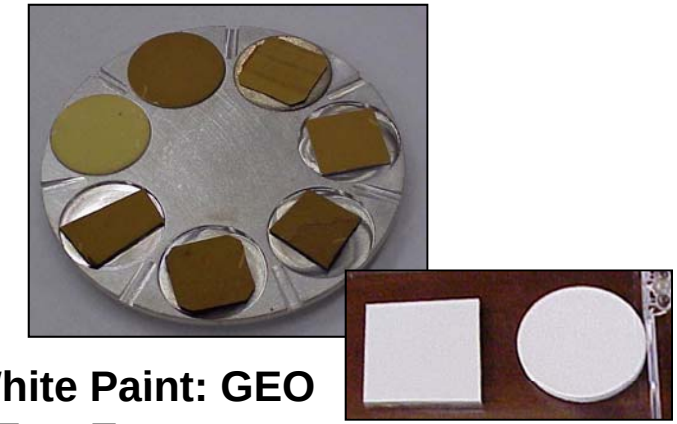


Materials suffer from UV/EUV and particle radiation (Grads on surfaces!) through changes in:

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

Tedlar: 3-4 Yrs GEO Test Exposure





White Paint: GEO Test Exposure

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

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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

*P. Willis, JPL

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MITIGATION TECHNIQUES FOR RADIATION

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Total Ionizing Dose Effects

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**

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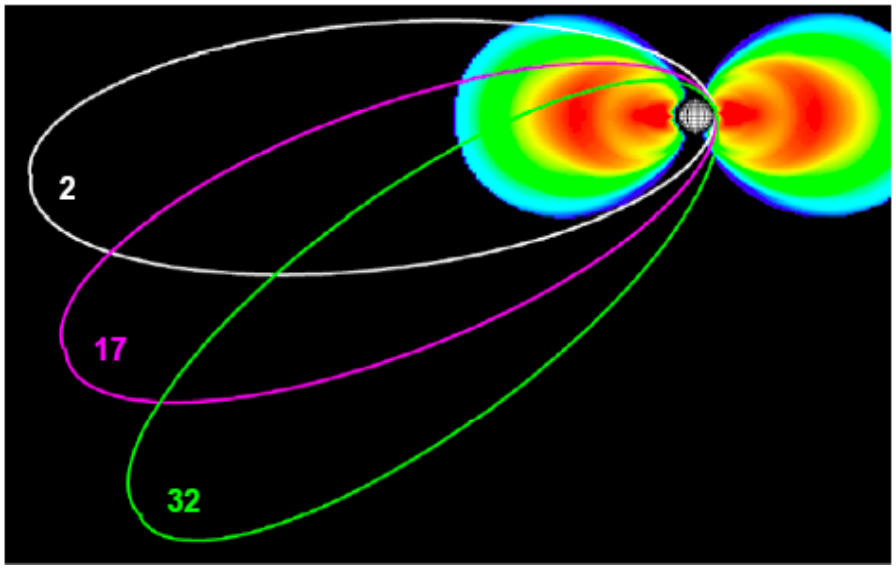
Principles of Radiation Protection

- Minimize the Time of Exposure
  - Careful selection of trajectory, e.g., Juno.
  - Europa Orbiter would also stay out of the intense radiation belt in the early phase of Jovian tour.
- Maximize the Distance from the Source
  - Place flight electronics and science instruments away from MMRTG.
  - Not possible in the space radiation environment.



Perijove Passage through Jupiter's Radiation Environment

- Design using Radiation Hardened Parts or Sensors
  - Cost
- Use Shielding (as a last resort)

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