INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANIZATION

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WORKSHOP ON SPACE PHYSICS:
"Materials in Micorgravity"
27 February - 17 March 1989

"Space Environment"

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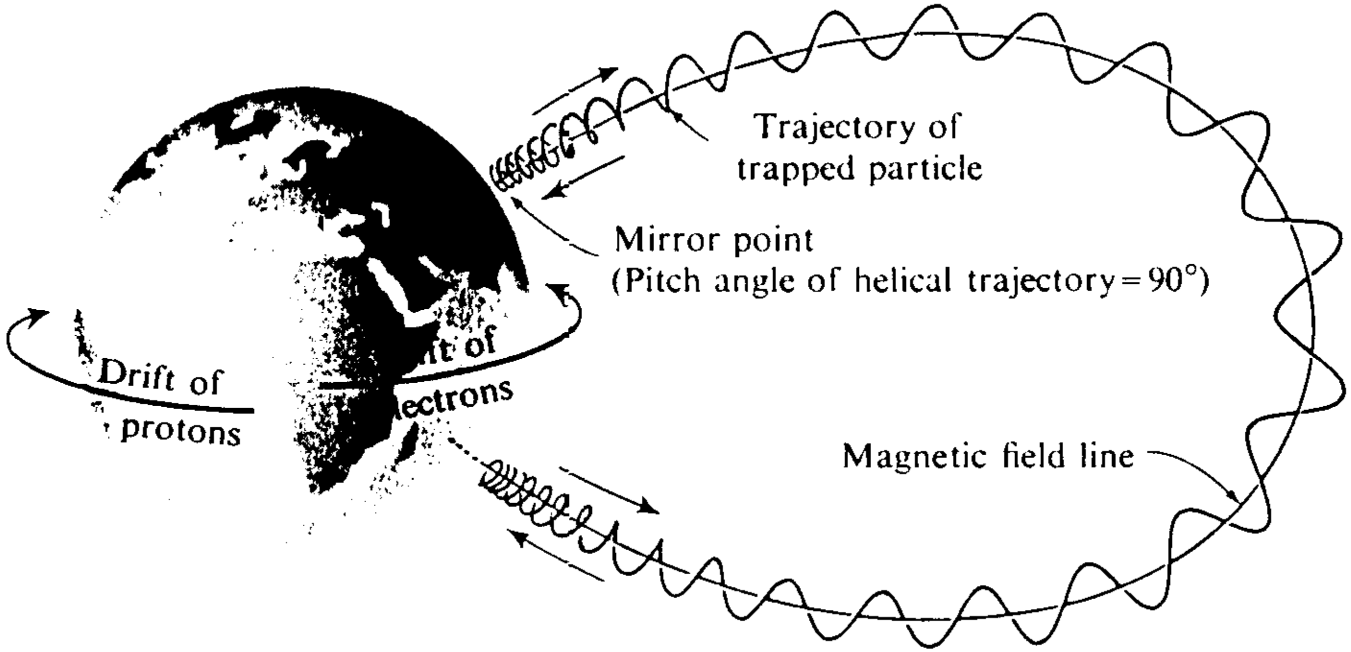
SPACE ENVIRONMENTS

E.J. Daly, ESA/ESTEC

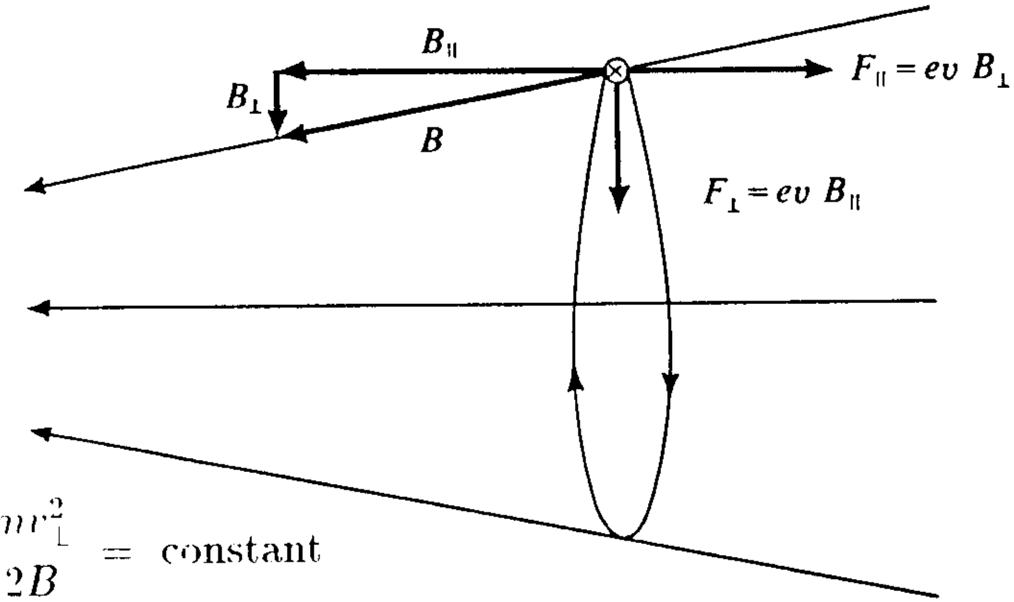
Natural and induced space environments have important deleterious effects on space systems and payloads. "Troublesome" environments include:

- Energetic charged particles -
  - geomagnetically trapped particles
  - solar-flare particles
  - cosmic-rays
- Plasmas - magnetospheric, auroral and ionospheric
- Atmosphere (including atomic oxygen)
- Fields
- Meteoroids and Debris
- Contamination
- Thermal

ENVIRONMENT	EFFECTS/INTEREST
ENERGETIC PARTICLES (radiation belt, solar flares)	radiation damage - components and materials; instrument interference; radiobiological effects
COSMIC-RAYS	single-event upset; latch-up; interference; radiobiological effects
MAGNETOSPHERIC PLASMAS (high altitude) IONOSPHERIC PLASMAS (low-altitude)	High-level charging → discharges; interference; enhanced contamination ram-wake formation; power-leakage and discharges on elevated-voltage systems; interference; tether, beam-interactions etc.
AURORAL PLASMAS	... + high-level surface charging
MAGNETIC FIELD	v × B fields; torquing; tethers; plasma experiments
NEUTRAL ATMOSPHERE	drag; erosion (atomic O); glow interference
DEBRIS/METEOROIDS	structural damage; interference
CONTAMINATION (plumes, outgassing, venting ...)	deposition and interference
THERMAL (Sun, Earth, Space)	temperature control required

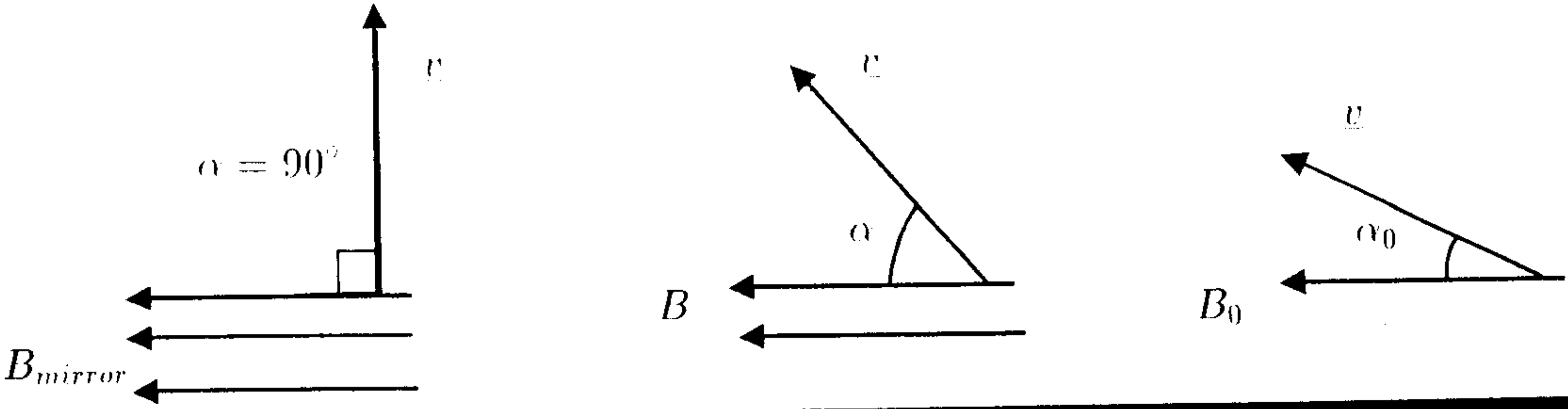


Motion of a charged particle in a dipole field.



magnetic moment $\mu = \dfrac{mv_{\perp}^2}{2B} = $ constant

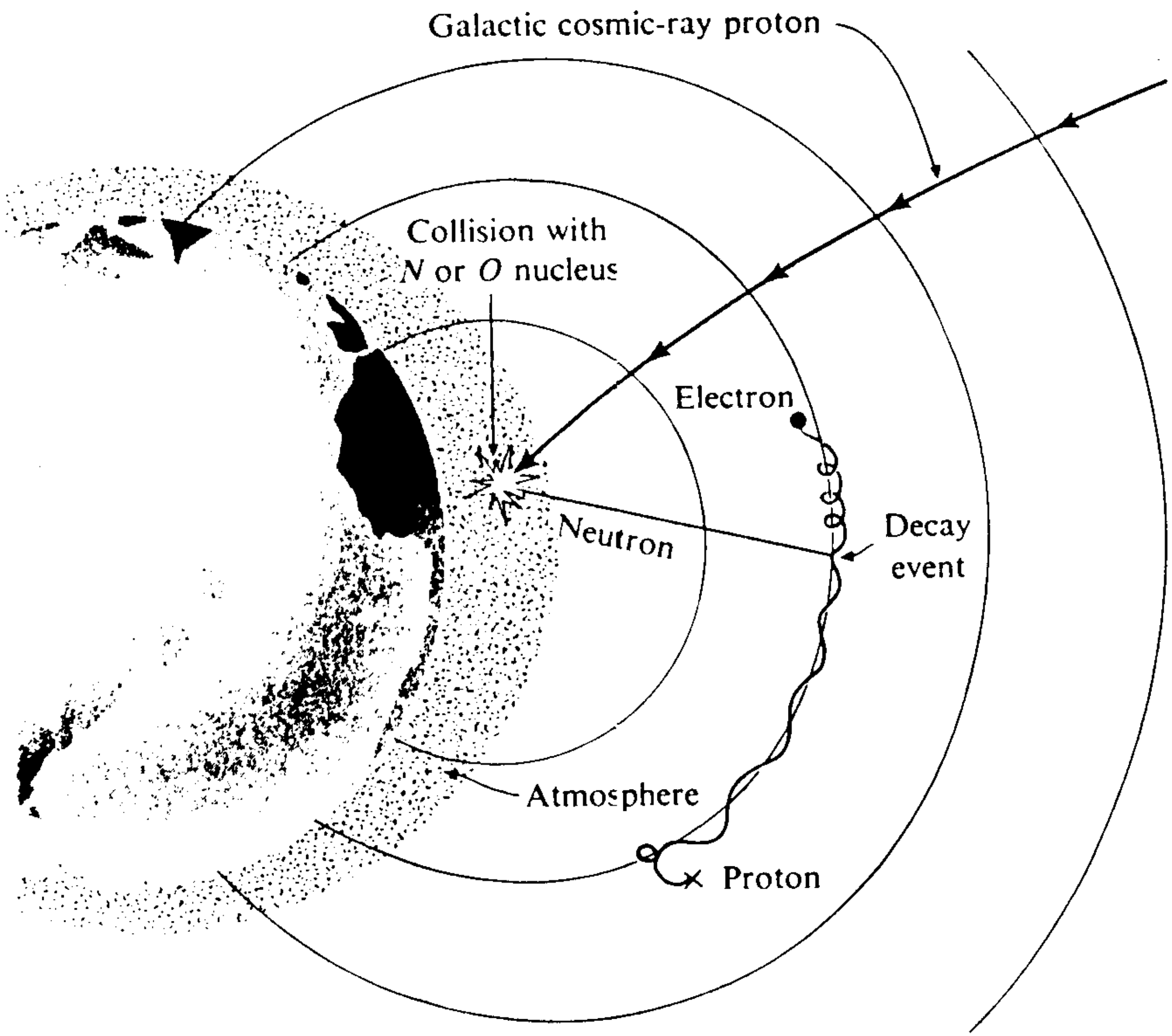
$$mv_{\perp}^2 = mv^2 \sin^2 \alpha \rightarrow \frac{\sin^2 \alpha}{B} = \text{const.} \rightarrow \frac{\sin^2 \alpha_0}{B_0} = \frac{1}{B_{mirror}}$$



TYPICAL CHARACTERISTICS OF ENERGETIC PARTICLE MOTIONS AT LOW ALTITUDE

Particle	Gyration radius	Gyration period	Bounce period	Azimuthal drift period	β ($=v/c$)
10MeV proton	50 km	0.01 sec	0.5 sec	4 min	0.2
1MeV electron	0.6 km	10^{-5} sec	0.1 sec	1 hour	0.9

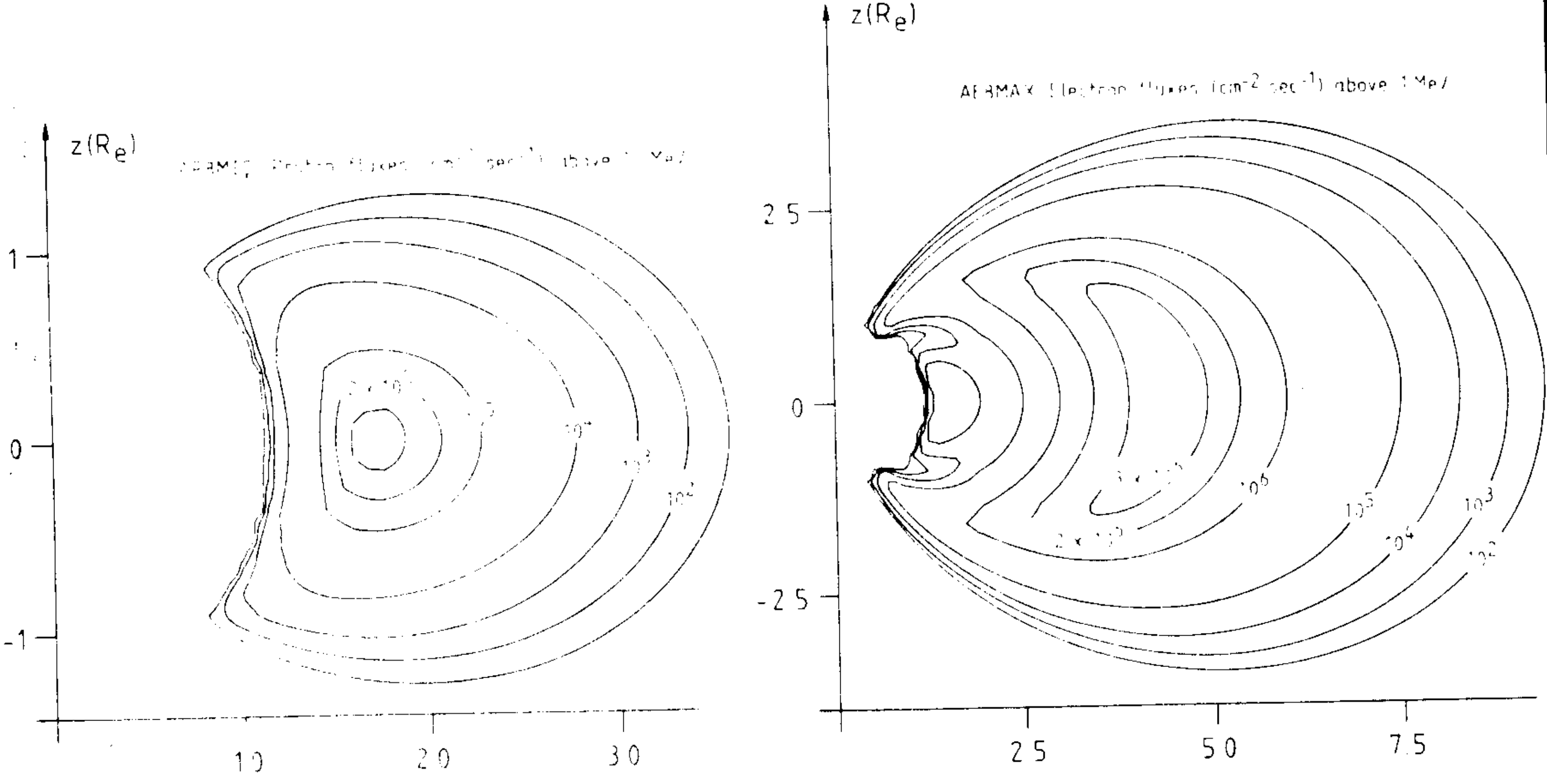
ESA/ESTEC/WM
space environment analyses



RADIATION

For future projects:

- Pressure to use:
  - advanced VLSI components,
  - lightweight solar cells,
  - new materials, etc.
- Flight of more sensitive detectors on telescopes
- Extended manned activities - long stay, EVA and polar(?)
  - what is effect of prolonged low-level exposure?
  - what is effect of HZE particles - how to quantify?
  - what is relevance of on-Earth experience? synergistic effects?
- Mission planning trade-offs may lead to problem orbits
- Internal charging of dielectric materials
- Planetary Missions


z(Re)
1
0
-1
10
20
30
10^4
10^3
10^2
z(Re)
(cm^-2 sec^-1) above
2.5
0
-2.5
25
50
75
10^6
10^5
10^4
10^3
10^2

THE "RADIATION BELTS":

- Electrons up to 10 MeV - mainly at high altitude.
- Protons up to 500 MeV - most energetic at low altitude.

Geomagnetic field is offset and tilted:

- trapped radiation belts brought to lowest altitude over South Atlantic
- = *South Atlantic Anomaly* (SAA)
- most radiation in low orbits ($h < 800$ km, $i < 40^{\circ}$) is from SAA
- important for ISS, Columbus, Hermes, EVA, etc.

Electron fuxes reach low altitude at high latitude:

- = *Polar Horns*
- important for polar orbiters.

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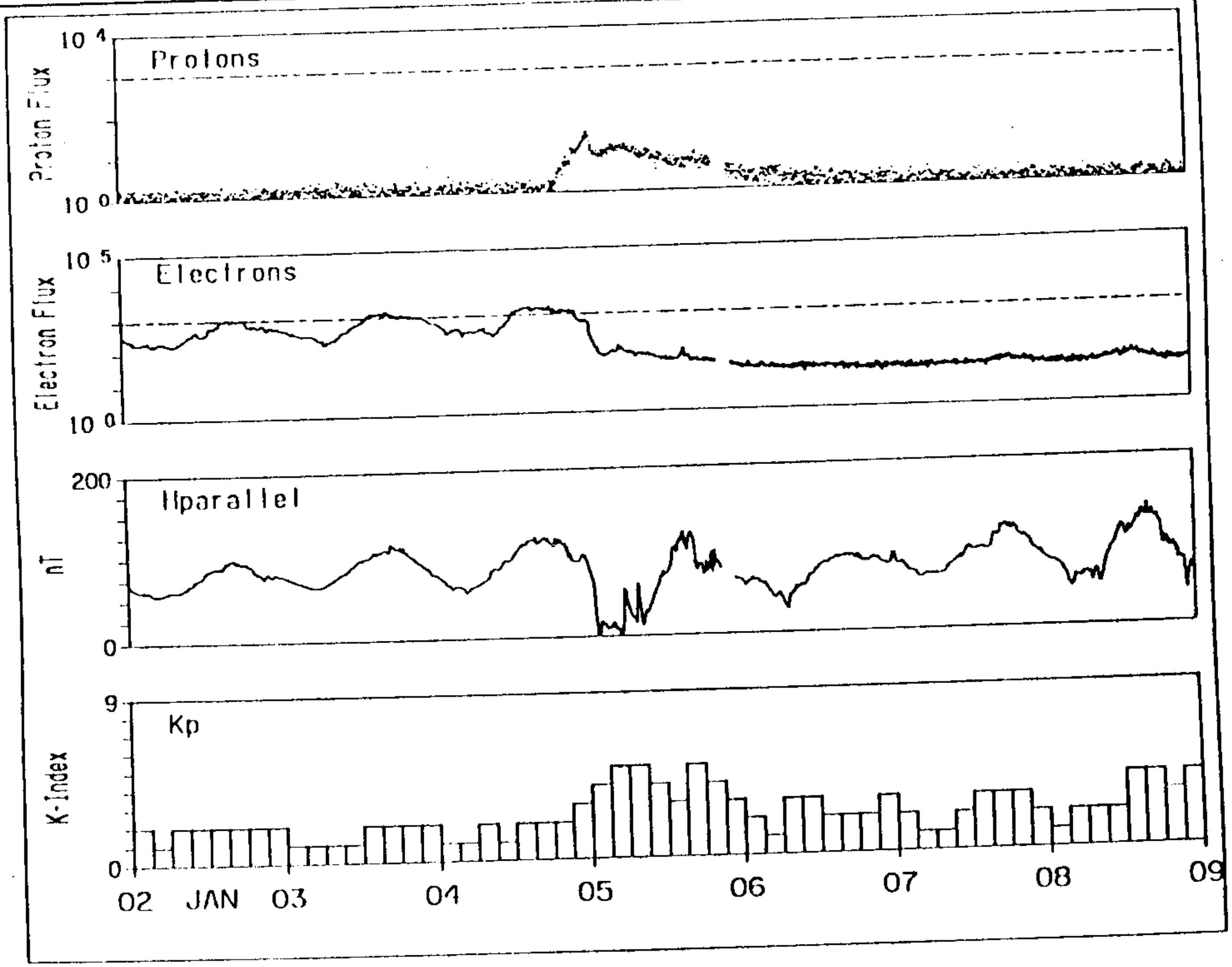
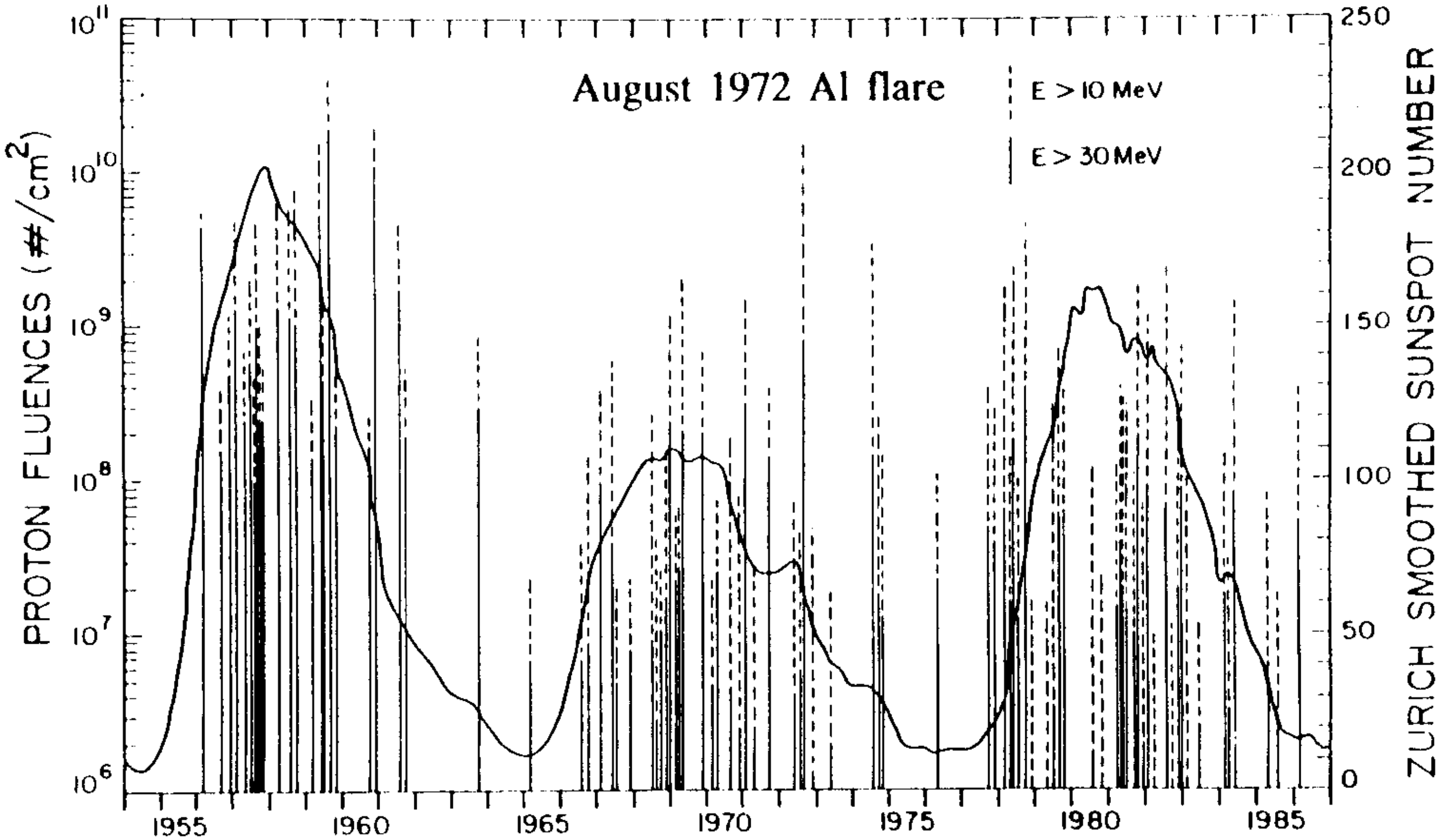
space environment analyses



Weekly Geosynchronous Satellite Environment Summary
Week Beginning 02 January 1989



from Goswami, McGuire, Reedy, Lal & Jha (1988)

SOLAR FLARE PARTICLE EVENTS

- last ~ days
- high fluxes of energetic particles (Aug '72 - > 10^6protons/cm^2/sec above 10MeV)
- integrated dose can be high (lethal)
- strongly influenced by the earth's field - *geomagnetic shielding*
- unpredictable in:
  - time of occurrence
  - magnitude (peak and integrated flux)
  - duration
  - composition

TYPICAL PREDICTED RADIATION LEVELS AT 500km ALTITUDE

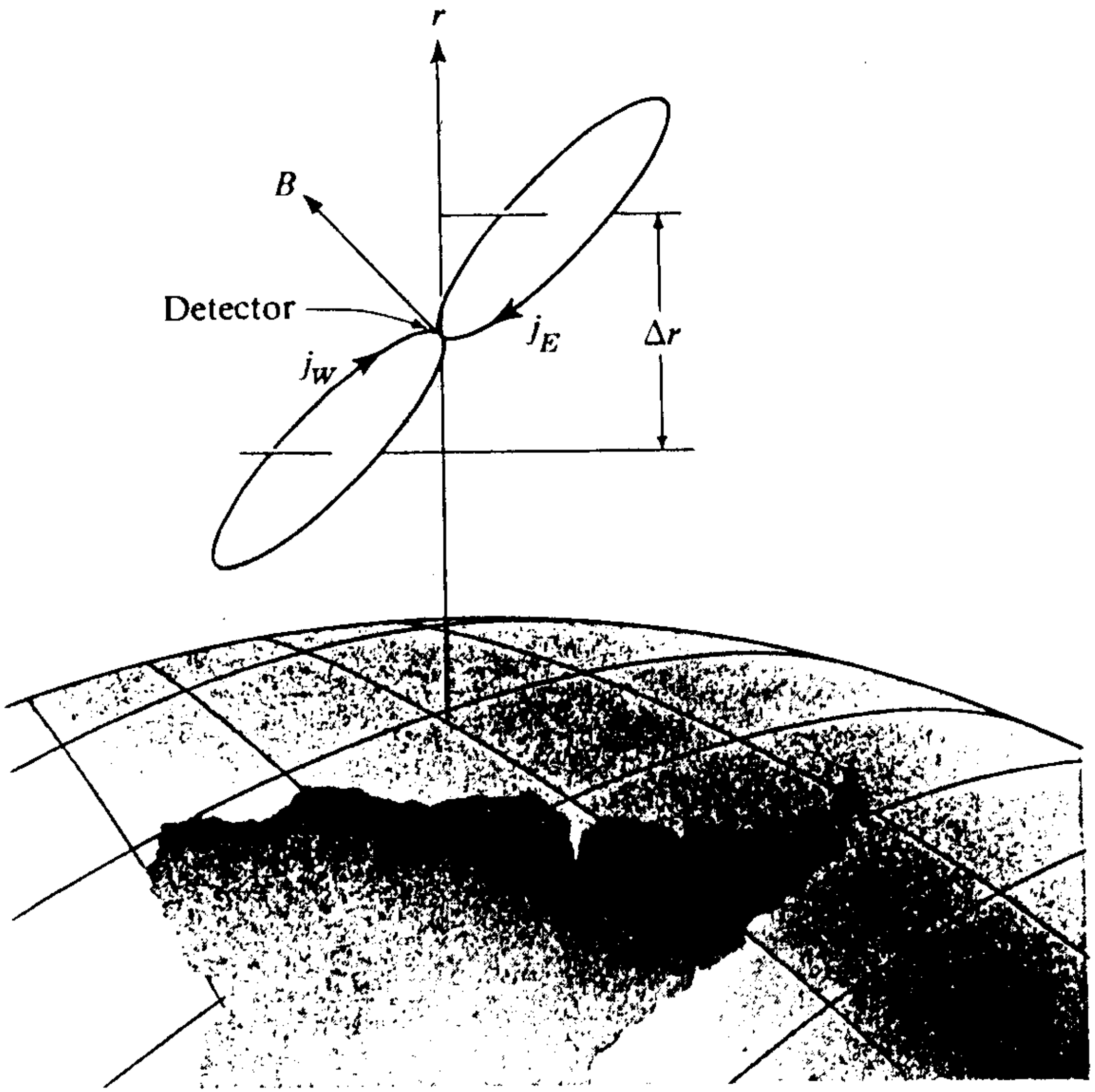
excluding cosmic-ray contributions

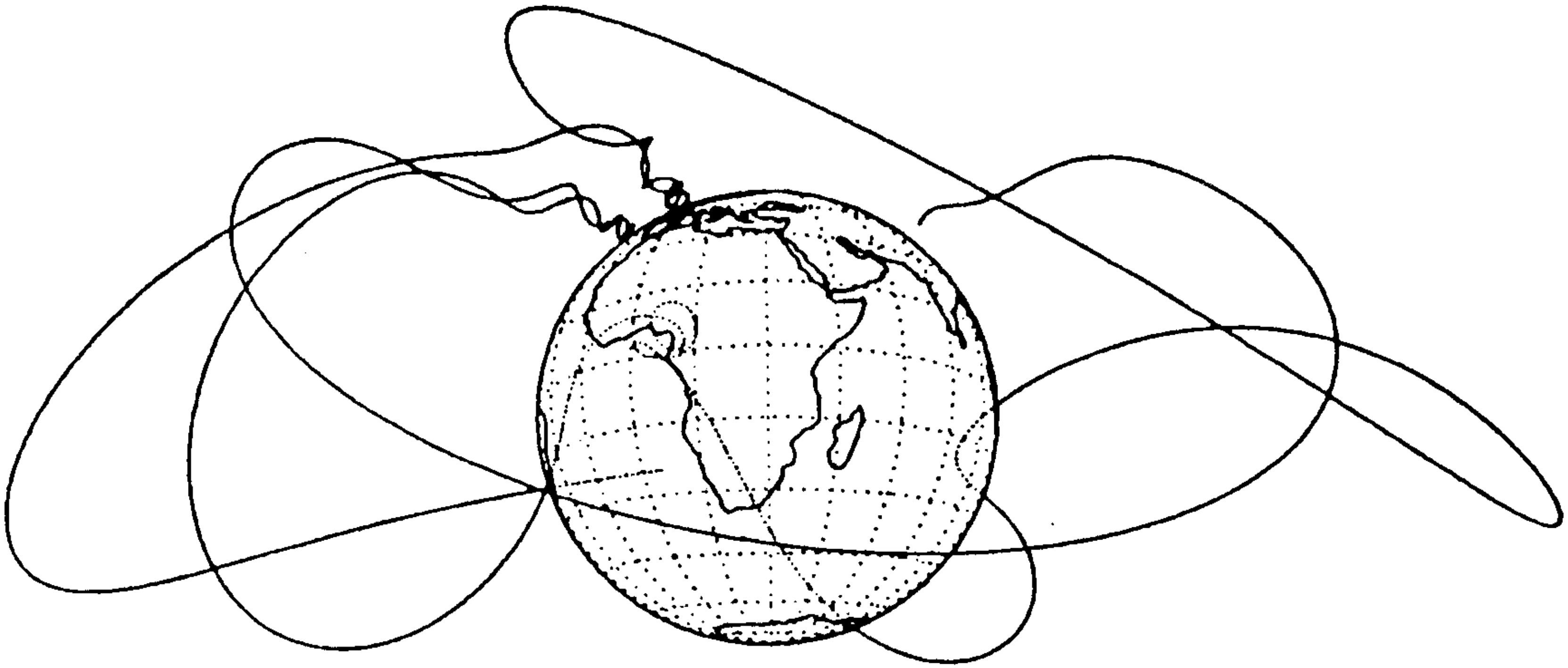
	100-day dose (rads) with Al shielding:		
case	1mm	4mm	10mm
low inclination:			
30° solar max	110	20	14
30° solar min	140	50	36
high inclination:			
100° solar max	1500	95	10
(+ solar flare*	1400	640	260)
100° solar min	810	71	21

*August 1972-class (anomalous) flare

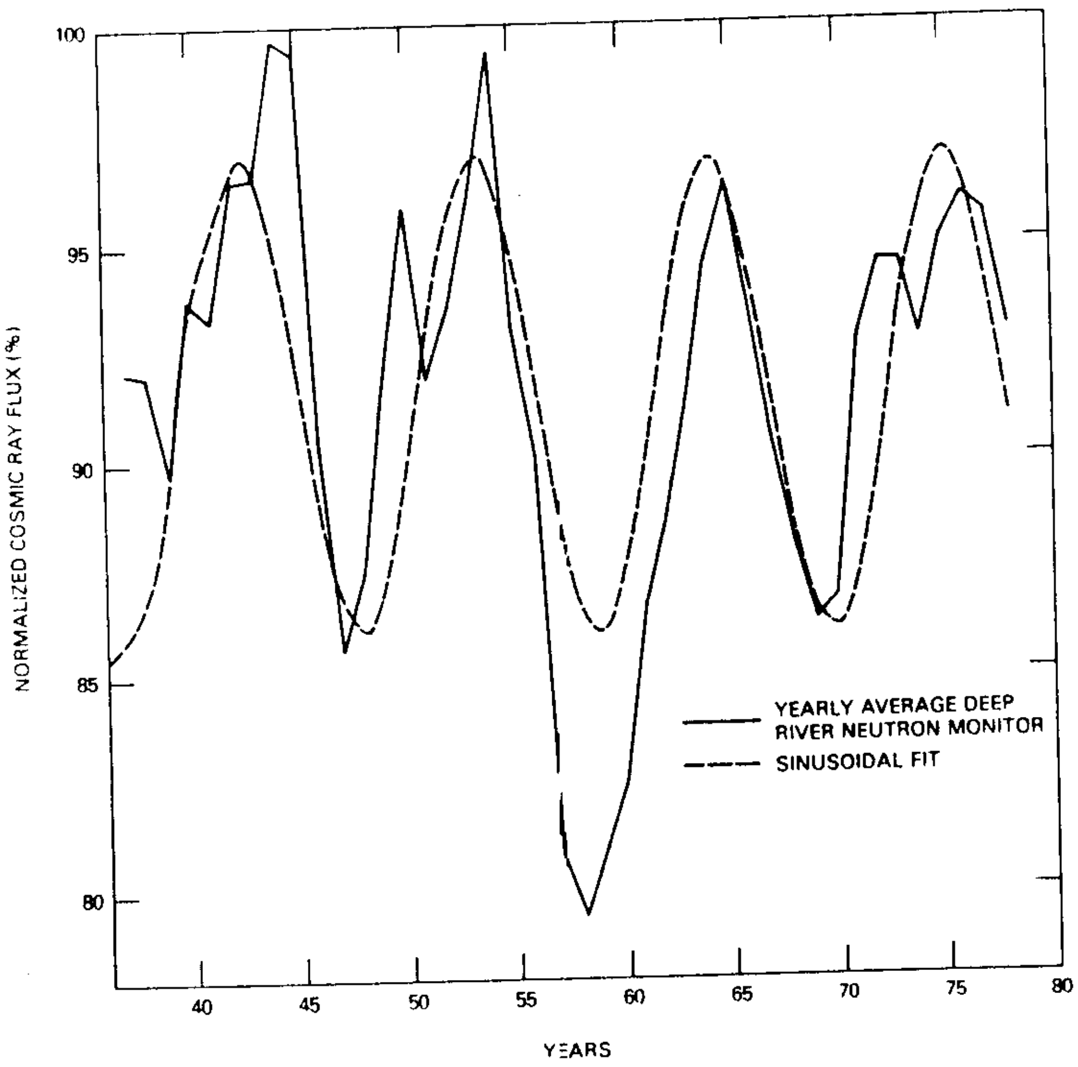
Proposed NASA limits (BFO rem dose) are:

- 25 per 30 days
- 50 per year
- 100-400 per career depending on age and sex.


r
B
Detector
j_E
j_W
Δr



This figure shows the computed trajectory of a cosmic ray in the earth's magnetic field. Such complex trajectories are not unusual for cosmic rays in the penumbral shadow near the Stormer cutoff (Lund, 1980).


100
95
90
85
80
NORMALIZED COSMIC RAY FLUX (%)
40
45
50
55
60
65
70
75
80
YEARS
YEARLY AVERAGE DEEP RIVER NEUTRON MONITOR
SINUSOIDAL FIT

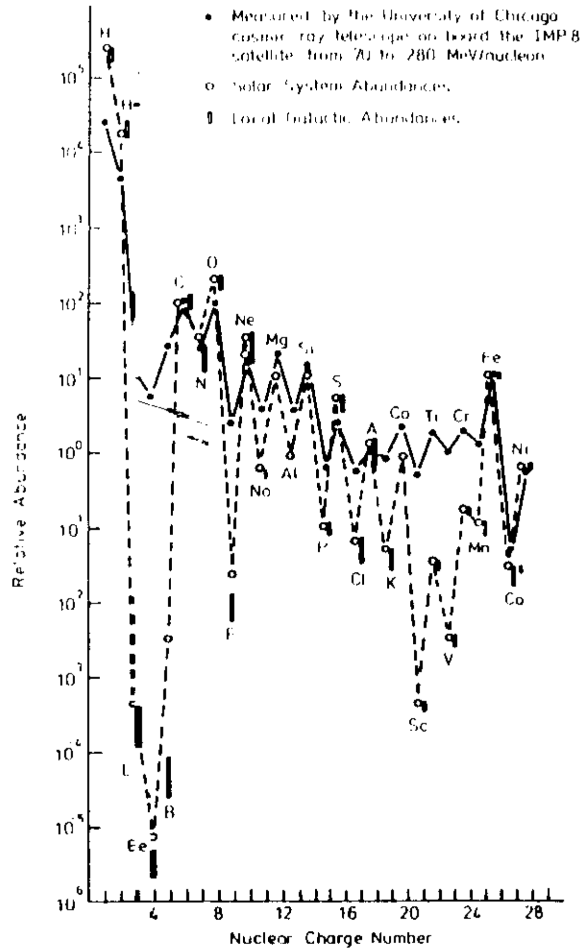


Fig 1. The element abundance of galactic cosmic rays compared with the solar system abundances (From Adams J.H. Jnr. et al, 1981)

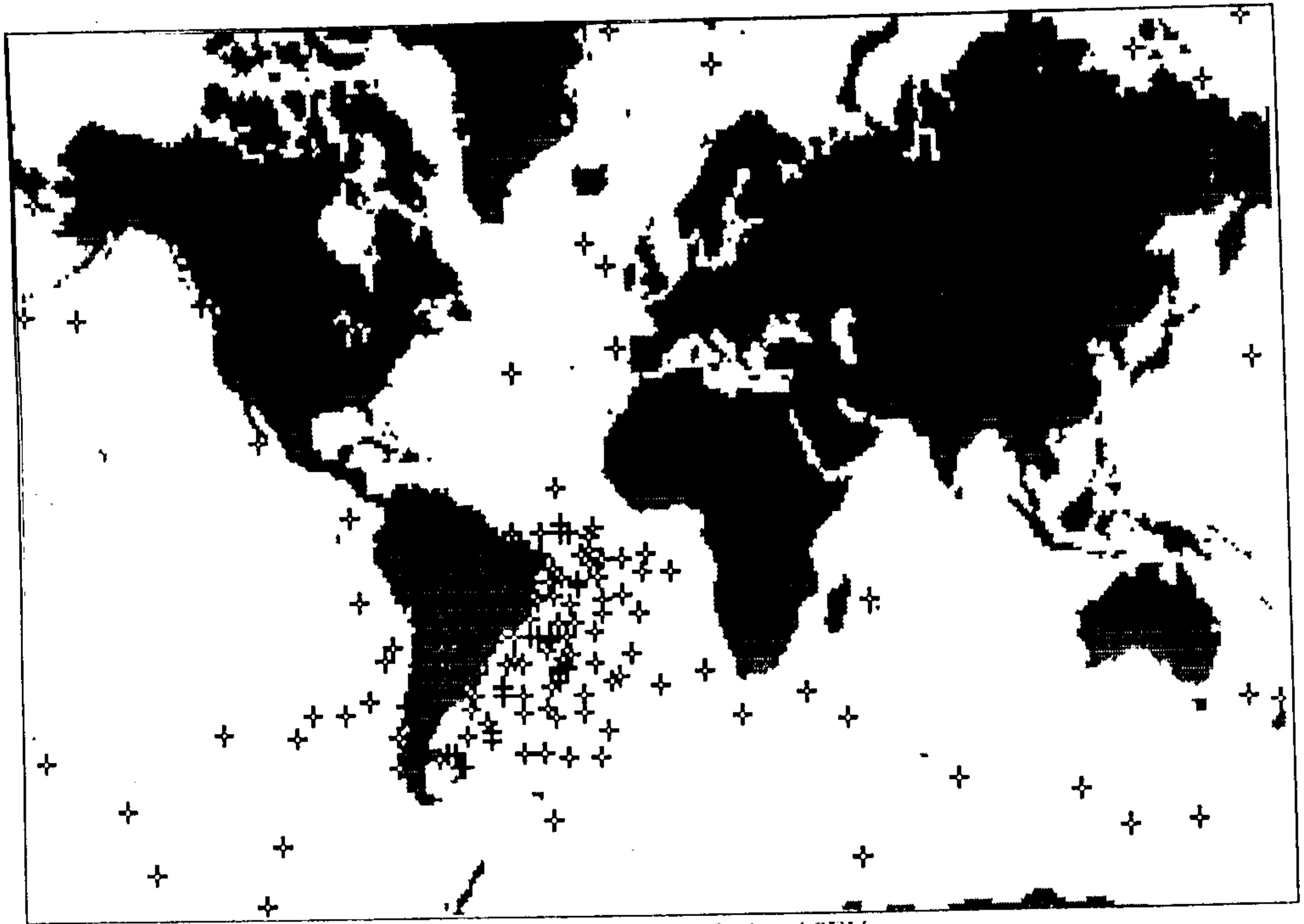


Figure 3-6 : 1802 OBC Isolated SEUs

GEOMAGNETIC FIELD

- Approximately dipolar at low altitude:

equation of field line $R = R_0 \cos^2 \lambda$

field strength $B = \frac{M}{R^3}[1 + 3\sin^2 \lambda]^{1/2}$

λ is the geomagnetic latitude; radius $R = R_0$ at geomag. equator;

M is geodipole moment
7.9×10^{25} gauss.cm^3 = 0.304 gauss.R_E^3 - decreasing by 0.1% per year.

- Non-dipolar contributions are important:
  - best described by numerical models of the field
  - also account for offset and tilt

- Spherical harmonic expansion of scalar potential V:

$$\mathbf{B} = -\nabla V$$

$$V = a \sum_{n=1}^{k} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} (g_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m(\theta)$$

Model gives coefficients h, g.
Limiting expansion to degree and order 1 ($n = 1, m = 0, 1$):

$$V = \frac{1}{r^2}(g_1^0 a^3 \cos\theta + g_1^1 a^3 \cos\phi \sin\theta + h_1^1 a^3 \sin\phi \sin\theta)$$

Potential of a dipole:

$$V = \frac{\mathbf{m}.\mathbf{r}}{r^3} = \frac{1}{r^2}(m_z \cos\theta + m_x \cos\phi \sin\theta + m_y \sin\phi \sin\theta)$$

since

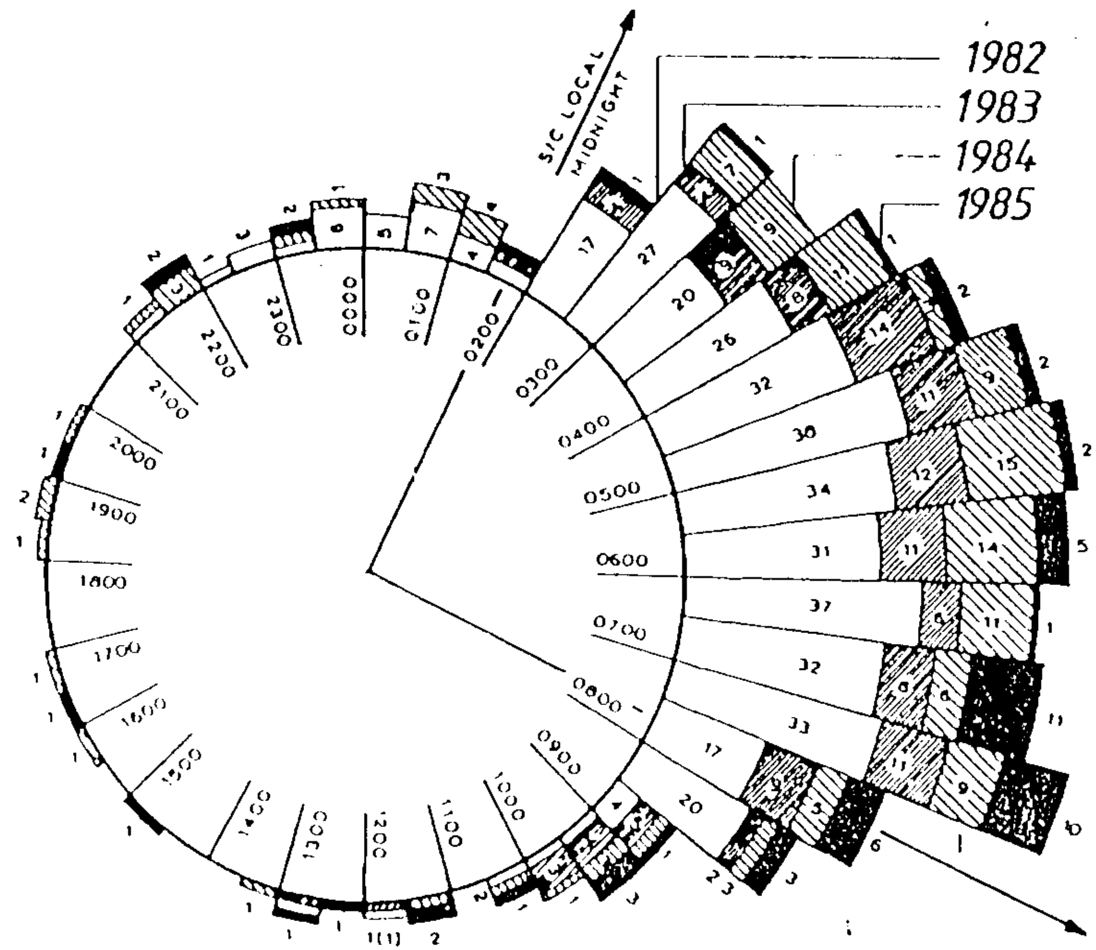
$$\mathbf{m} = m_x\,\hat{i} + m_y\,\hat{j} + m_z\,\hat{k} \text{ and } \mathbf{r} = r\sin\theta\cos\phi\,\hat{i} + r\sin\theta\sin\phi\,\hat{j} + r\cos\theta\,\hat{k}.$$

Moment is therefore

$$M = a^3\{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2\}^{\frac{1}{2}}.$$

ESA/ESTEC/WM

space environment analyses



PLASMA ENVIRONMENTS

Spacecraft Charging (mainly high altitude):

Current Balance to Surfaces in Equilibrium

$$I_e + I_p + I_{se} + I_b + I_{si} + I_\gamma + I_R + \ldots = 0$$

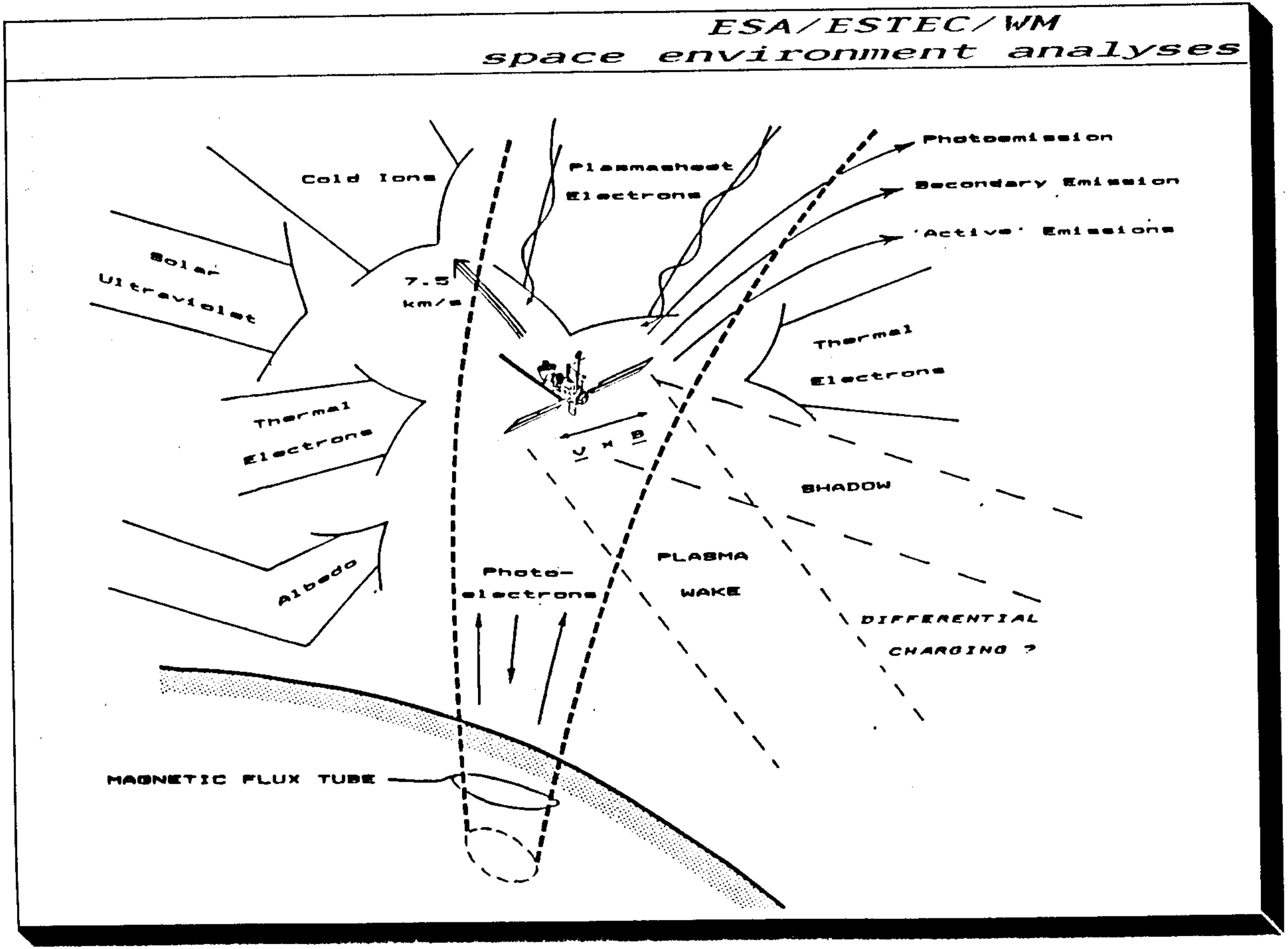
Currents are functions of:

- Plasma environment - complex and dynamic; in substorm, tenuous ($1/cm^3$), hot plasma (10-20 KeV) with large Debye length.
- Surface potentials and electric fields - on and around spacecraft
- Material properties - are many, and not always well-behaved.

In the simple case: $I_e + I_p = 0 \rightarrow$ surface floats at 2-3 $\times - T_e$ (in Volts)

But modifying factors are very important

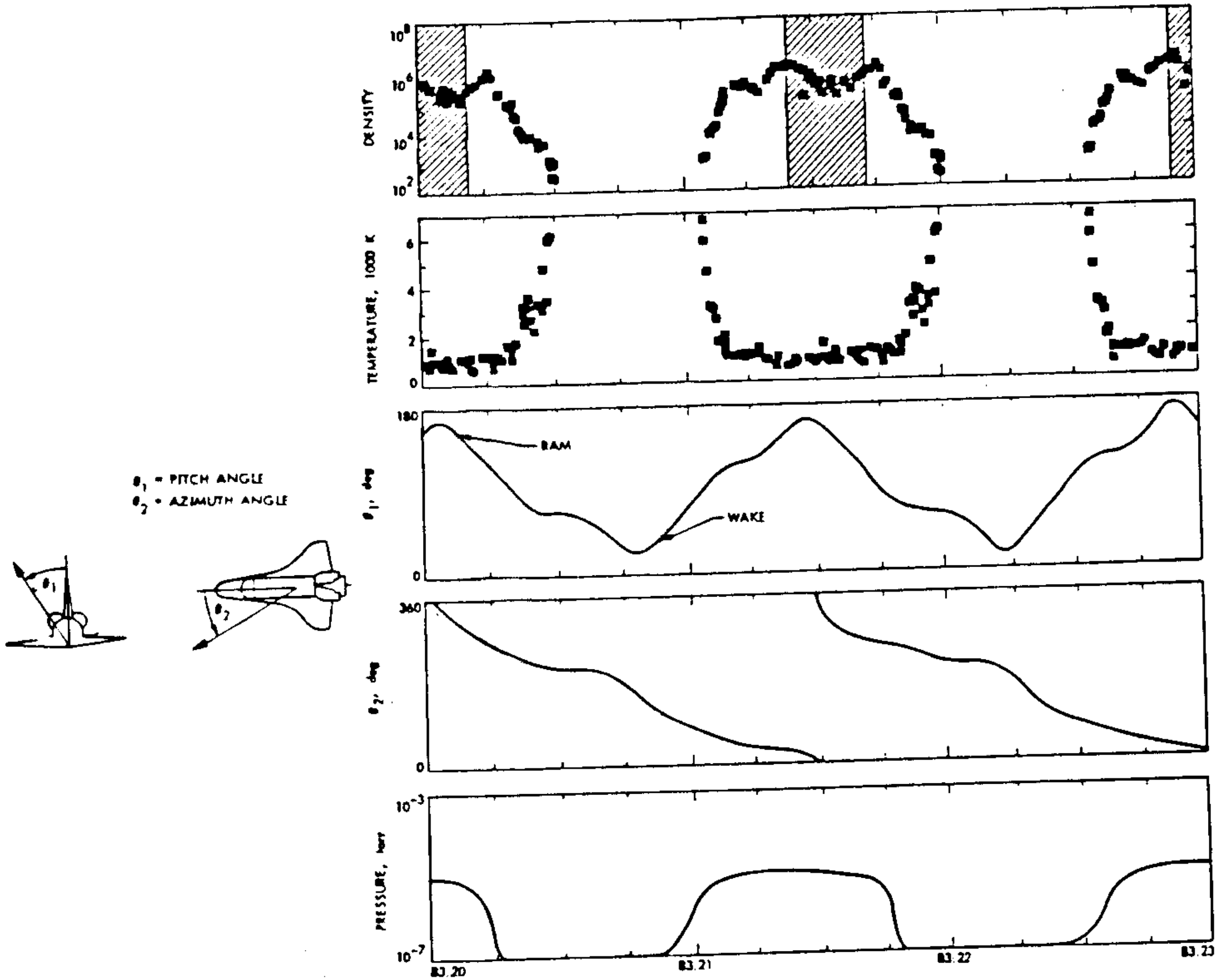
- material properties
  - dielectric resistivity - not generally a constant in space
    - illumination-, temperature-, radiation-, field-dependent
  - dielectric thickness
  - secondary electron emission: yields as functions of incident particle energy:
    * electron-induced secondary emission
    * electron backscatter
    * ion-induced secondary emission
  - dielectric constant
  - surface resistivity
  - photoemission current
- 3-d effects:
  - shadowing (photoemission)
  - electric field effects (barrier formation)
  - inter-material currents
- therefore a 3-d computer codes necessary for analyses:
  NASCAP code developed by S-Cubed for NASA


ESA/ESTEC/WM
space environment analyses
Cold Ions
Plasmasheet
Electrons
Photoemission
Secondary Emission
'Active' Emissions
Solar
Ultraviolet
7.5
km/s
Thermal
Electrons
Thermal
Electrons
V x B
SHADOW
Albedo
Photo-
electrons
PLASMA
WAKE
DIFFERENTIAL
CHARGING ?
MAGNETIC FLUX TUBE

PLASMA INTERACTIONS AT LOW ALTITUDES

$$I_e + I_p + I_{se} + I_b + I_{si} + I_\gamma + I_R + ... = 0$$

- Plasma is normally cold and dense. Debye length is short, so sheath effects are important.
- $$v_{\theta i} < v_{\text{Spacecraft}} < v_{\theta e}$$
- Deep wakes form behind spacecraft and a ram ion current is collected
- Surfaces or bodies in the wake can charge if exposed to energetic electron fluxes such as found during auroral "inverted V " events (e.g. RVD and astronauts).
- DMSP satellite observed to charge to several hundred volts in darkness, during auroral events, with depleted ambient densities.
- Elevated-voltage systems drive current through the local plasma: can be larger than expected because of sheath geometry effects = *Snapover*


θ1 = PITCH ANGLE
θ2 = AZIMUTH ANGLE
θ1
θ2
DENSITY
TEMPERATURE, 1000 K
θ1, deg
RAM
WAKE
θ2, deg
PRESSURE, torr
83.20
83.21
83.22
83.23

NASCAP/LEO and *POLAR* computer codes:

Same 3-dimensional treatment as original NASCAP code

Same material properties

Treat short-Debye-length regimes

LEO is for evaluating anomalous current collection - snapover

POLAR is for evaluating charging expected in the auroral oval (and $v \times B$ effects).

Other approaches:

2-D particle-in-cell (PIC) simulations: load a grid with many particles and number-crunch the problem, e.g.

- Simulation of phenomena near solar array interconnects
- Simulation of spacecraft + wake + auroral-electron interactions

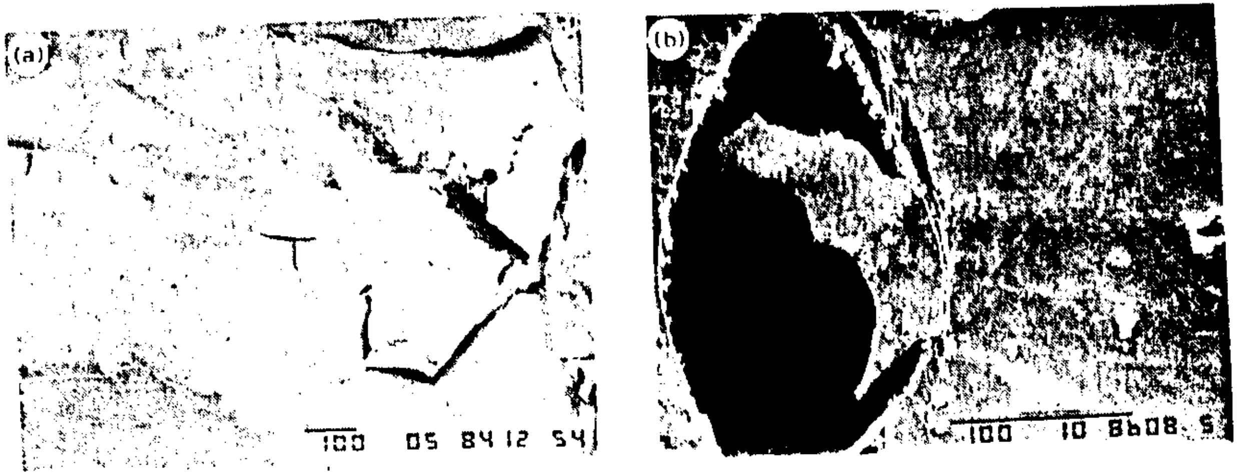


Fig 5 Silver oxide flakes after atomic oxygen attack in flight
a) Bulk silver (x100)
b) Silver interconnector (x350)
[Photos A. de Rooij]

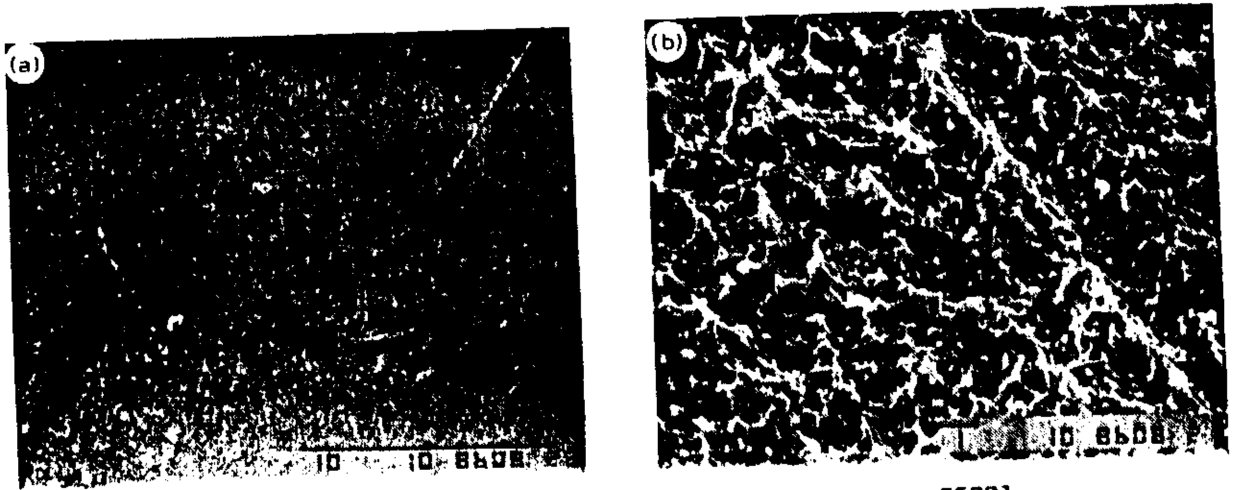
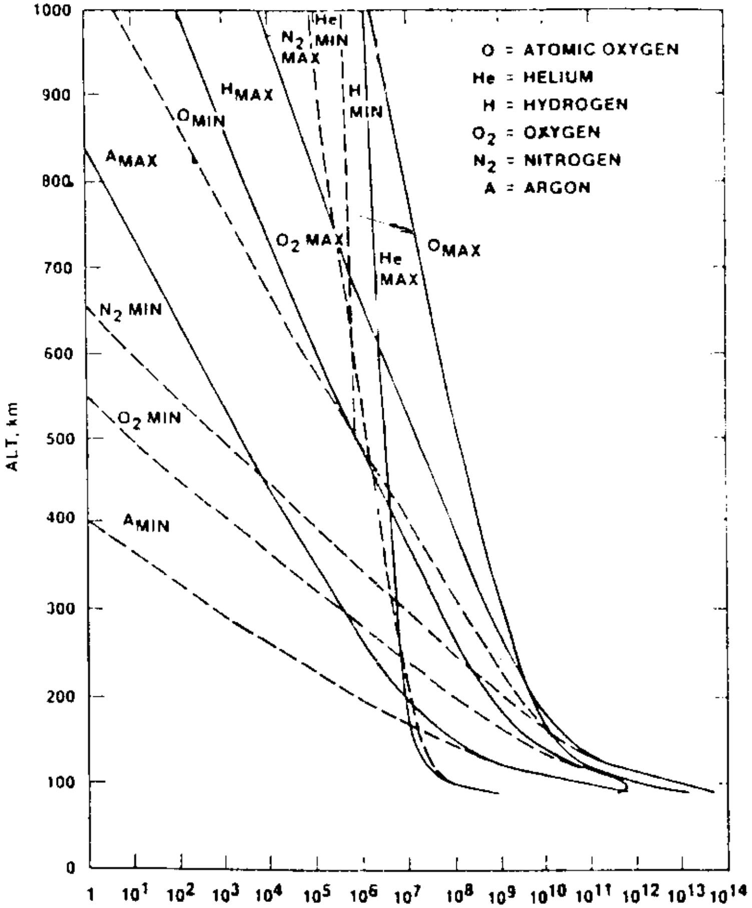


Fig 6 Kapton H surfaces [SEM photos x7500]
a) before flight
b) after flight on SIS 5
[Photos A. de Rooij]

Atmospheric Composition



MIN SOLAR CONDITIONS: 0400 hr USING $\bar{F}_{10.7} = 70$ & $\bar{A}p = 0$

MAX SOLAR CONDITIONS: 1400 hr USING $\bar{F}_{10.7} = 230$ & $\bar{A}p = 35$

ATOMIC OXYGEN ENVIRONMENTS

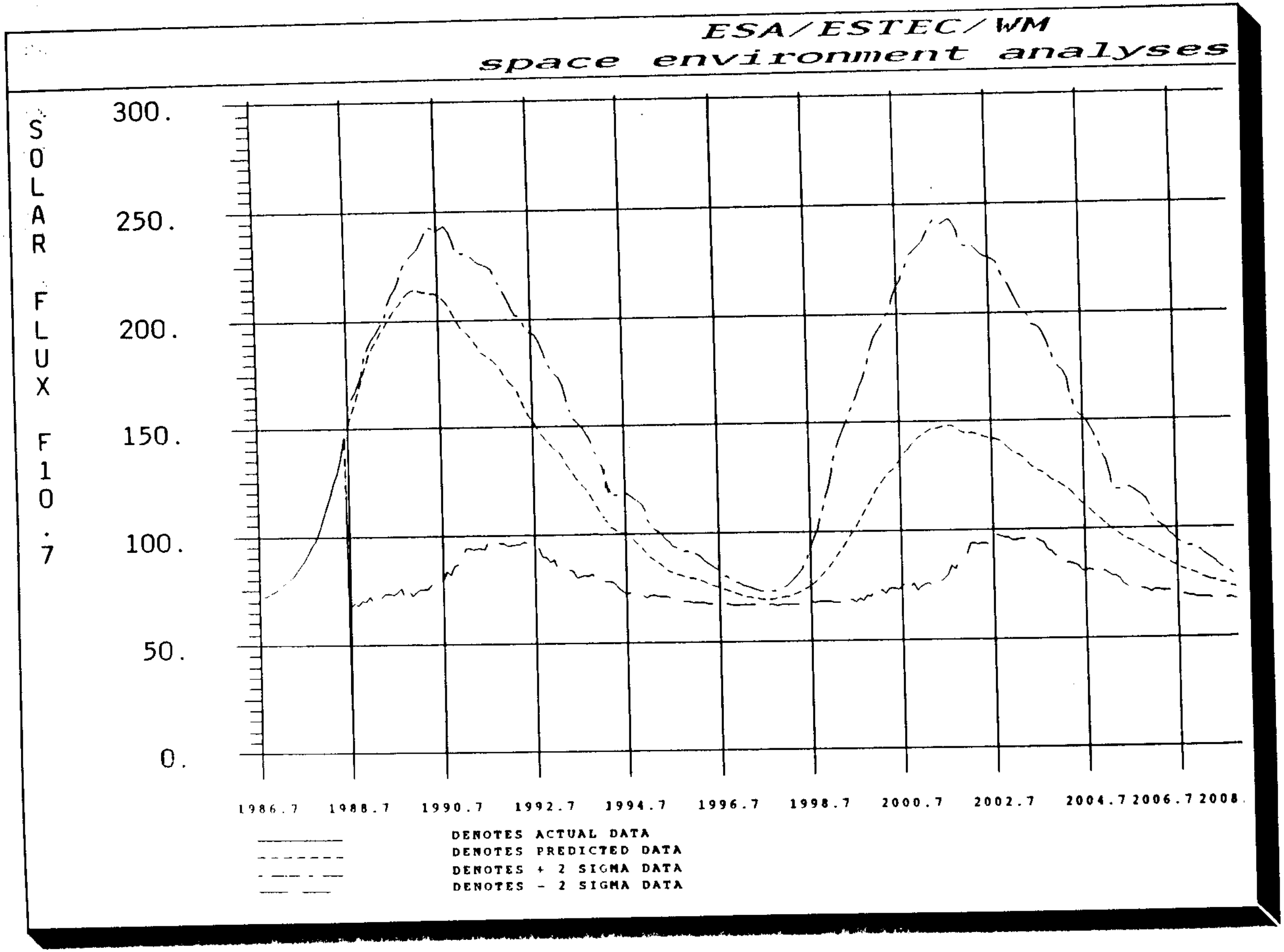
POTENTIALLY SERIOUS PROBLEMS ARE CAUSED BY SPACECRAFT MOTION THROUGH RESIDUAL ATMOSPHERIC ATOMIC OXYGEN

- FLUX OF ATOMIC OXYGEN DEPENDS ON:
  - atomic oxygen density
  - relative spacecraft velocity
  - orientation of spacecraft surfaces
- MATERIALS OXIDIZED AND ERODED OR DEGRADED
- RECESSION RATE PROPORTIONAL TO FLUENCE Φ (= time-integrated flux) - material dependent
- KAPTON RECEDES AT 3 μm PER 1×10^{20} Atoms/cm^2 (a surface can easily accumulate 1×10^{21} Atoms/cm^2)
- (NASA PRELIMINARY PREDICTIONS FOR SPACE STATION - RAM SURFACES COULD RECEDE AT 360 μm /SOLAR CYCLE)

BASIC ATOMIC OXYGEN FLUENCE PREDICTION IS BASED ON:

- ORBIT (position, velocity $\vec{v}$) use SAPRE orbit generator - mission evolution treated
- SURFACE ORIENTATION ($\vec{s}$) with respect to velocity vector
- ATOMIC OXYGEN DENSITY N_O:
  MSIS-86 (≡ CIRA-87) model atmosphere of Hedin et al. is used to derive density, a function of:
  - altitude h,
  - local time t_l,
  - day of year d,
  - solar/geomagnetic activity $F_{10.7}$, A_p,
  - latitude lat,
  - longitude $long$
- SOLAR ACTIVITY prediction (or observation) NASA-MSFC distributed predictions at 50% (mean) and 97.7% (+2.sigma) confidence levels

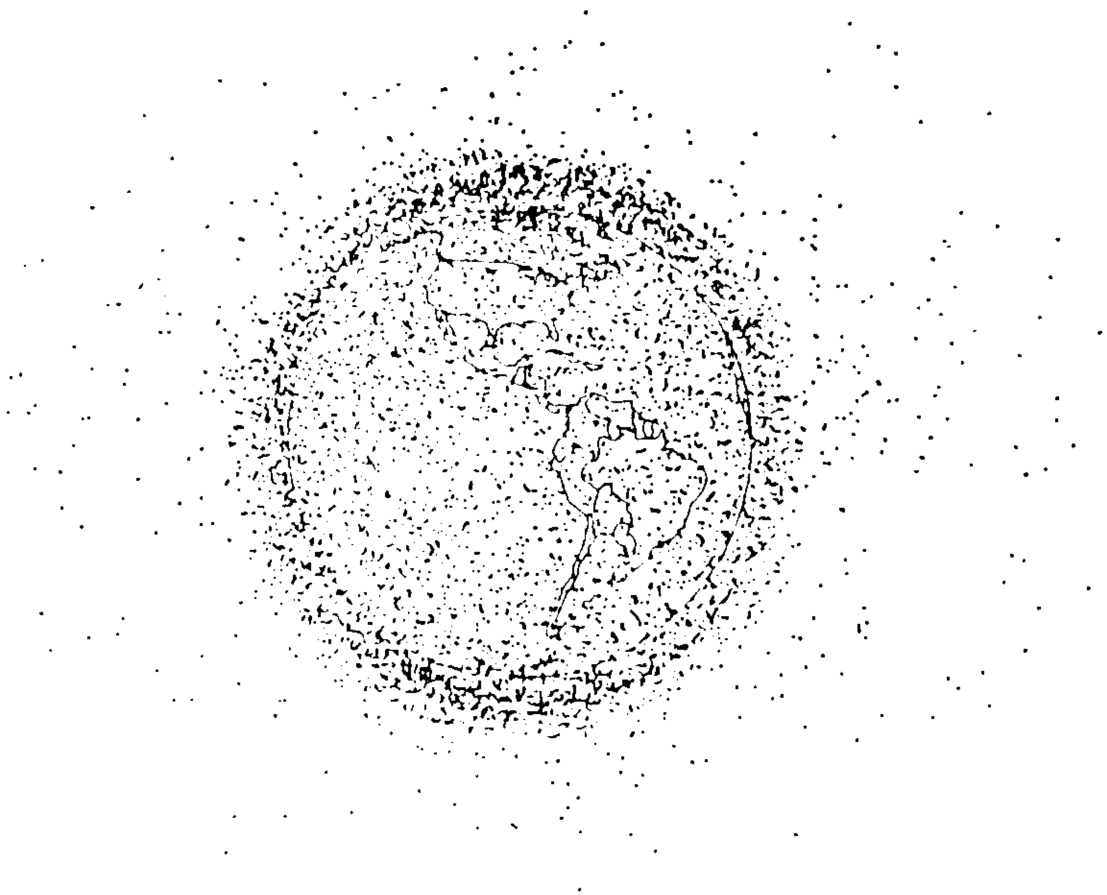
$$\Phi = \int_T N_O(h, t_l, d, F_{10.7}, A_p, lat, long)\vec{v}.\vec{s}dt$$

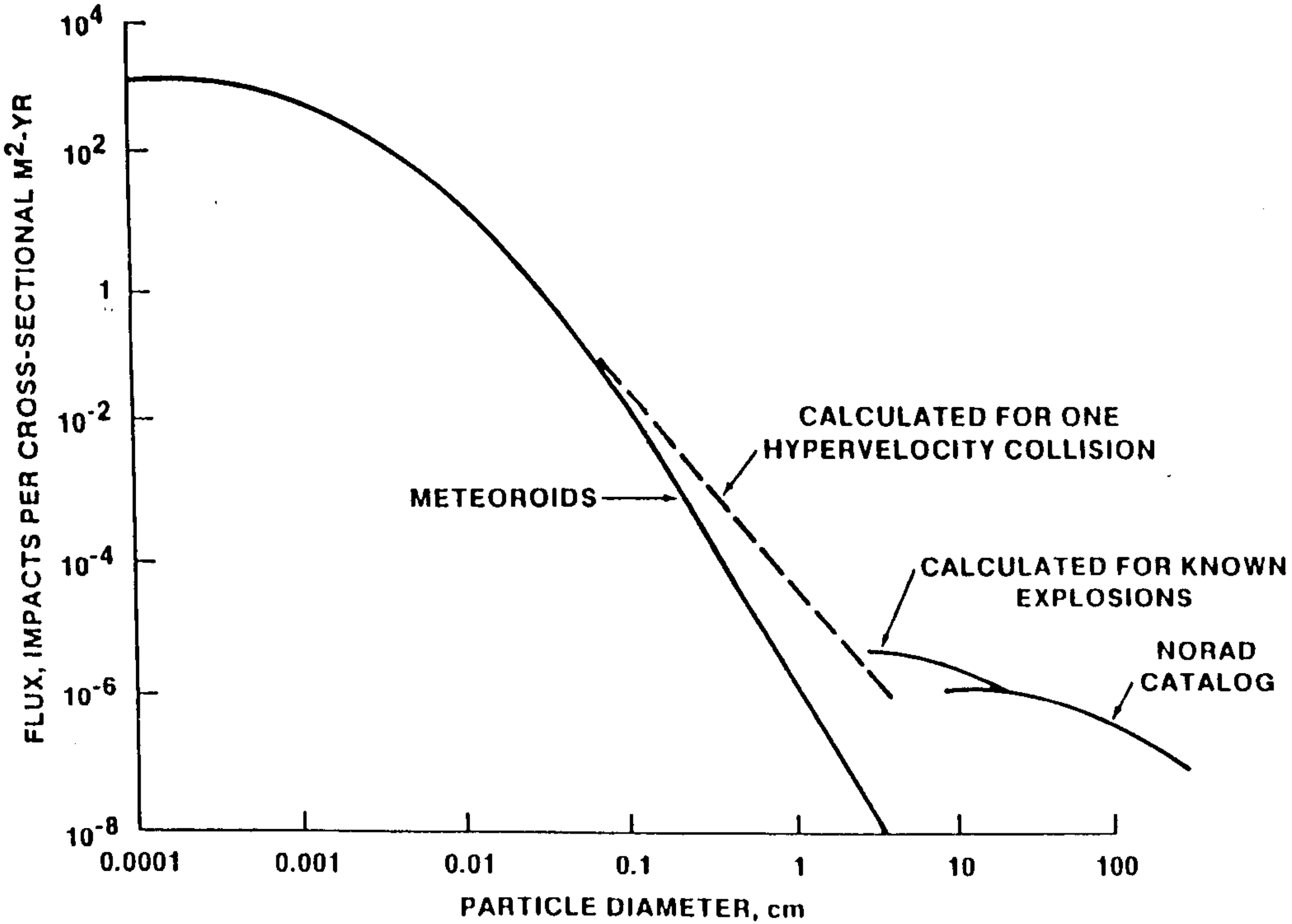

ESA/ESTEC/WM
space environment analyses
SOLAR FLUX F10.7
300.
250.
200.
150.
100.
50.
0.
1986.7
1988.7
1990.7
1992.7
1994.7
1996.7
1998.7
2000.7
2002.7
2004.7
2006.7
2008.
DENOTES ACTUAL DATA
DENOTES PREDICTED DATA
DENOTES + 2 SIGMA DATA
DENOTES - 2 SIGMA DATA

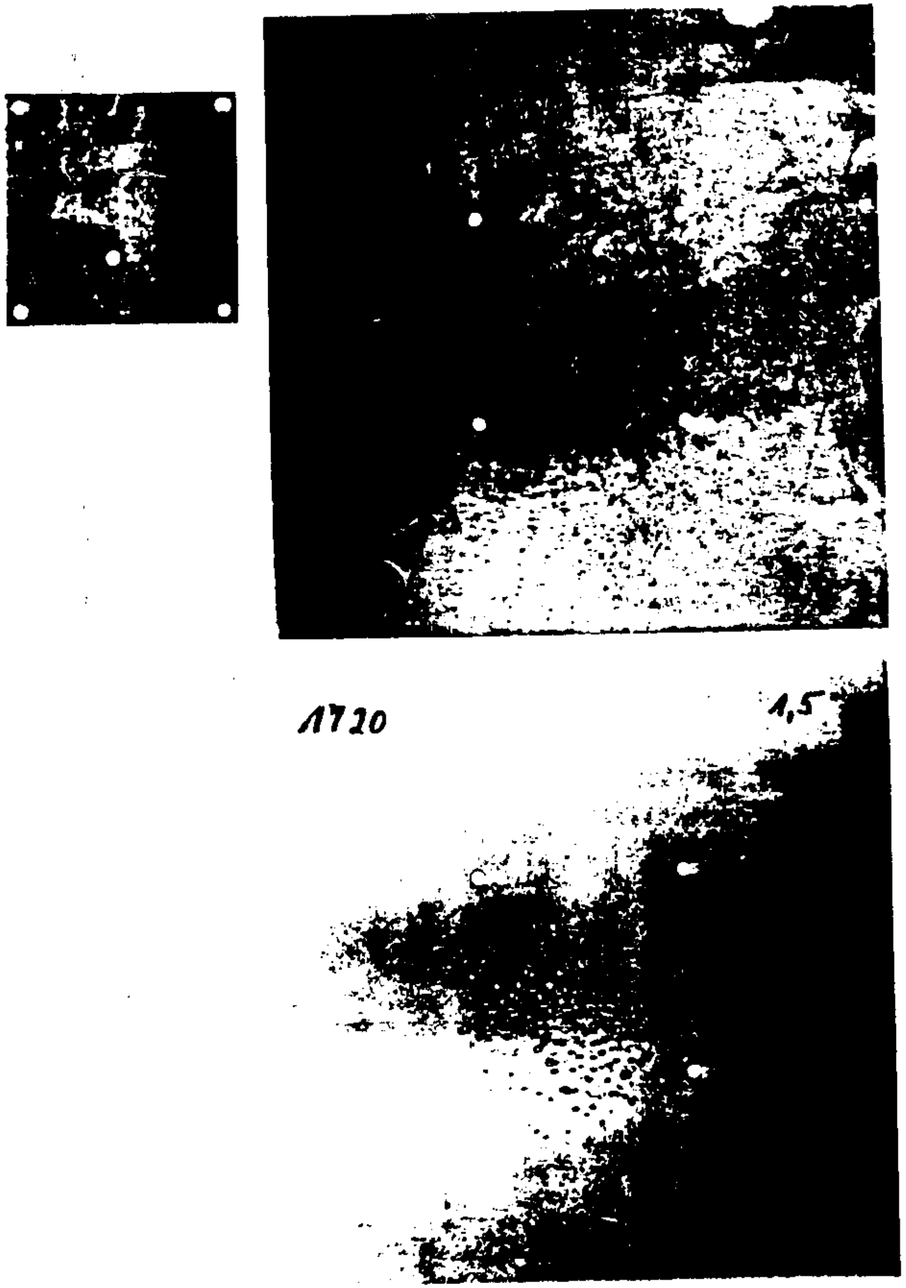
METEOROIDS/SPACE DEBRIS

- Potentially catastrophic effects for manned spacecraft.
- ISS (large area, long life) has double-wall design to protect it.
- Risk assessment based on environment + knowledge of what particle properties are necessary to penetrate a given shield design (design formulae).
- Environment uncertain and expected to evolve significantly (collisions)
- Based on a limited number of hypervelocity impact experiments and numerical simulations.
- Flight data required - LDEF return is very valuable
- Debris also interferes with payloads, particularly astronomy

ESA/ESTEC/WM
space environment analyses

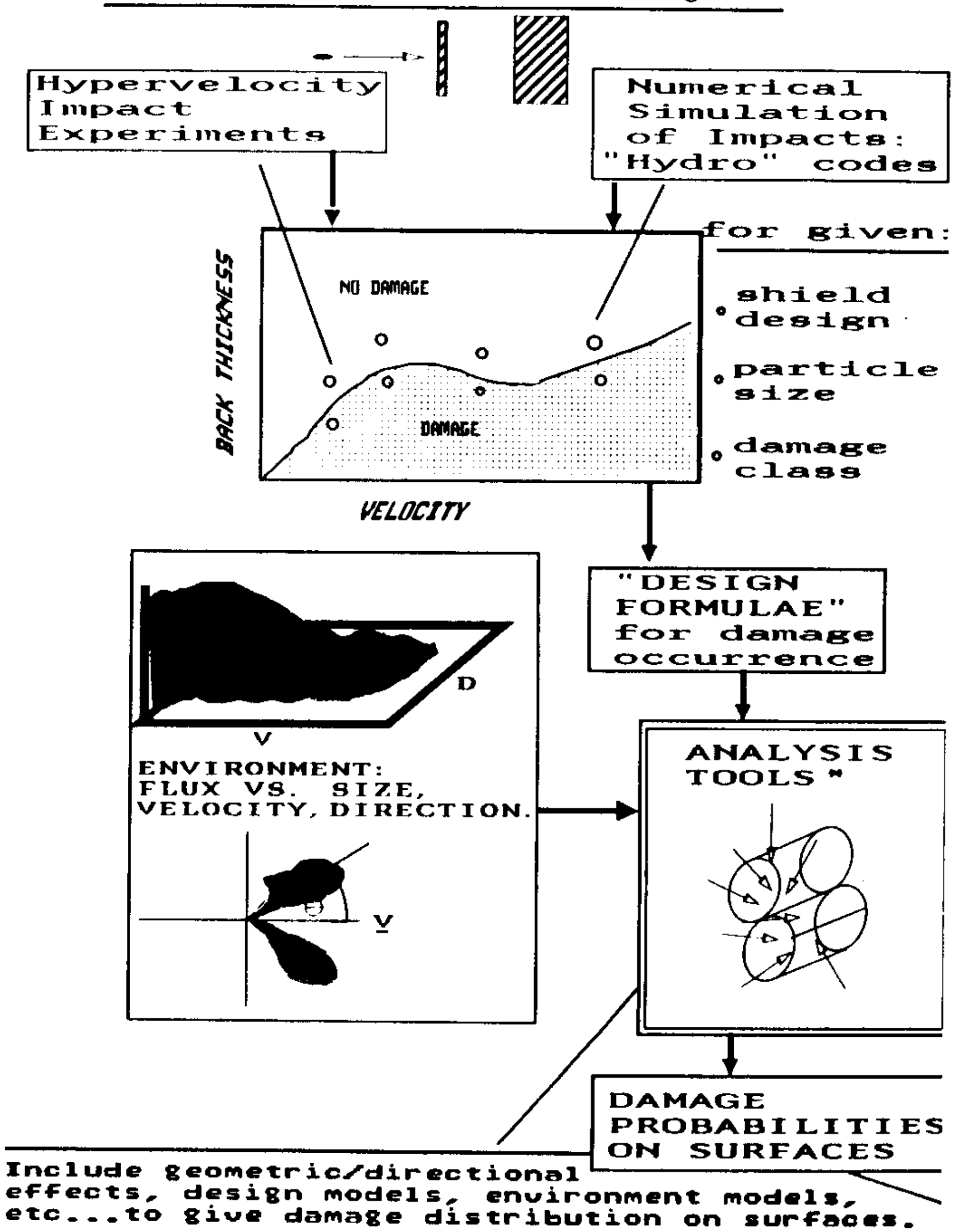



10^4
10^2
1
10^-2
10^-4
10^-6
10^-8
FLUX, IMPACTS PER CROSS-SECTIONAL M2-YR
CALCULATED FOR ONE HYPERVELOCITY COLLISION
METEOROIDS
CALCULATED FOR KNOWN EXPLOSIONS
NORAD CATALOG
0.0001
0.001
0.01
0.1
1
10
100
PARTICLE DIAMETER, cm



Exp. 1720 Proj. diam. 5 mm, velocity 5.6 km/s
bumper plate thickness 1.5 mm (front side), hole diam. 10.4 mm
backup plate thickness 1.5 mm (front and rear sides) 10 cm

Meteoroids/Debris Analysis

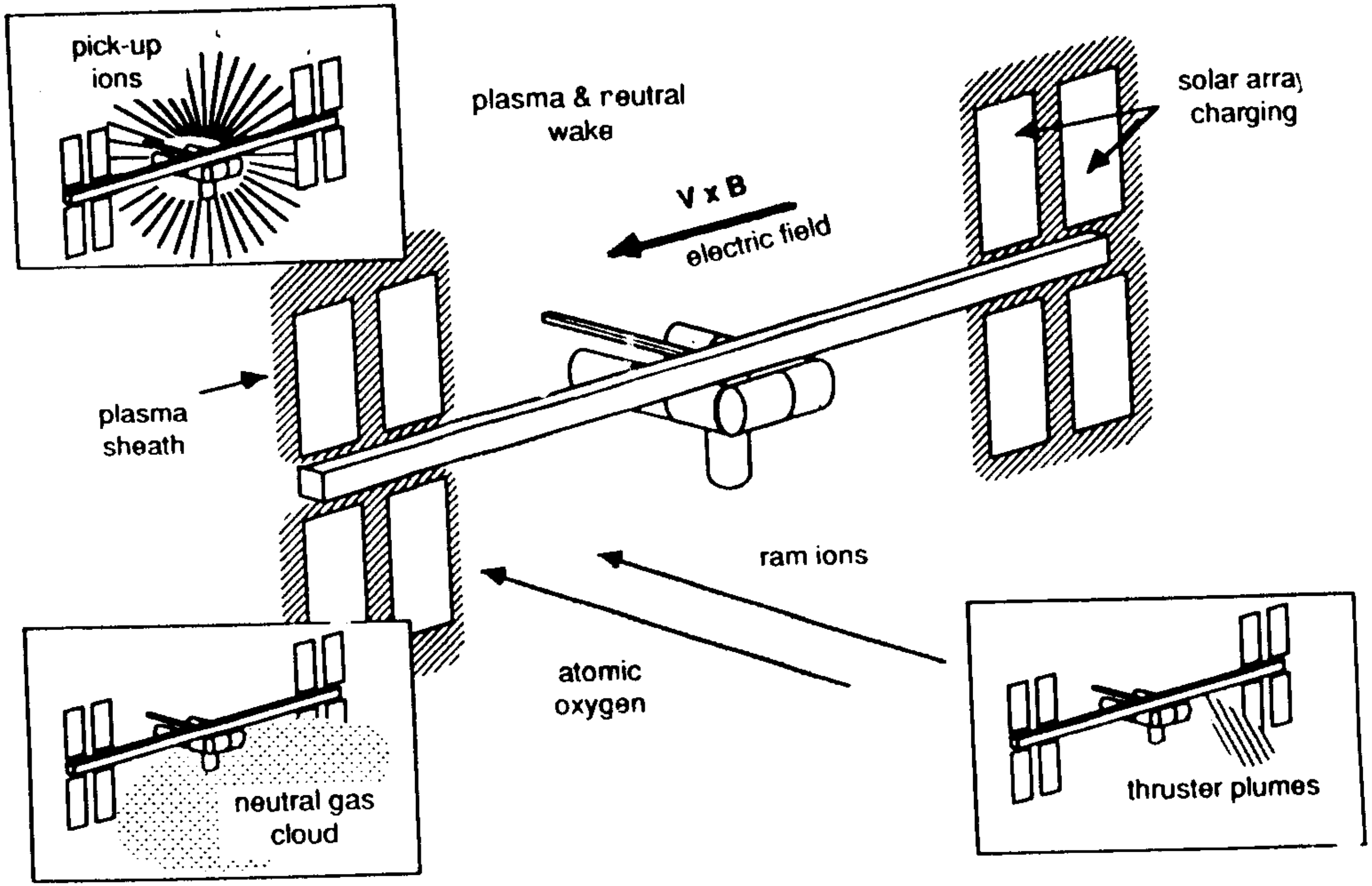


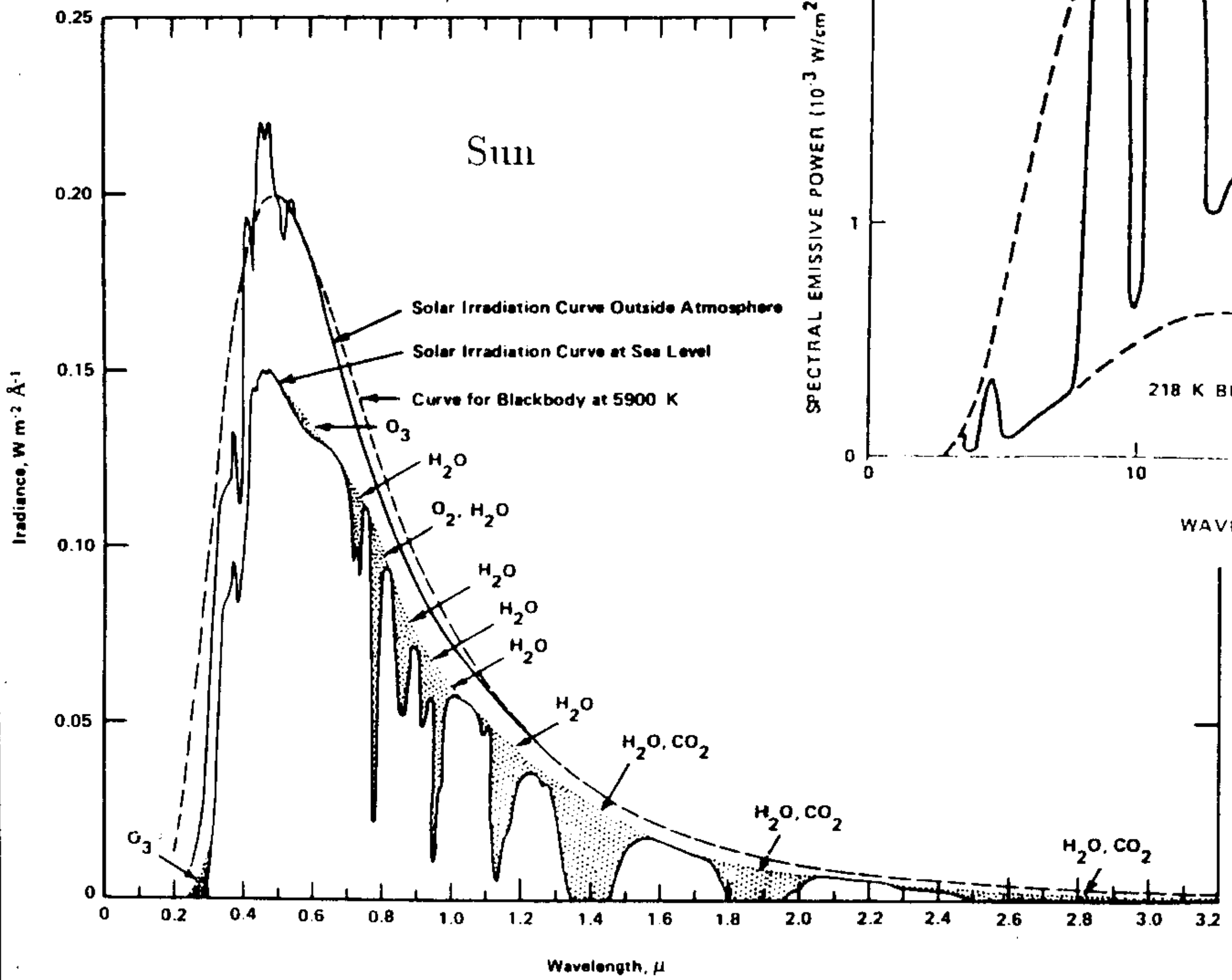
CONTAMINATION

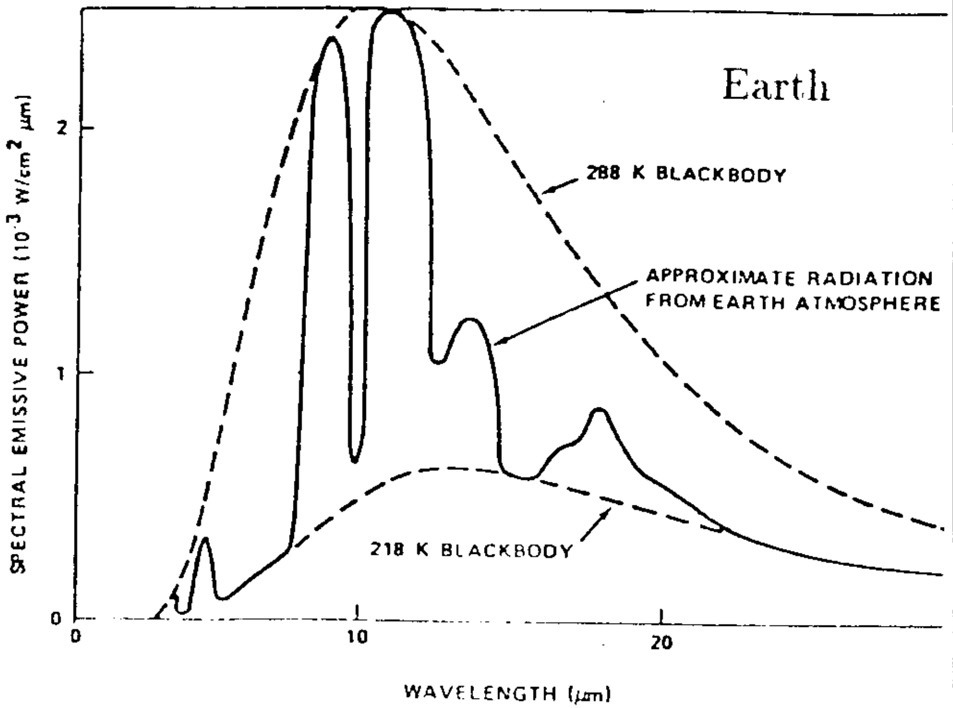
- Is an important consideration for space-station payloads - both contaminant deposition on experiments and contaminants in fields of view of telescopes.
- sources include surface outgassing, venting, thruster firing, particulates
- visits to station of servicing spacecraft (Shuttle, Hermes ...)
- linked to "ram glow" and debris problems
- complex interactions: station/plasma/contaminant/neutral atmosphere

ESA/ESTEC/WM

space environment analyses




Sun
Solar Irradiation Curve Outside Atmosphere
Solar Irradiation Curve at Sea Level
Curve for Blackbody at 5900 K
O_3
H_2O
O_2, H_2O
H_2O
H_2O
H_2O
H_2O
H_2O, CO_2
H_2O, CO_2
H_2O, CO_2
O_3
Irradiance, W m^{-2} Å^{-1}
0.25
0.20
0.15
0.10
0.05
0
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2
Wavelength, μ


Earth
288 K BLACKBODY
APPROXIMATE RADIATION
FROM EARTH ATMOSPHERE
218 K BLACKBODY
SPECTRAL EMISSIVE POWER (10^{-3} W/cm^2 μm)
2
1
0
0 10 20
WAVELENGTH (μm)

ESABASE Framework

ESABASE is a multi-disciplinary computer-aided engineering tool for system-level, geometry-related analyses.

Framework features:

- GEOMETRY DESCRIPTION LANGUAGE
- DATA STRUCTURE
- COMMON COMPUTATIONAL ROUTINES - attitude, orbit, etc.
- GEOMETRY VIZUALIZATION: pre- and post-processing
- UTILITIES

Analyses:

- RADIATION
- ELECTROSTATIC CHARGING (NASCAP)
- ATOMIC OXYGEN
- THERMAL
- OUTGASSING
- PLUME (thermal and torques)
- PERTURBATION
- OCCULTATION
- POINTING
- AOC
- MASS-PROPERTIES
- HARNESS

under study:

- CONTAMINATION
- μMETEOROID/DEBRIS