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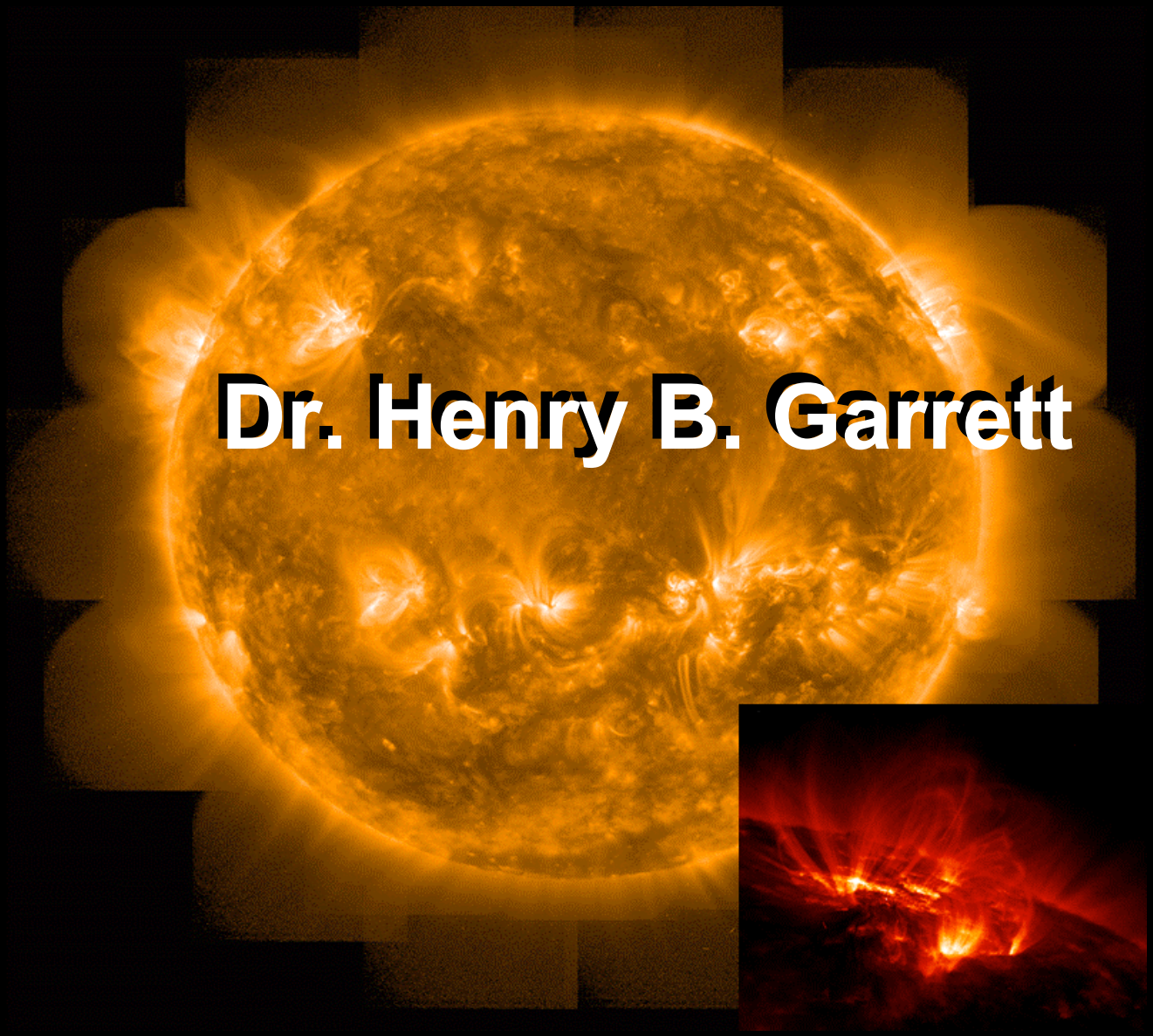
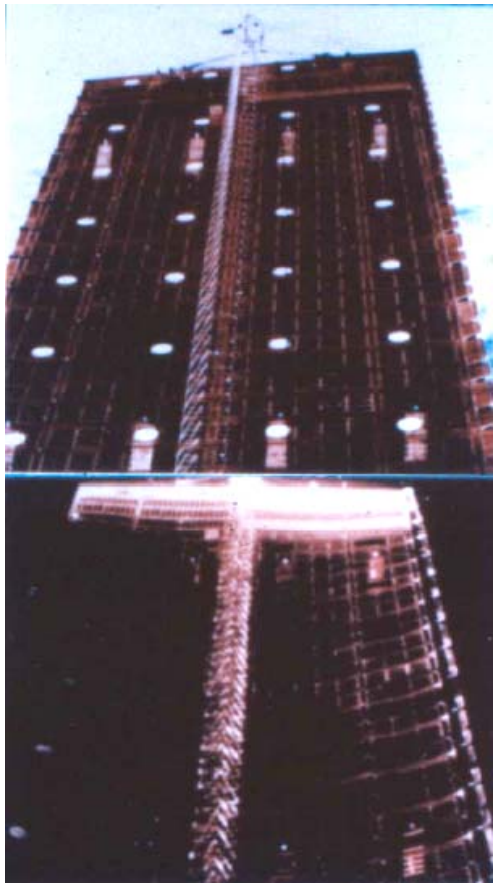
Space Environment Effects on Materials



Dr. Henry B. Garrett

WHY DO WE CARE?

- 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 effects on materials have been studied since the dawn of the space age, there are still many unknowns
- With careful design, many space environment effects on materials can be limited at a relatively low cost



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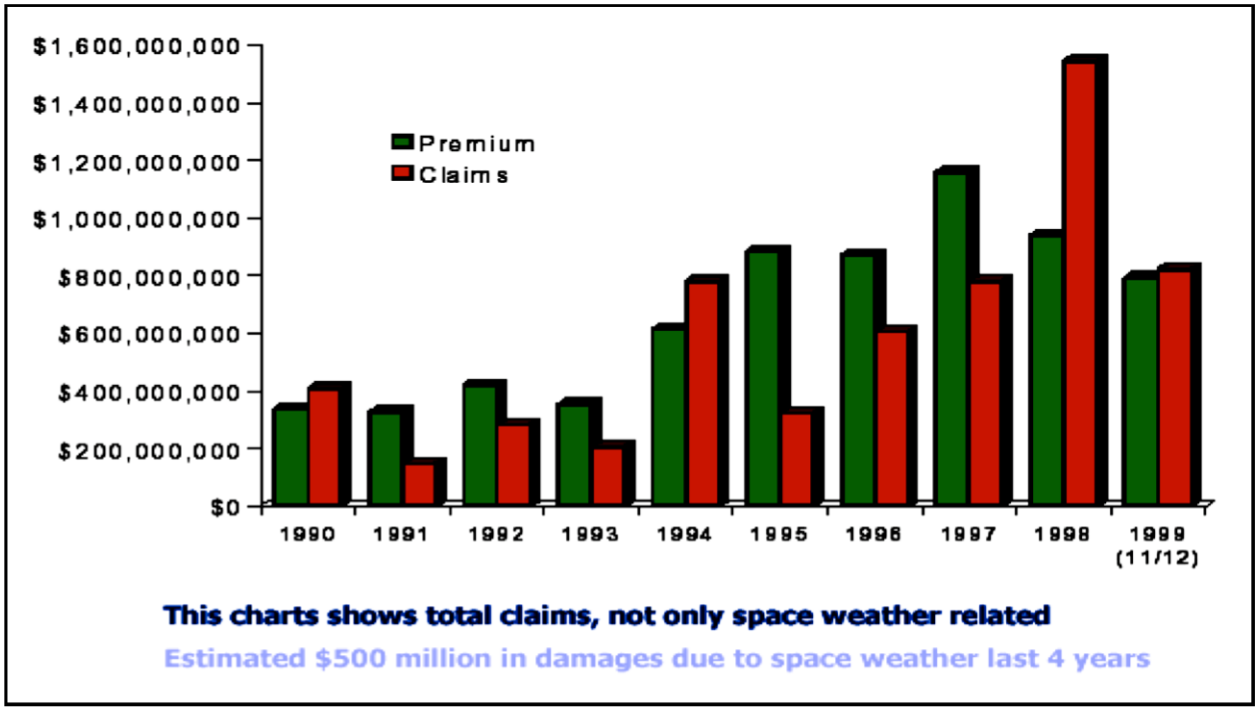
Impact of Space Effects on Spacecraft Costs

- 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 the next 10 years with a potential insured value of $80 billion!



After E. Daly, Alpbach Summer School

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Space Environment Effects on Spacecraft by Source†

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

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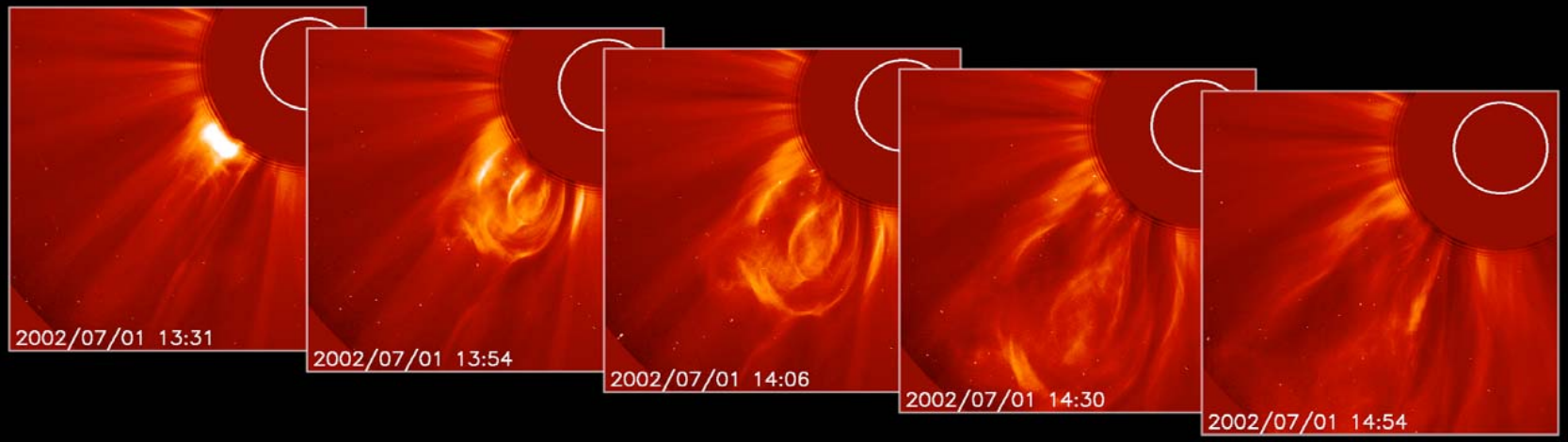
PRIMARY SOURCE OF SPACE EFFECTS: THE SUN



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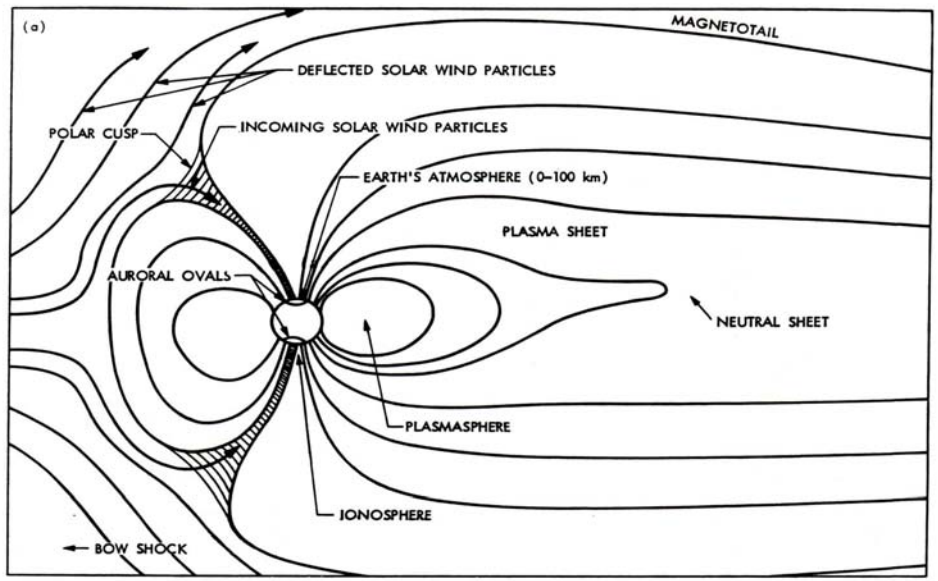
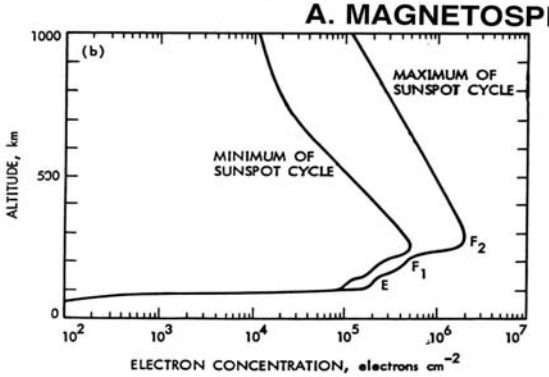
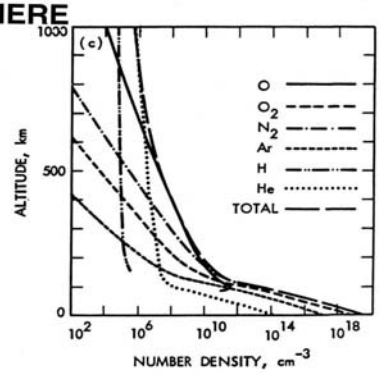
THE EARTH'S ENVIRONMENT



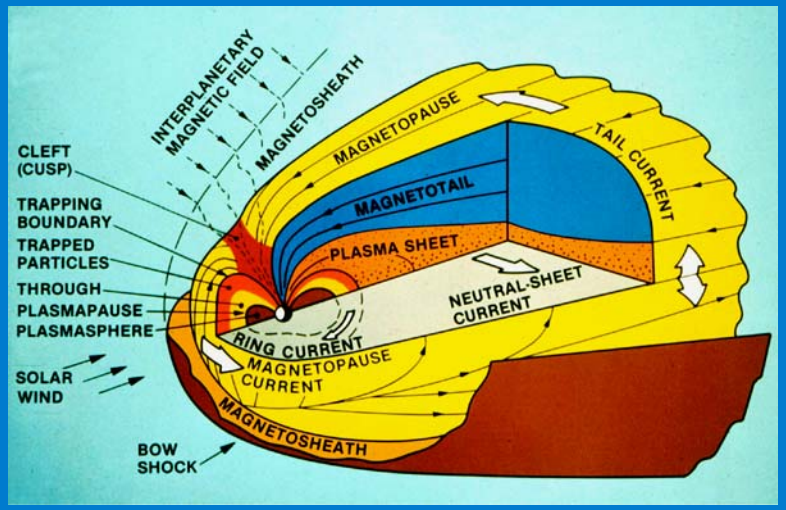
A. MAGNETOSPHERE

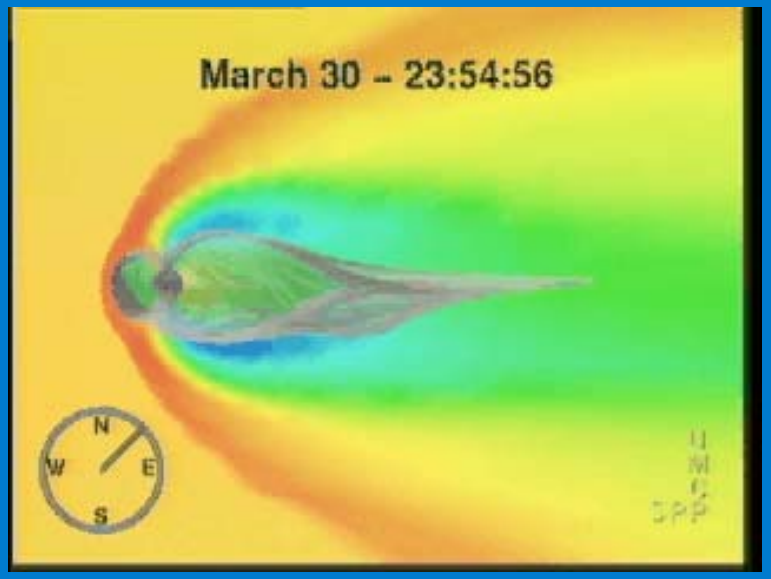


B. IONOSPHERE



C. ATMOSPHERE





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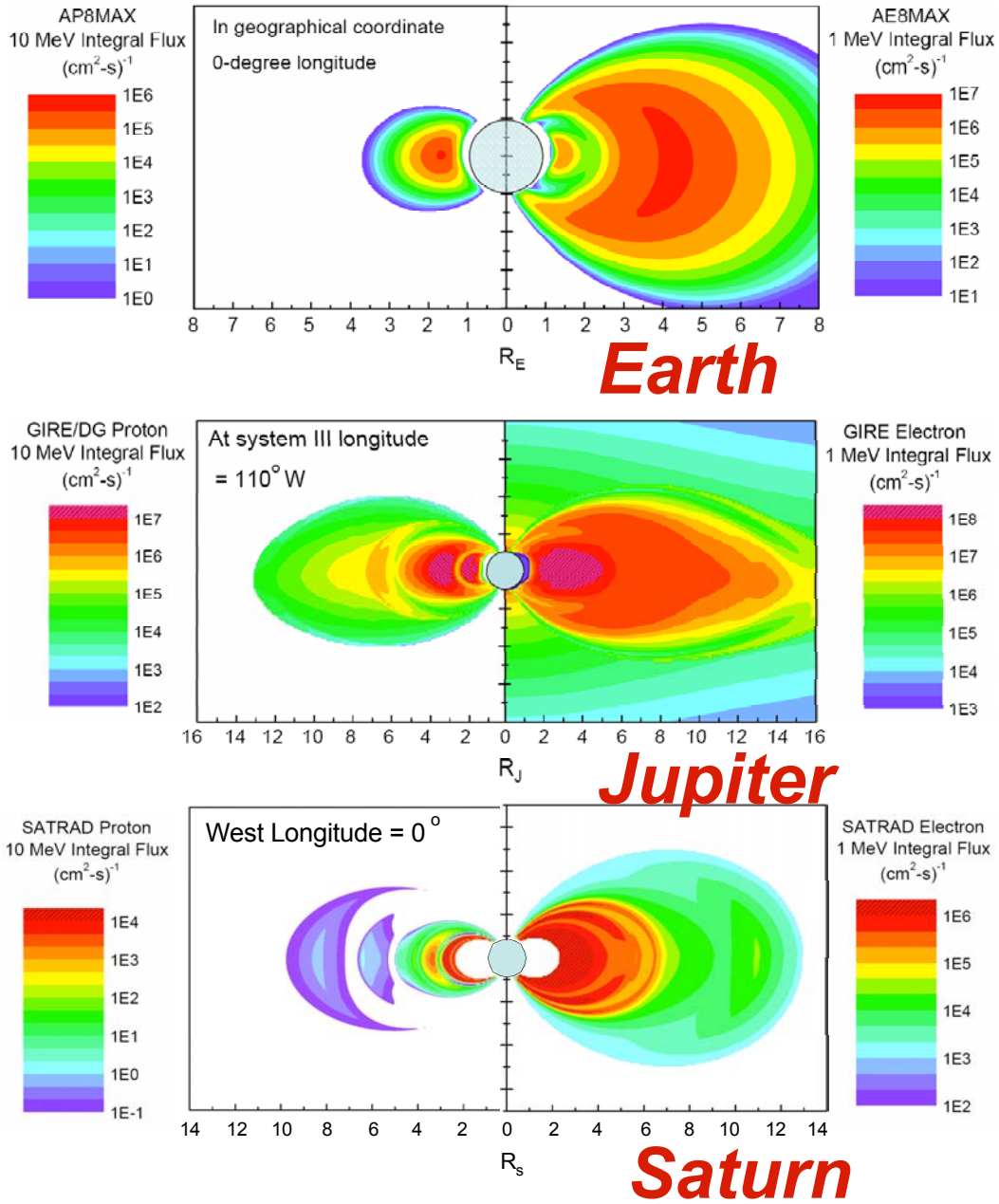
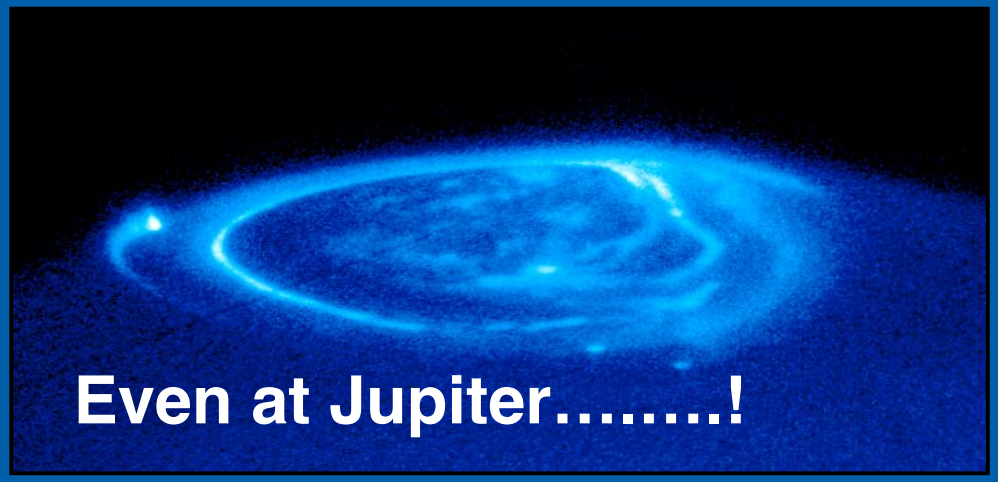
TRAPPED RADIATION BELTS



Aurora Are Everywhere…



SPACECRAFT INTERACTIONS

- ***ATMOSPHERIC INTERACTIONS***
- ***CONTAMINATION EFFECTS***
- ***HYPERVELOCITY IMPACTS***
- ***SPACECRAFT CHARGING***
- ***PLASMA INTERACTIONS***
- ***RADIATION INTERACTIONS***
  - ***Particles***
  - ***UV/EUV***

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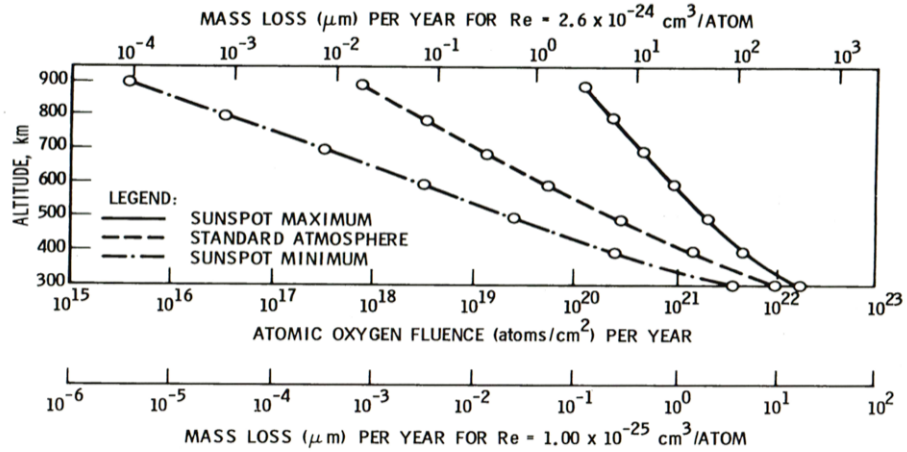
ATMOSPHERIC EFFECTS

Atomic Oxygen Fluence/Mass Loss Nomograph for Different Atmospheric Assumptions as a Function of Altitude for a Circular Orbit

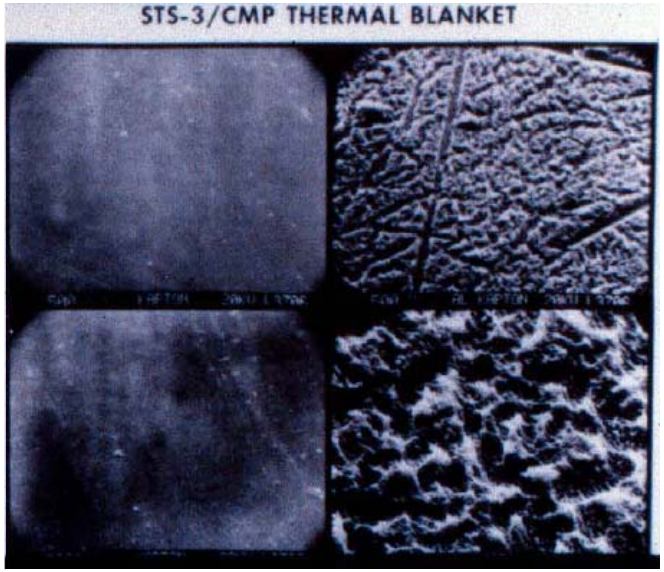


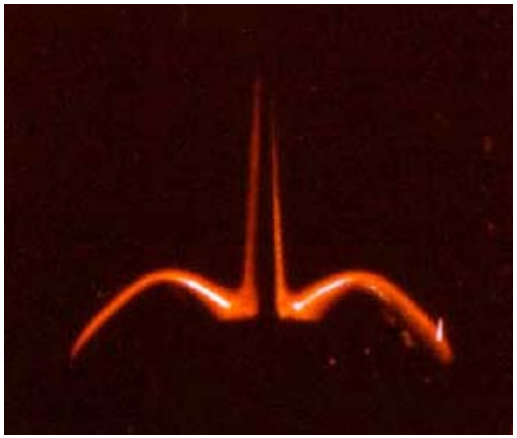
ASSUMPTIONS:

- EXPOSED SURFACES ARE INERTIALLY FIXED AND NORMAL TO ORBIT PLANE
- MASS LOSS IS FOR KAPTON ($Re = 2.6 \times 10^{-24}$) AND TEFLON ($Re = 1.09 \times 10^{-25}$) COVERED SURFACES
- ORBITS ARE CIRCULAR WITH FRONT AND BACK SURFACES EXPOSED

(COURTESY LEGER ET AL.)

OXYGEN EROSION





GLOW

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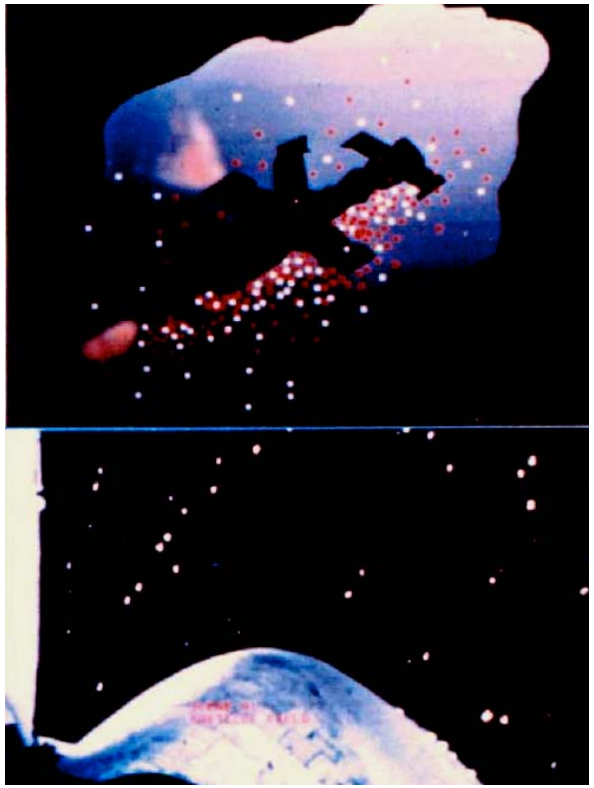
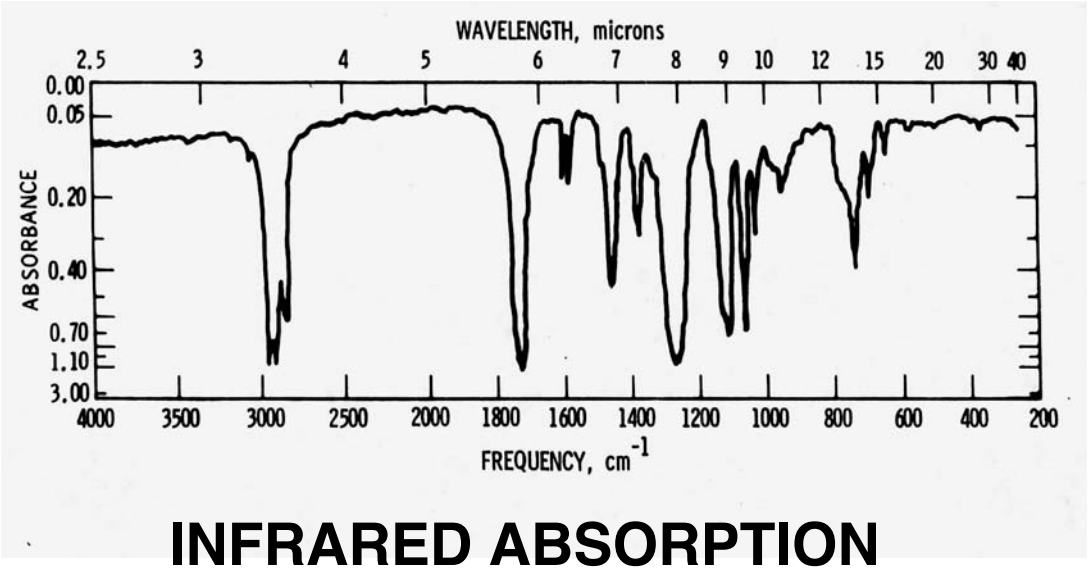
CONTAMINANT EFFECTS ON MATERIALS

DEBRIS AND CONTAMINANT CLOUDS AROUND SPACECRAFT





INFRARED ABSORPTION SPECTRUM OF DIOCTYL PHTHALATE

A COMMON CONDENSABLE CONTAMINANT

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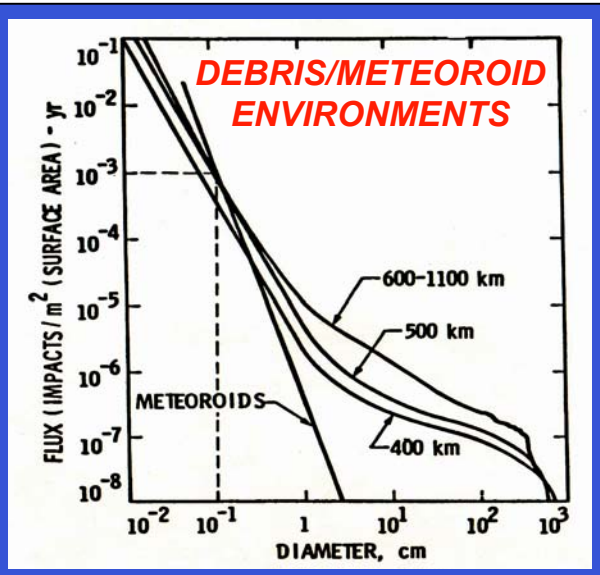
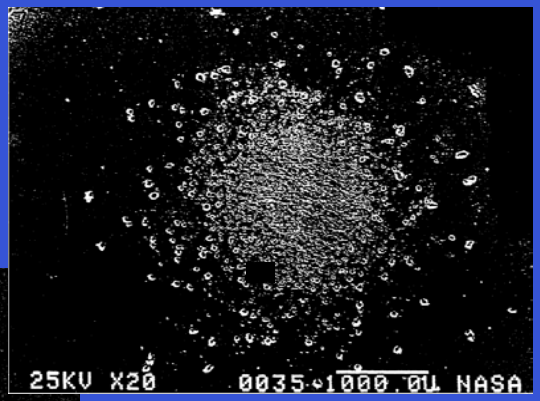
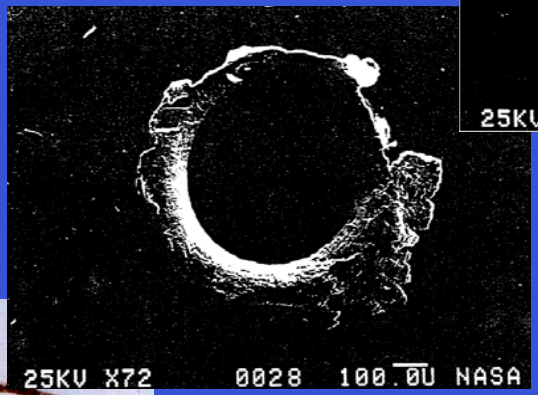
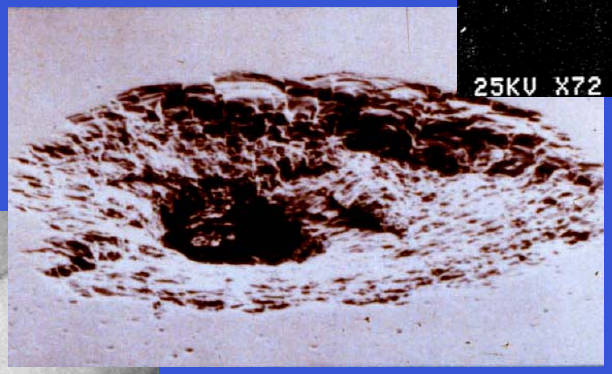
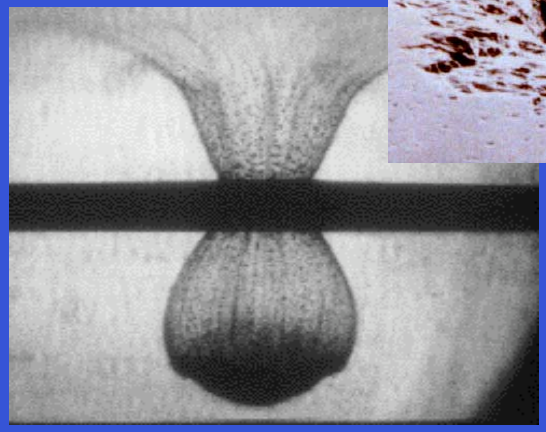
METEOROID/DEBRIS EFFECTS ON MATERIALS

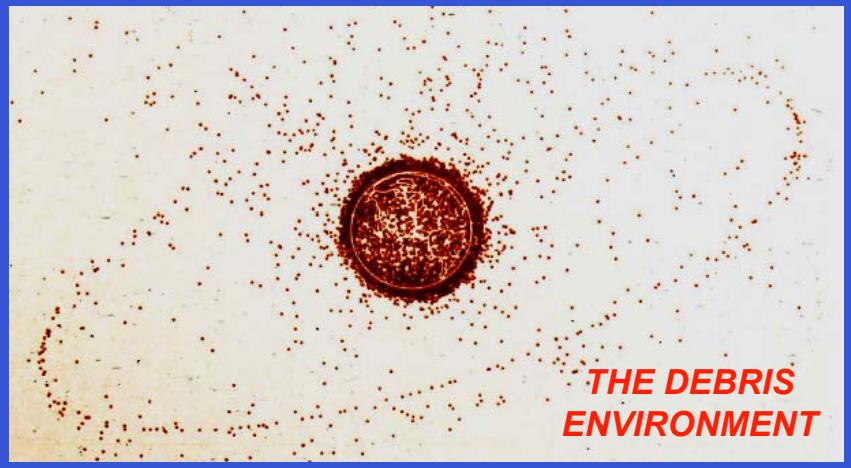












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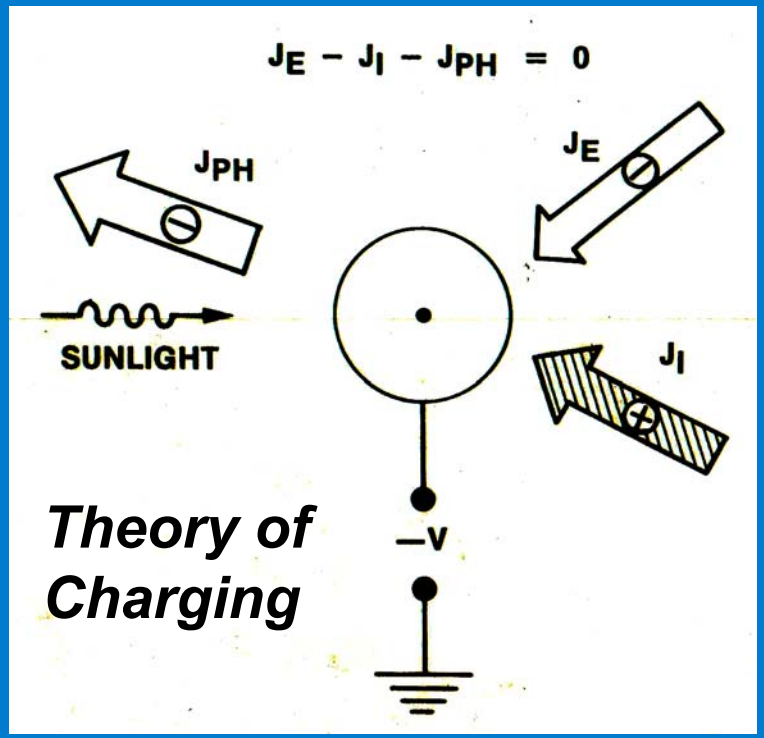
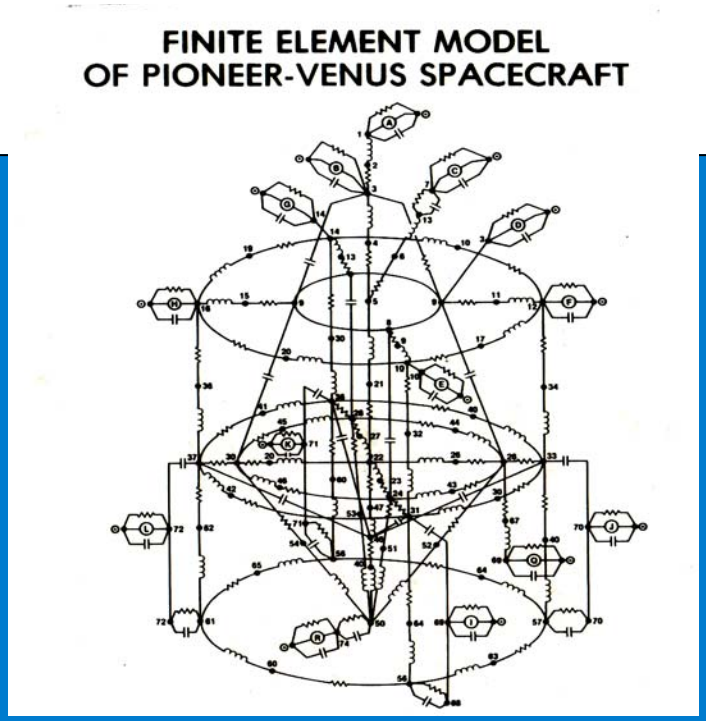
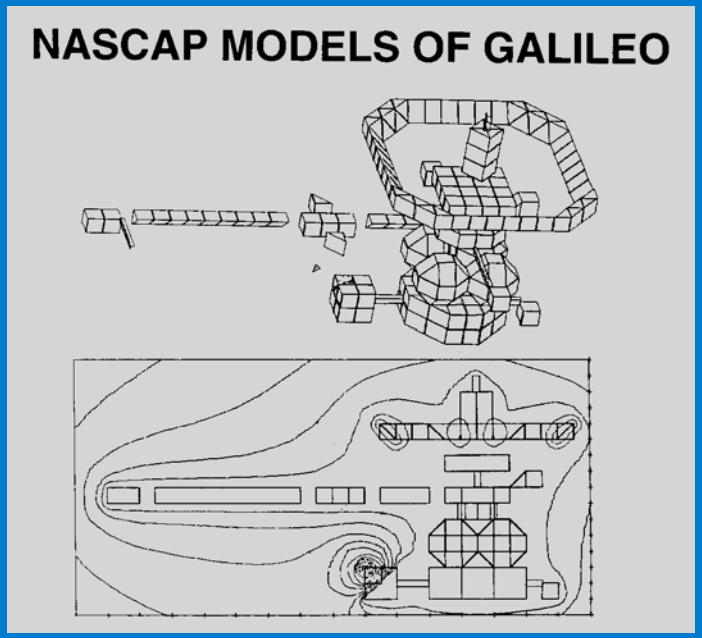
SPACECRAFT SURFACE CHARGING



Theory of Charging





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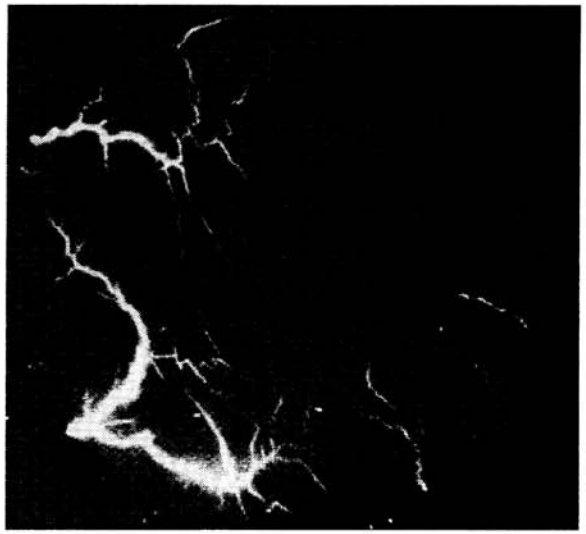
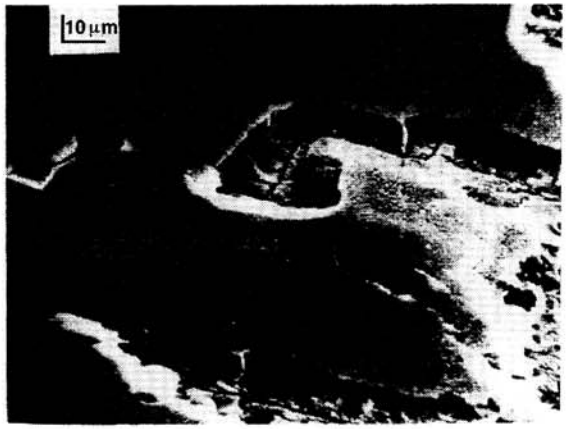
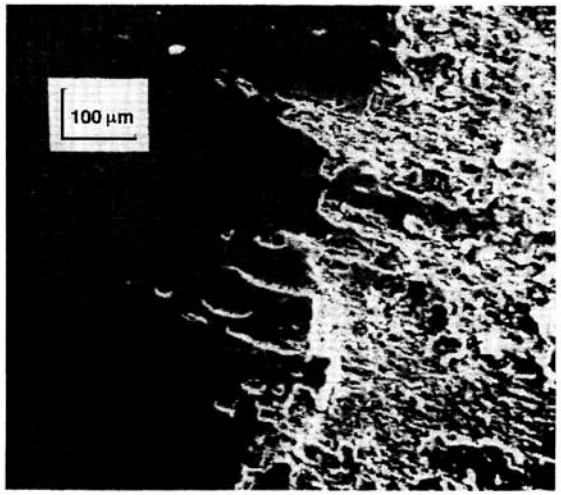
SURFACE DISCHARGE EFFECTS
(K.G. BALMAIN, 1980)



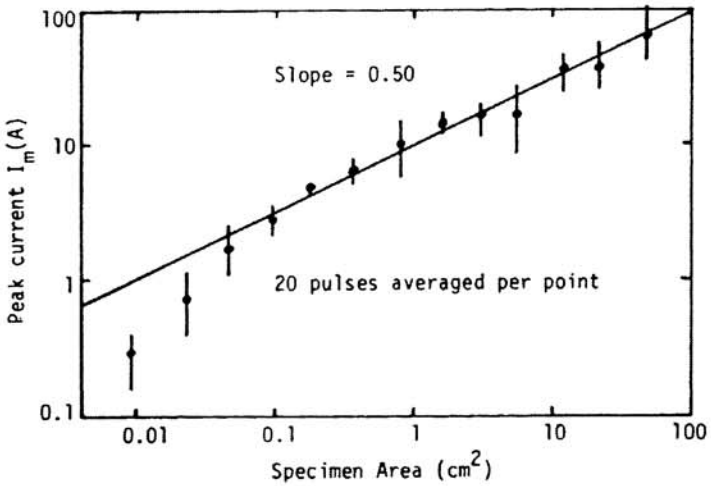
ARC DISCHARGE ON MYLAR
(area=48 cm^2)



MAGNIFIED VIEW OF ELECTRON MICROSCOPE IMAGE



ELECTRON MICROSCOPE IMAGE OF ARC DAMAGE



PEAK ARC CURRENT VS AREA
(CURRENT~LENGTH)

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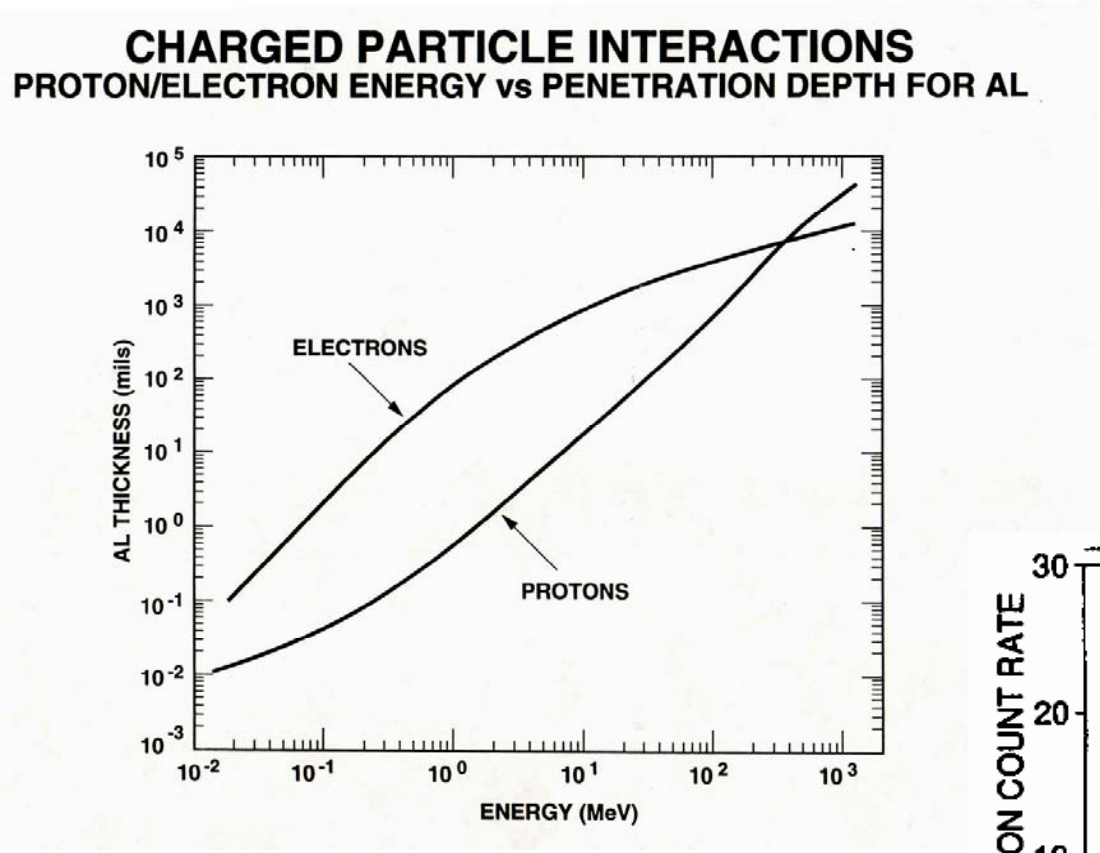
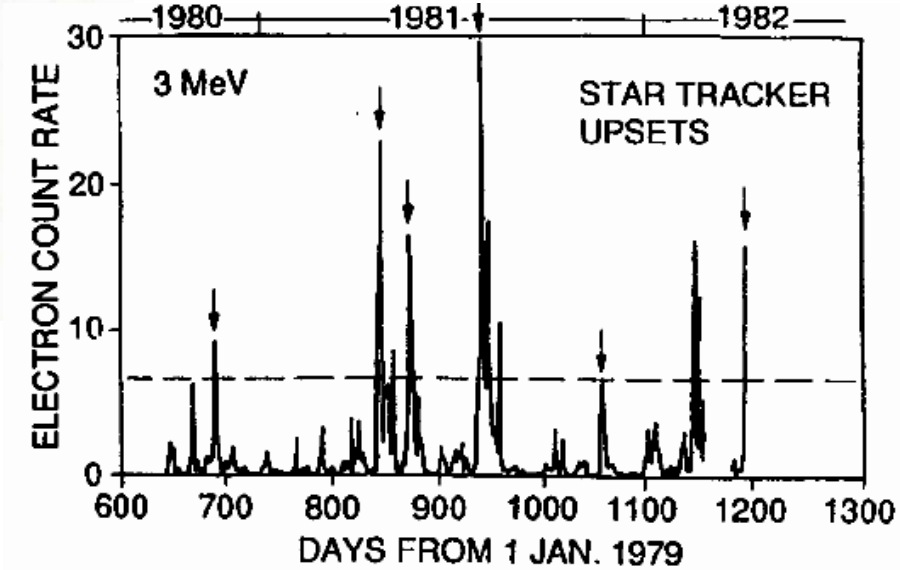
INTERNAL ELECTROSTATIC DISCHARGE--SATELLITE KILLER…



DISCHARGE PATTERN



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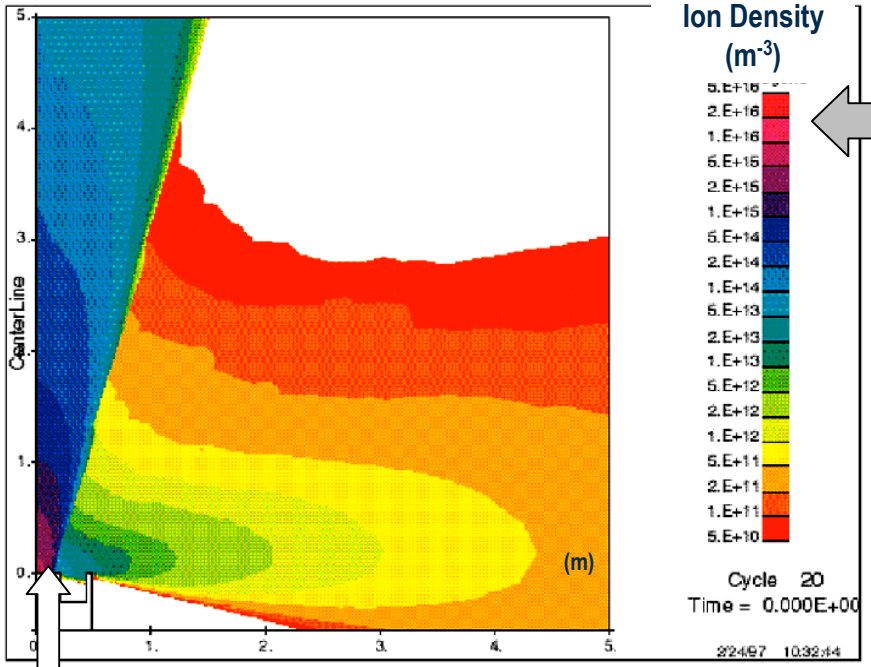
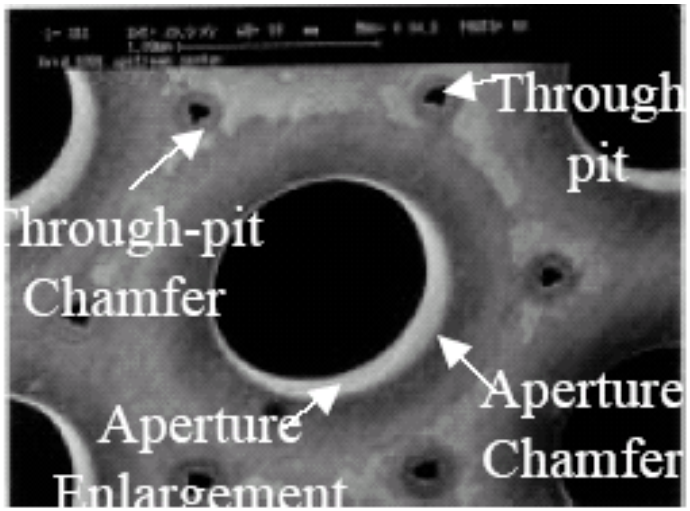
PLASMA INTERACTIONS DS-1 ION ENGINE



Computed[1] ion density contours for 30-cm NSTAR ion engine at full power (beam current ~ 1.8 A, ion engine power ~ 1.5 kW)

NSTAR Ion Thruster



EFFECTS OF CHARGE EXCHANGE (CEX) IONS

- DS-1: 10^{13}-10^{14} m^{-3} CEX ions within 50 cm radius along thruster exit plane implies currents of >10 mA/m^2
- As the negative accelerator grid can operate at less than -200 V, hundreds of mA/m^2 may bombard it
- Grid material is removed by a sputtering process from CEX ions
- Eventually the CEX ions will erode pits and grooves in the grid that limit the operating lifetime
- Sputtered material can deposit on nearby surfaces (solar arrays, radiators, science instruments)
- Ionization of Mo atoms in plume leads to non-line-of-sight transport and deposition

[1] Davis, V.A., *et al.* "Ion Engine Generated Charge Exchange Environment: Comparison Between NSTAR Flight Data and Numerical Simulations," AIAA Paper 00-3529, July 2000

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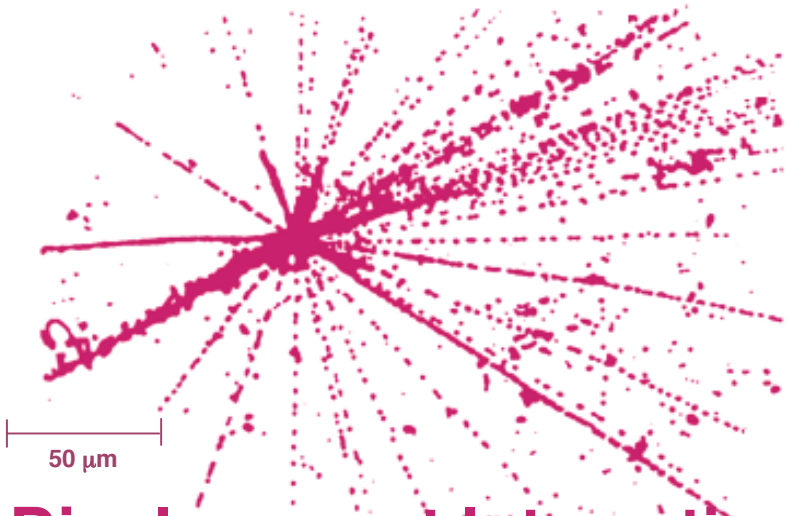
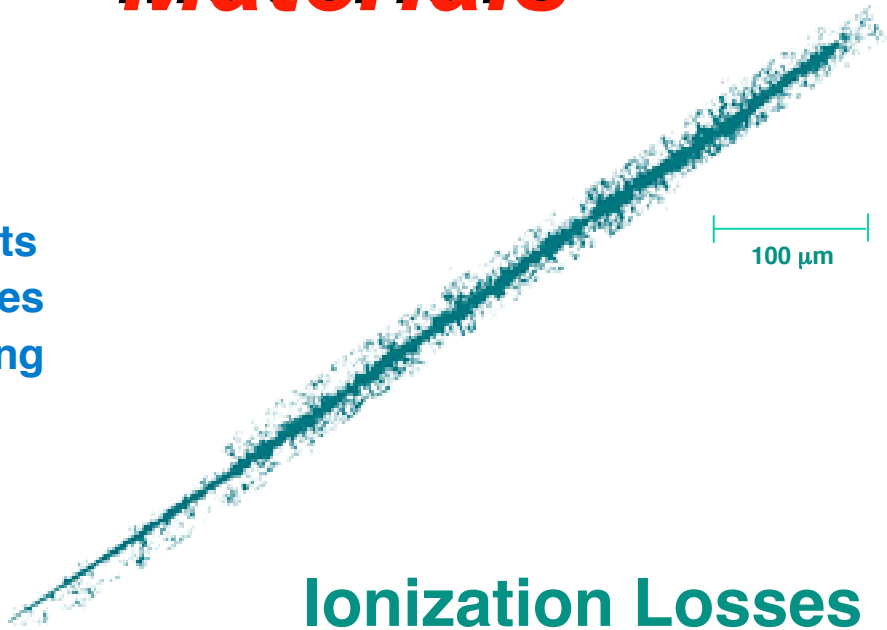
Radiation Effects on Spacecraft Systems and Materials



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

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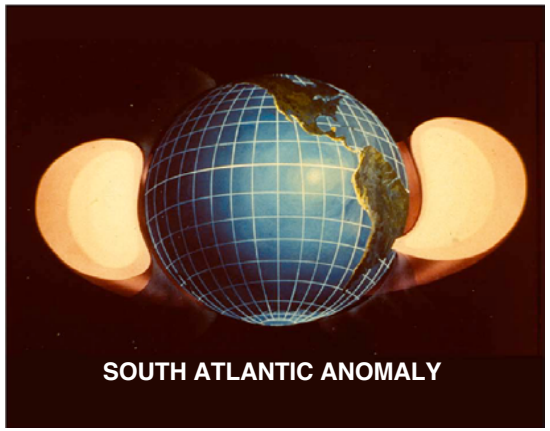
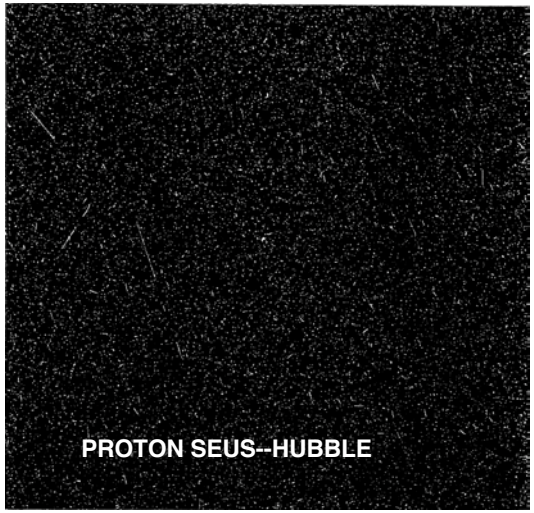
RADIATION EFFECTS ON MATERIALS





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

Courtesy P. Willis, JPL

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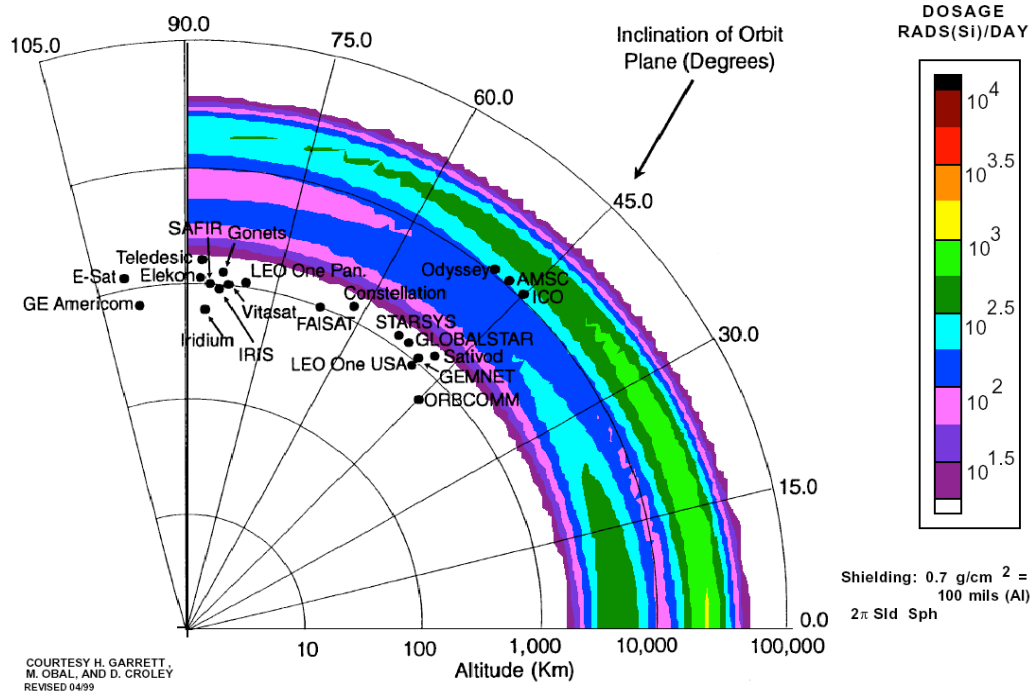
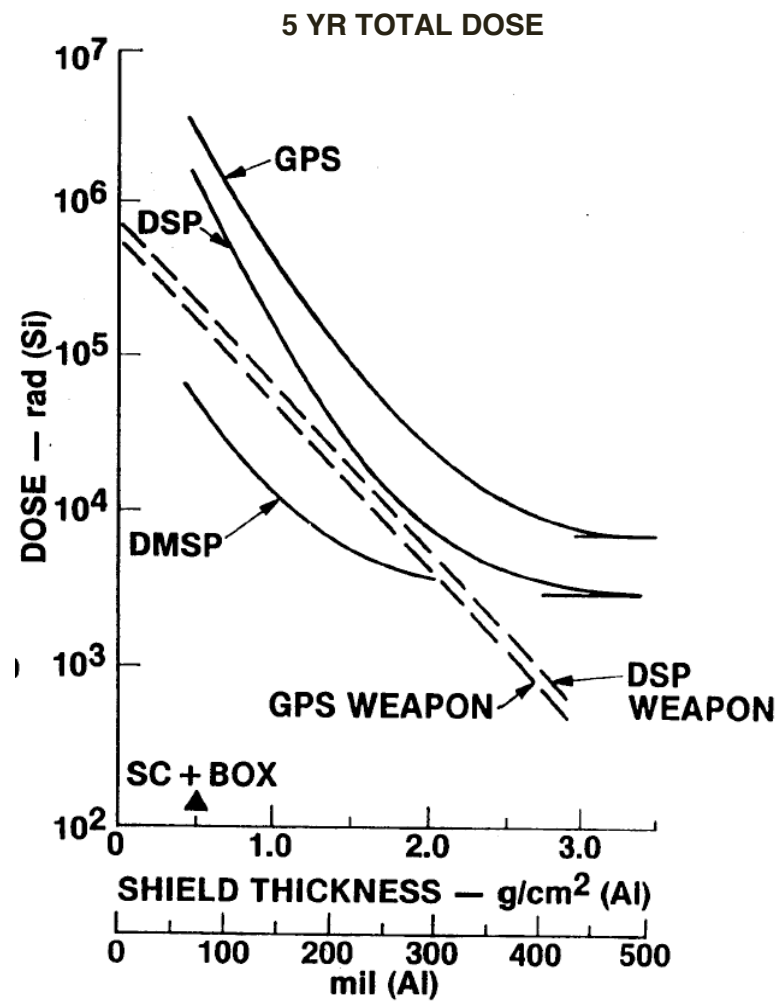
TOTAL IONIZING DOSE EFFECTS



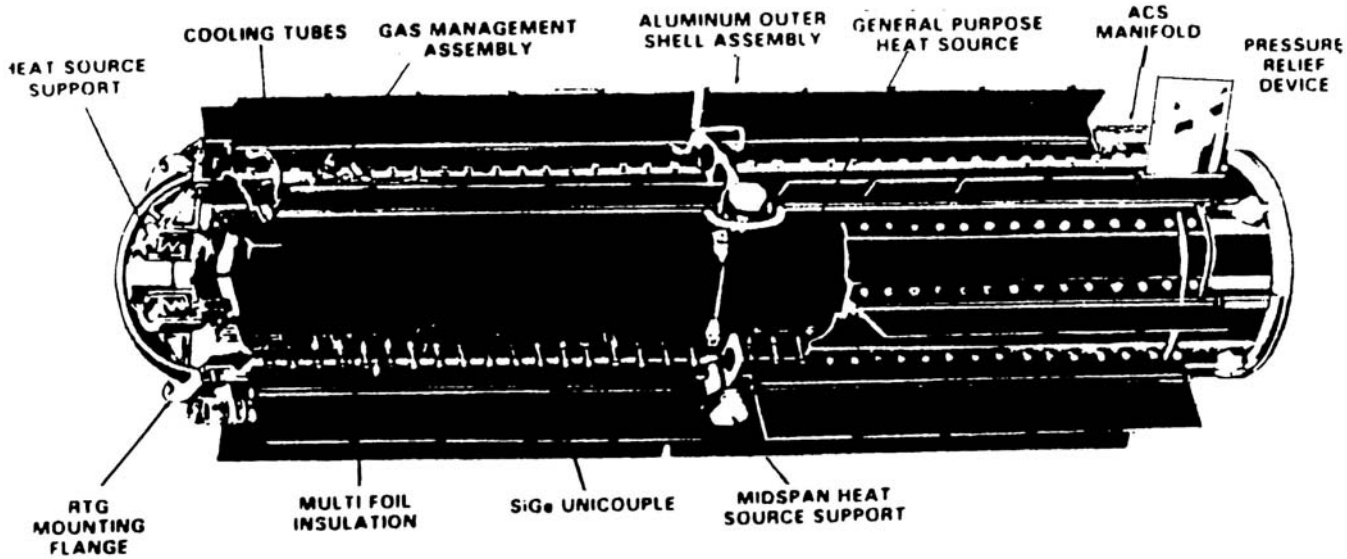


RADIATION HARDENING APPROACH

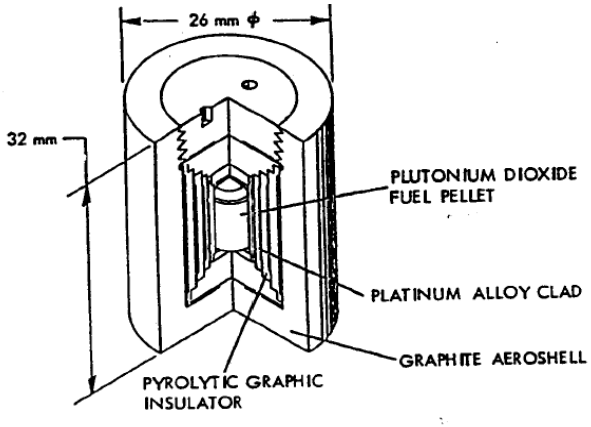
- Define the shielded radiation environment
- Parts parameter data--characterization screening
- Worst case circuit analysis--conservative design rules
- Shield to provide the part performance requirements
- Employ radiation tolerant circuit designs

MAN-MADE SOURCES OF SPACE EFFECTS

General Purpose Heat Source Radioisotope Thermoelectric Generator



Lightweight Radioisotope Heater Unit



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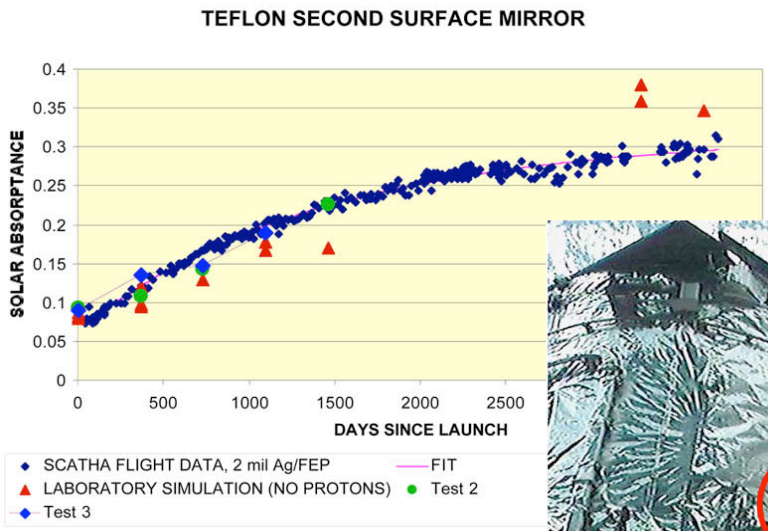
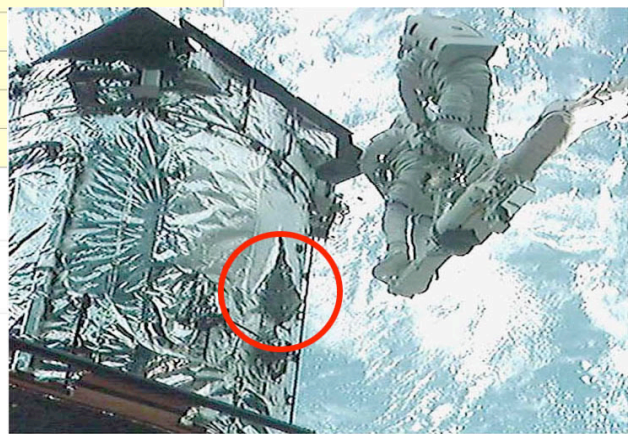
RADIATION EFFECTS ON MATERIALS



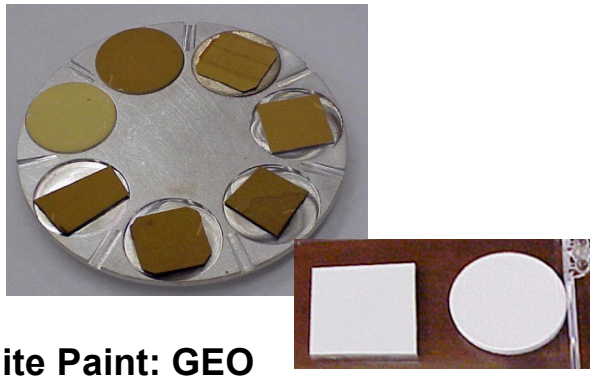
Silver Teflon: Flight Data



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

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

SPACE ENVIRONMENTS VERSUS INTERACTIONS

ENVIRONMENTS \ INTERACTIONS	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	
IONOSPHERIC PLASMA				x		X	X	x						
AURORA PLASMA				X										
TRAPPED RADIATION	X	X	x		X		X							
GALACTIC COSMIC RAY		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)