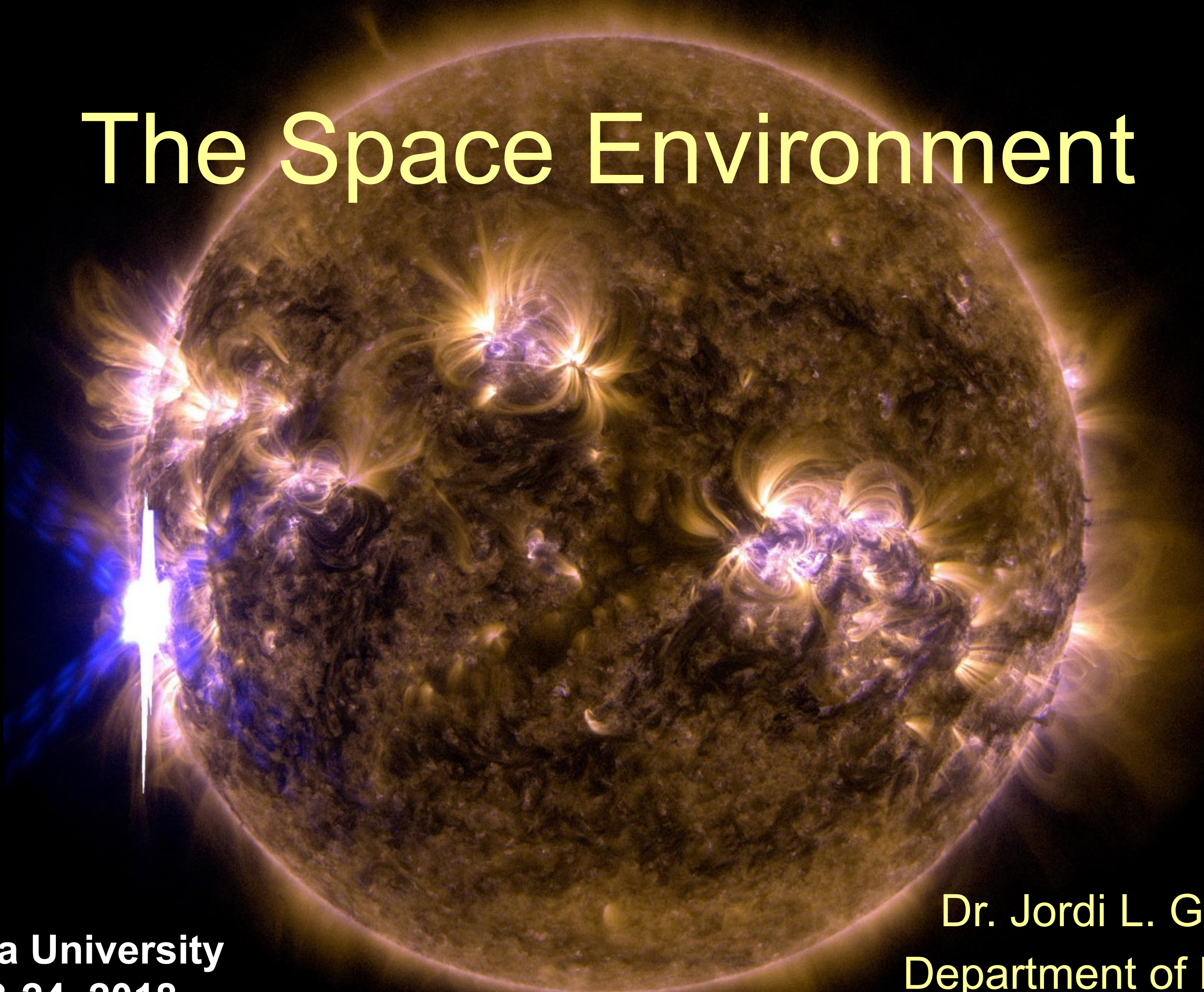
The Space Environment



Samara University
May 23-24, 2018

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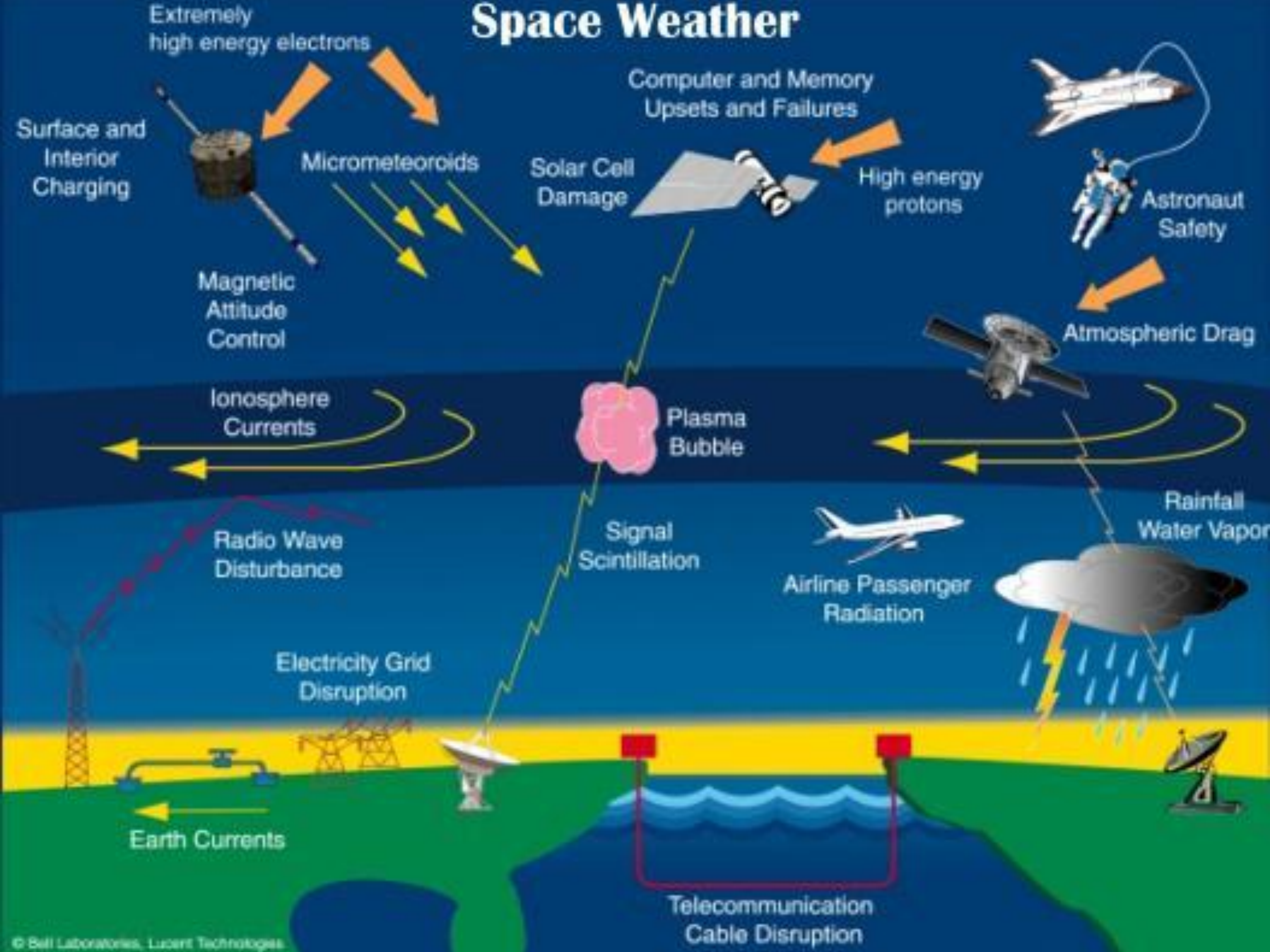
Department of Physics
Universitat Politècnica de Catalunya

Effects of the Space Environment

There are several phenomena that have a significant impact on Space Systems Architecture

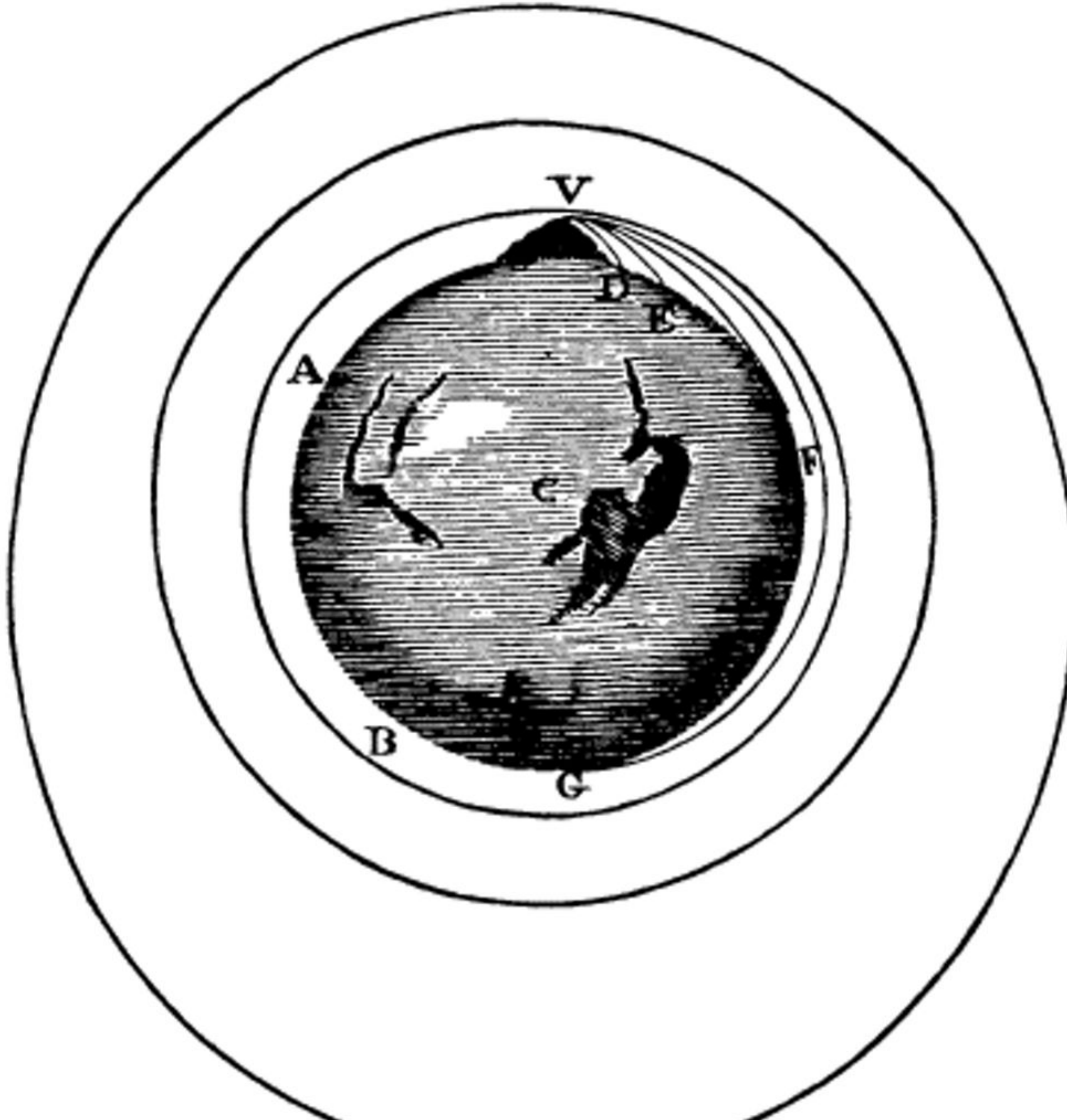
- Microgravity
- Van Allen belts
- High altitude atmosphere
- High vacuum
- Solar radiation (thermal control subsystem)
- Ionizing radiation

A single energetic particle can produce a single event phenomenon that seriously affects electronics


Space Weather
Extremely high energy electrons
Surface and Interior Charging
Micrometeoroids
Magnetic Attitude Control
Computer and Memory Upsets and Failures
Solar Cell Damage
High energy protons
Astronaut Safety
Atmospheric Drag
Ionosphere Currents
Plasma Bubble
Rainfall Water Vapor
Radio Wave Disturbance
Signal Scintillation
Airline Passenger Radiation
Electricity Grid Disruption
Earth Currents
Telecommunication Cable Disruption
© Bell Laboratories, Lucent Technologies

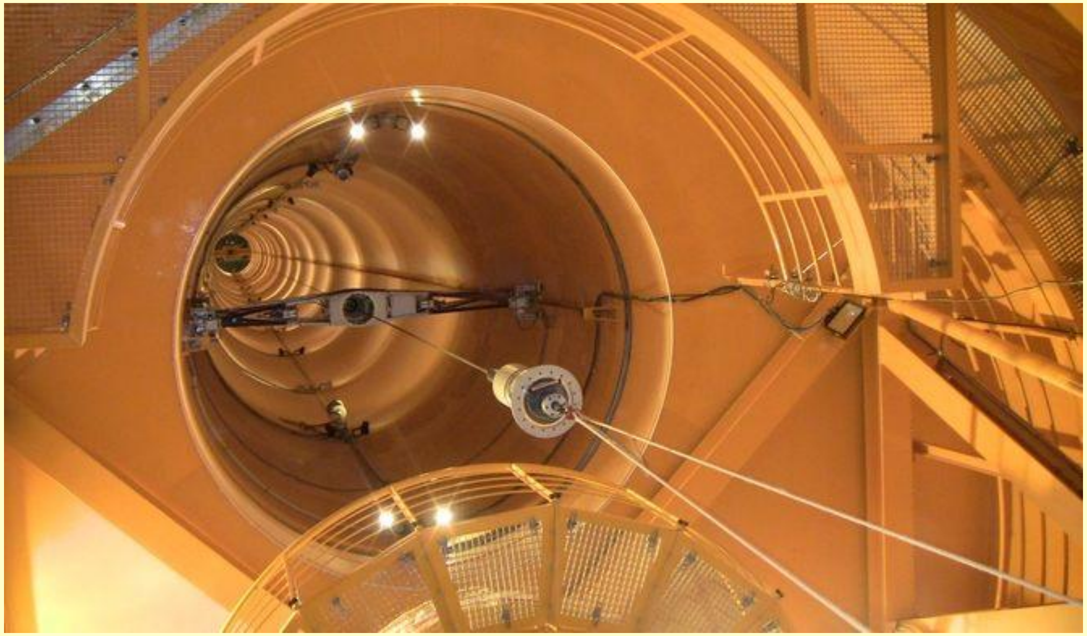
The gravitational field

- Obviously, all satellites in orbit around the Earth (or any other object) are experiencing an intense gravitational field
- The reason for them being n microgravity conditions is that they are in free-fall (equivalence principle), as was noted by Newton


V
D
E
A
F
c
B
G

Simulating microgravity

- Then, it is possible to simulate microgravity by letting fall an object (better in a reduced density atmosphere):
  - Drop towers
  - Parabolic flights
  - Small rockets
- This is always an approximation, and the duration of these tests is rather limited (from seconds to minutes)

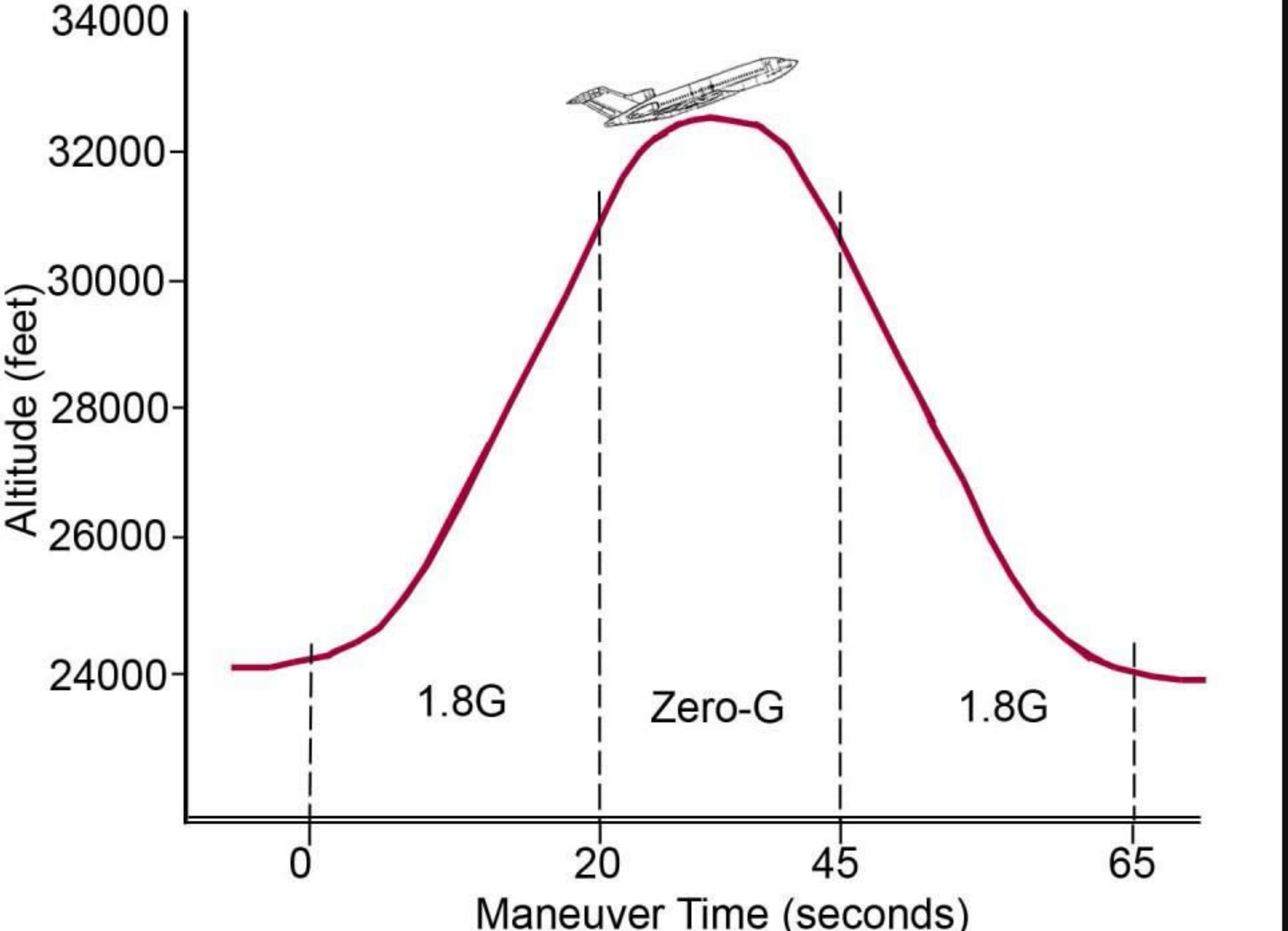


Interior of the Bremen test tower

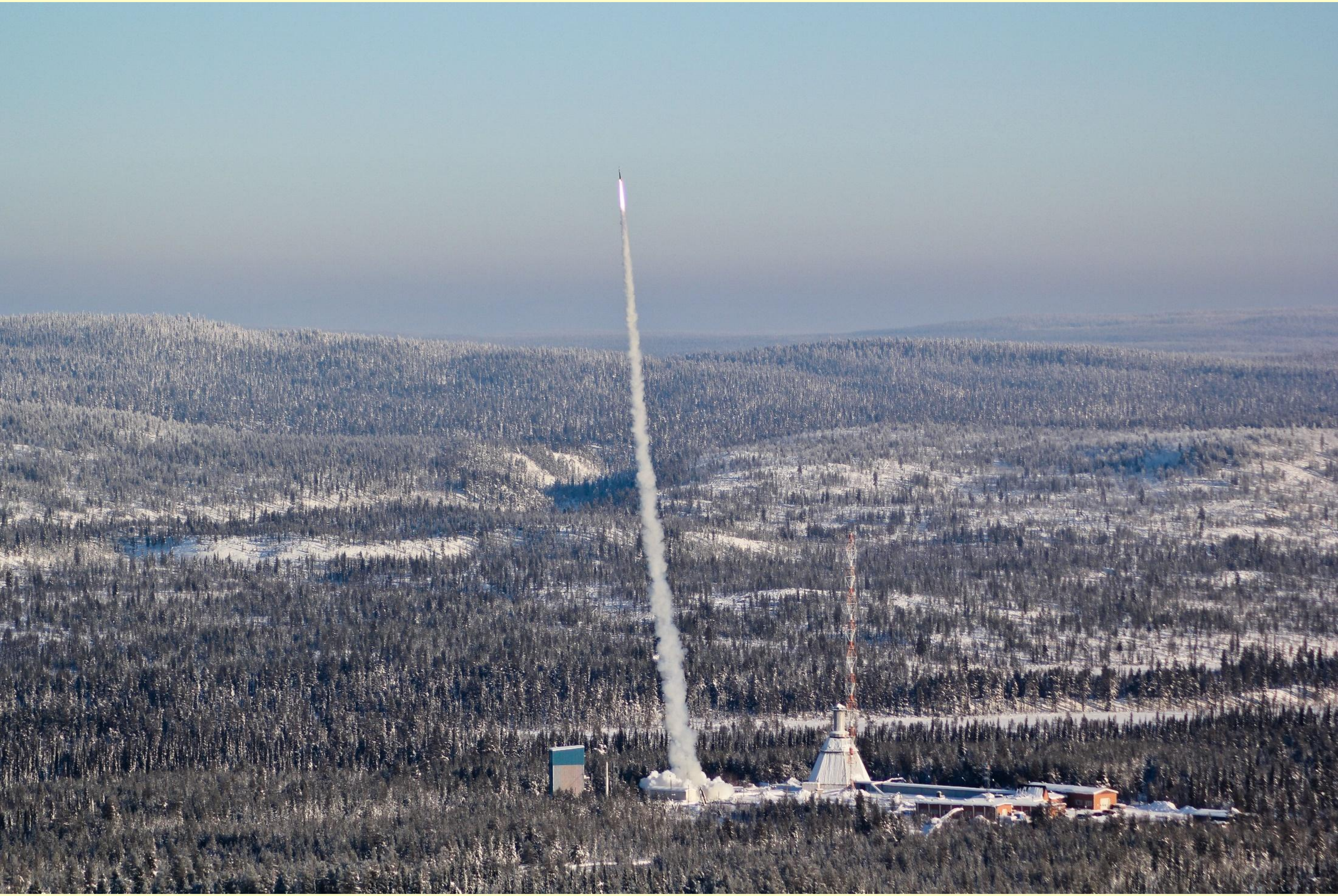

ЦЕНТР ПОДГОТОВКИ КОСМОН
РОСКОСМОС
RF-75353

ZERO-G
esa
cnes

NASA
930



34000
32000
30000
28000
26000
24000
Altitude (feet)
1.8G
Zero-G
1.8G
0
20
45
65
Maneuver Time (seconds)

ESA’s REXUS rocket



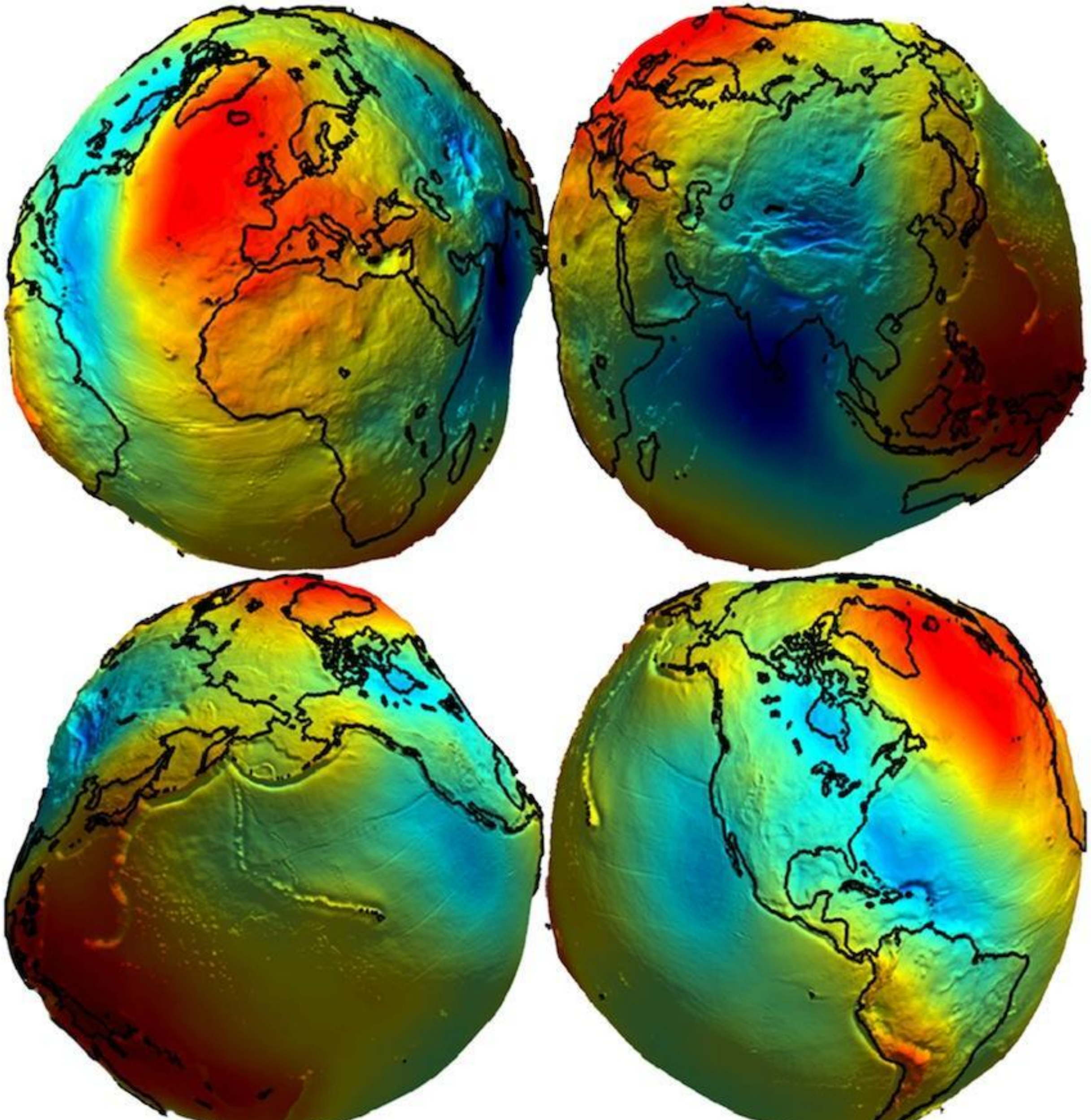
Gravitational field

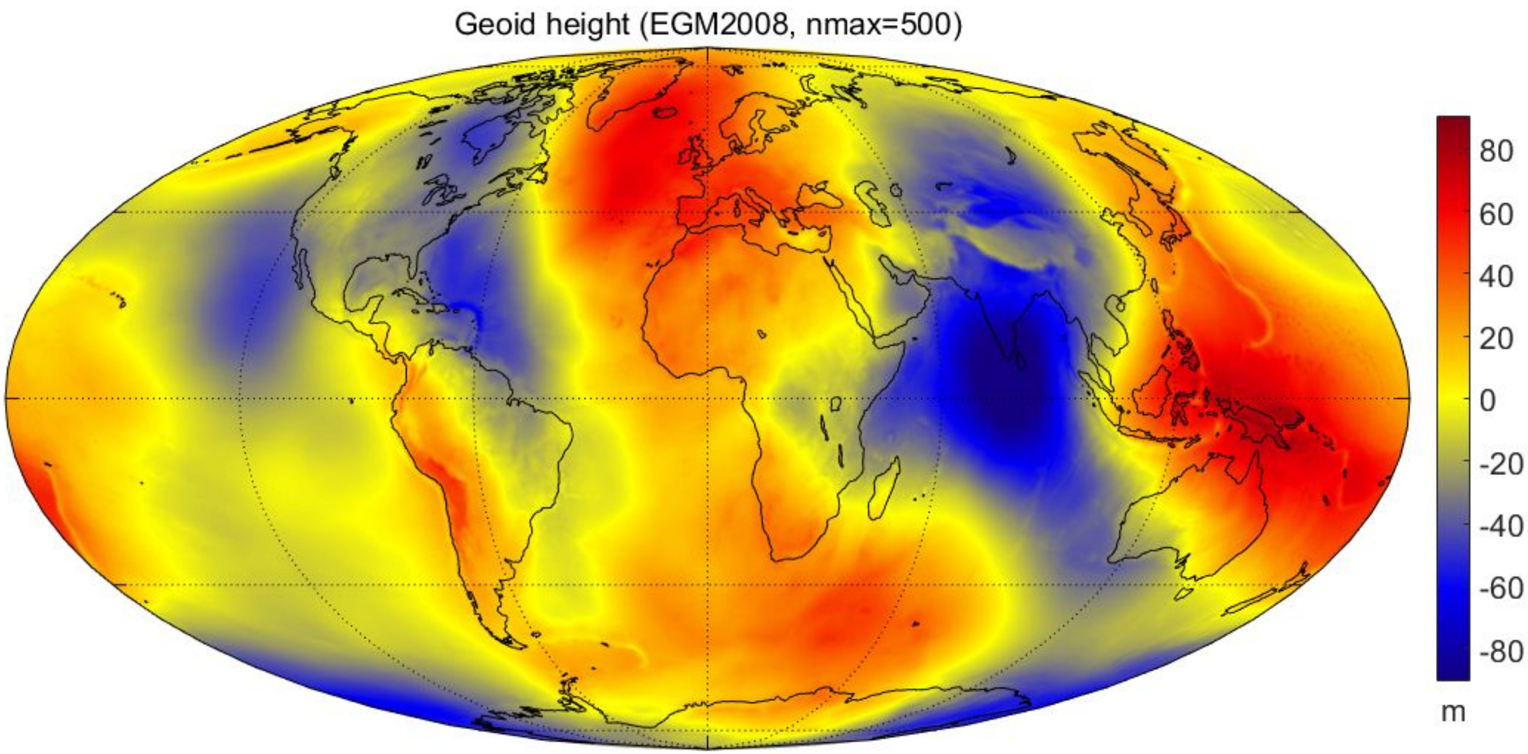
- The gravitational field of the Earth can be expressed in terms of a power series

$$U(r,\theta,\lambda) = \frac{\mu}{r}\left[1 - \sum_{l=2}^{\infty} J_l \left(\frac{R_\oplus}{r}\right)^l P_l[\sin\phi] + \sum_{l=2}^{\infty}\sum_{m=1}^{l}\left(\frac{R_\oplus}{r}\right)^l P_{l,m}[\sin\phi]\left\{C_{l.m}\cos\lambda + S_{l,m}\sin\lambda\right\}\right]$$

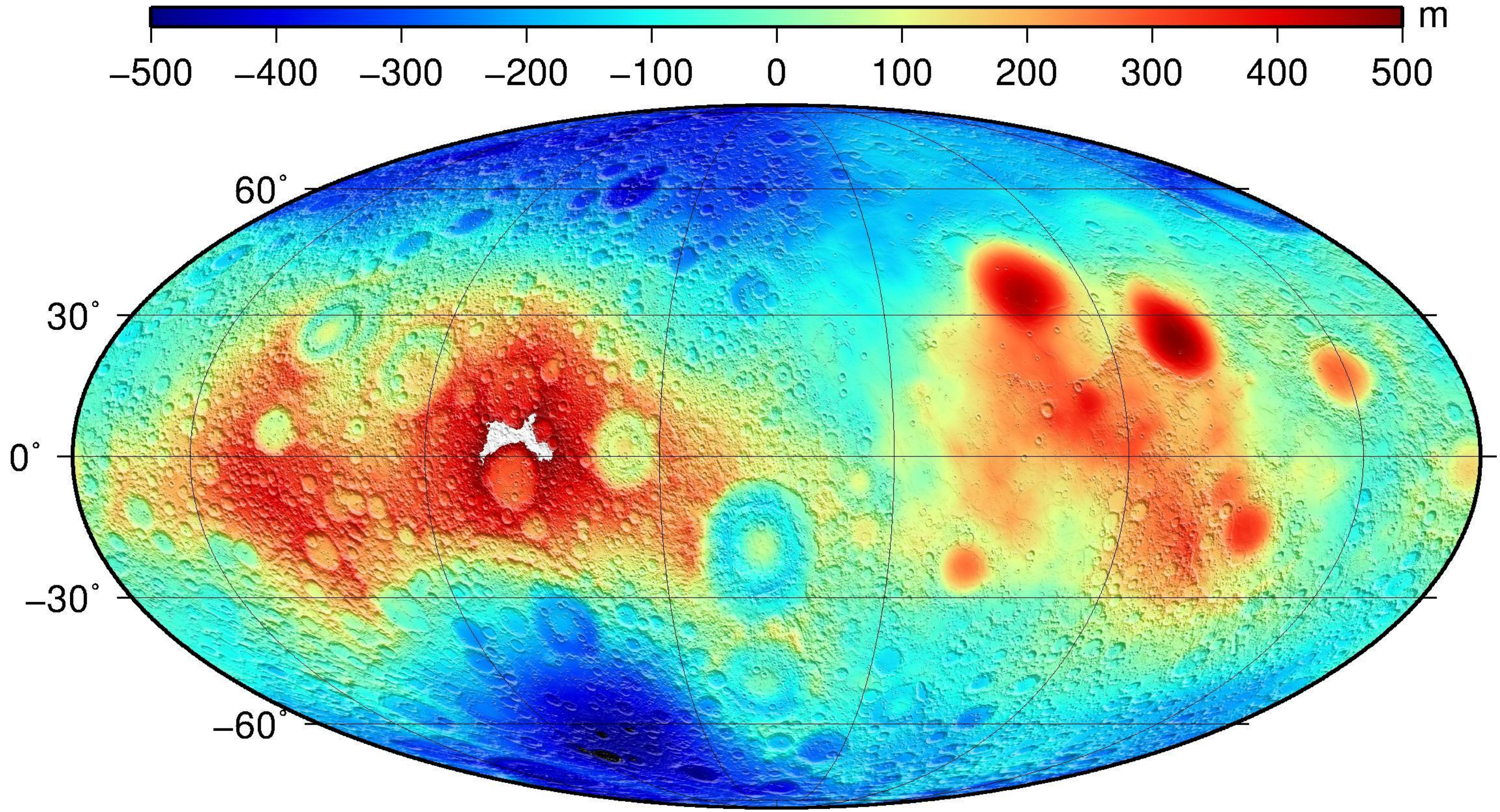
where

$$\mu = GM_\oplus$$




Geoid height (EGM2008, nmax=500)
80
60
40
20
0
-20
-40
-60
-80
m

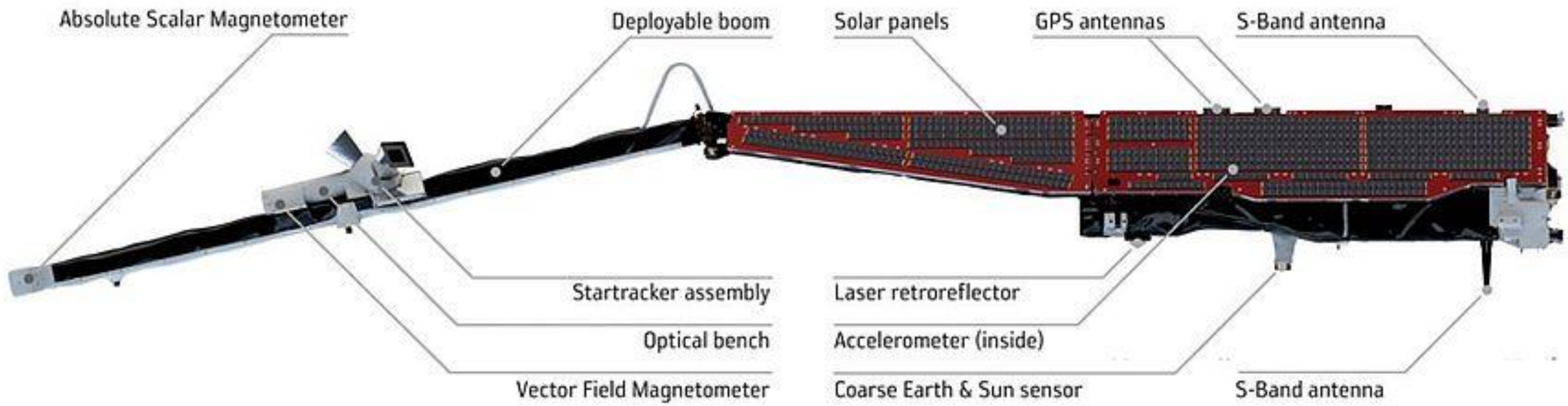
Other celestial bodies have, obviously, different gravitational fields



The magnetosphere and radiation belts

- The Earth is surrounded by radiation belts of energetic particles trapped inside the magnetosphere
  - The magnetic field of the Earth is roughly a magnetic dipole
  - Magnetic L shells defined by $R \approx L \cos^2\lambda$
  - Inner belt populated by high energy protons and electrons
  - Outer belts populated only by high energy electrons
- The origin of these energetic particles is the Sun
- Its particle density and spectrum are highly dependent on the Solar Cycle
- Also contributions by cosmic rays (rarer, but with very hard energetic spectrum)


IABG
IABG
ASTRIUM

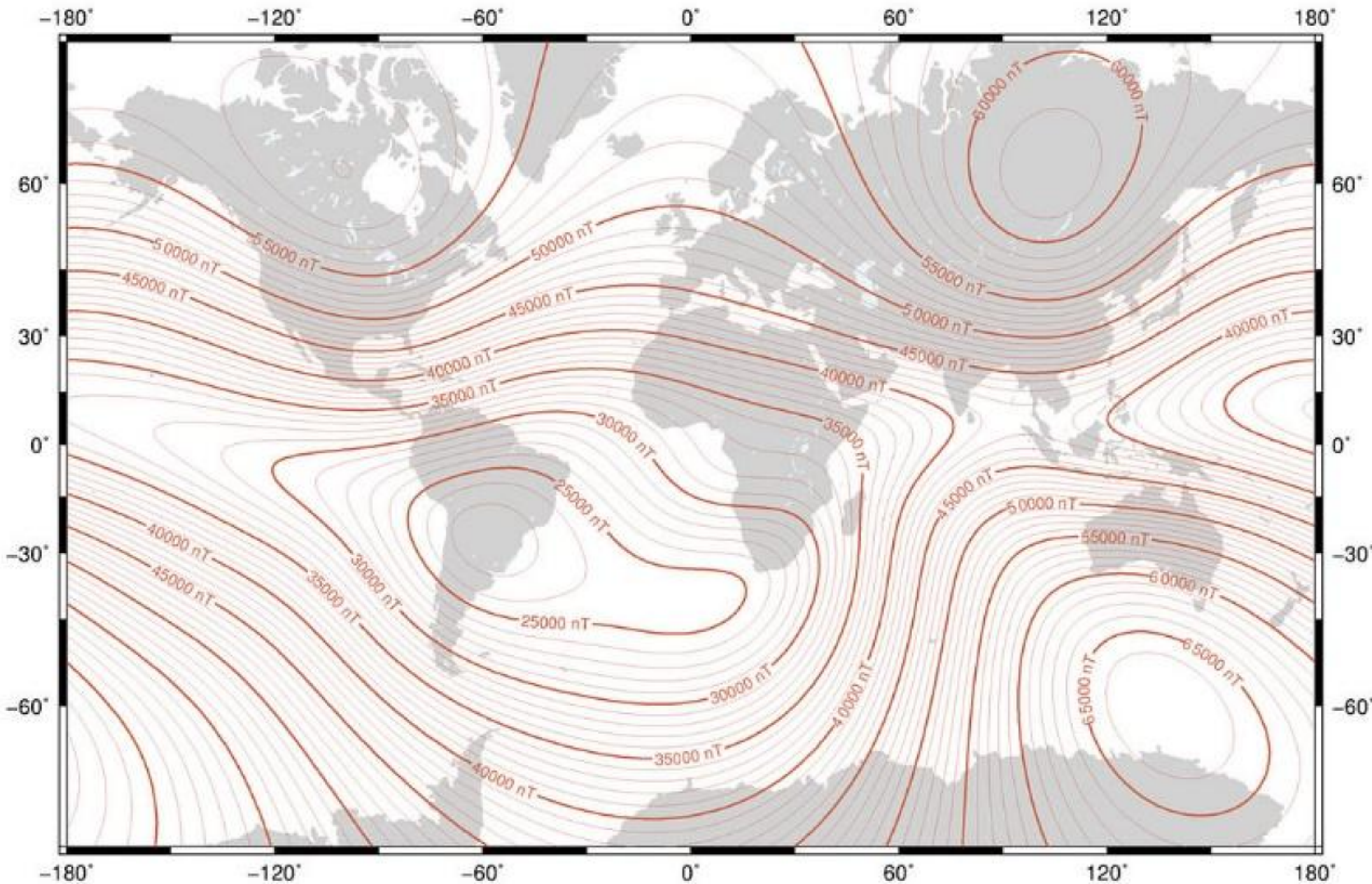

Absolute Scalar Magnetometer
Deployable boom
Solar panels
GPS antennas
S-Band antenna
Startracker assembly
Optical bench
Vector Field Magnetometer
Laser retroreflector
Accelerometer (inside)
Coarse Earth & Sun sensor
S-Band antenna

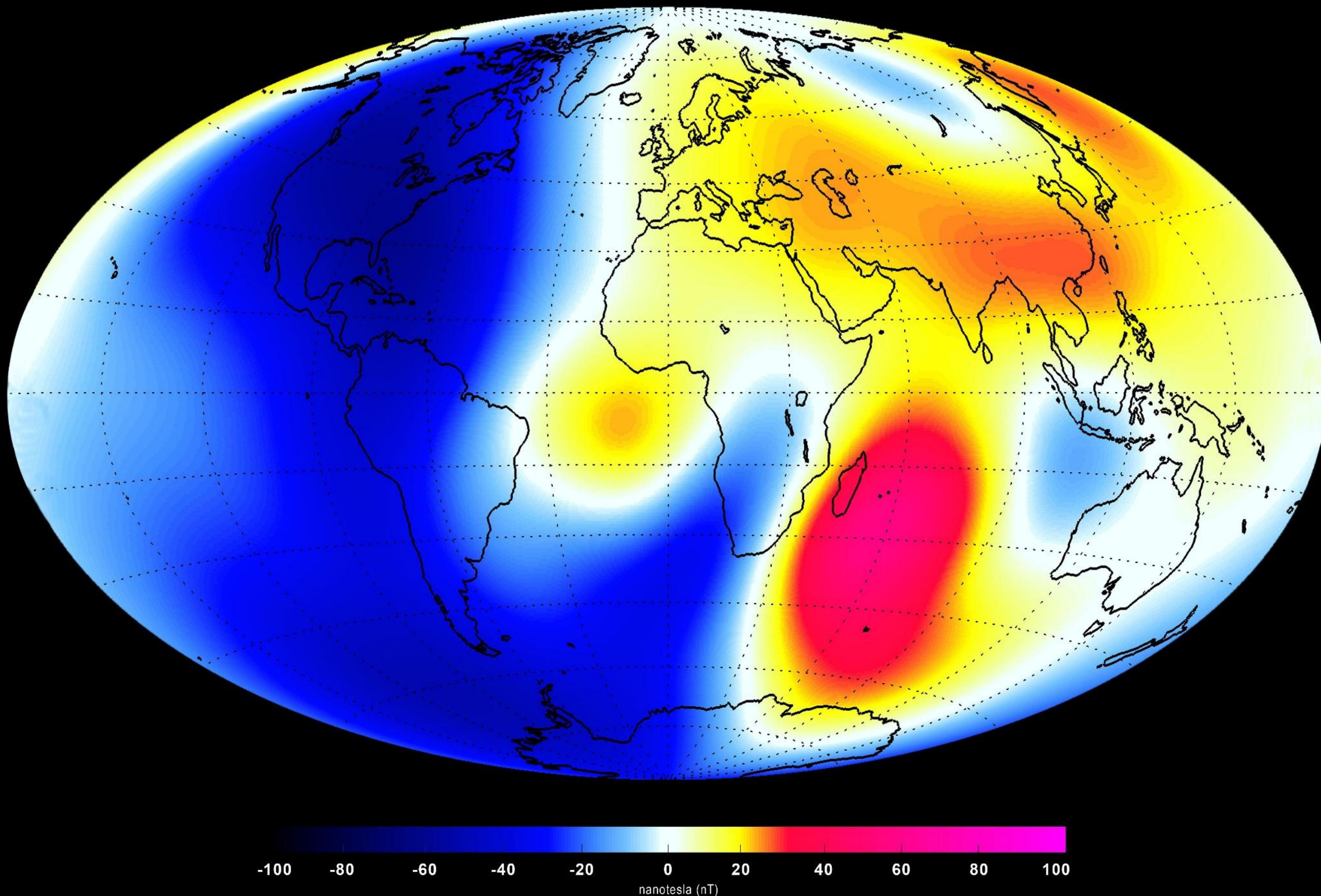
IGRF12

- The international Geomagnetic Reference Field: 12th generation, is one of the most widely used models for the magnetic field of the Earth.
- This model has thousands of adjustable parameters.
- Its expression reads

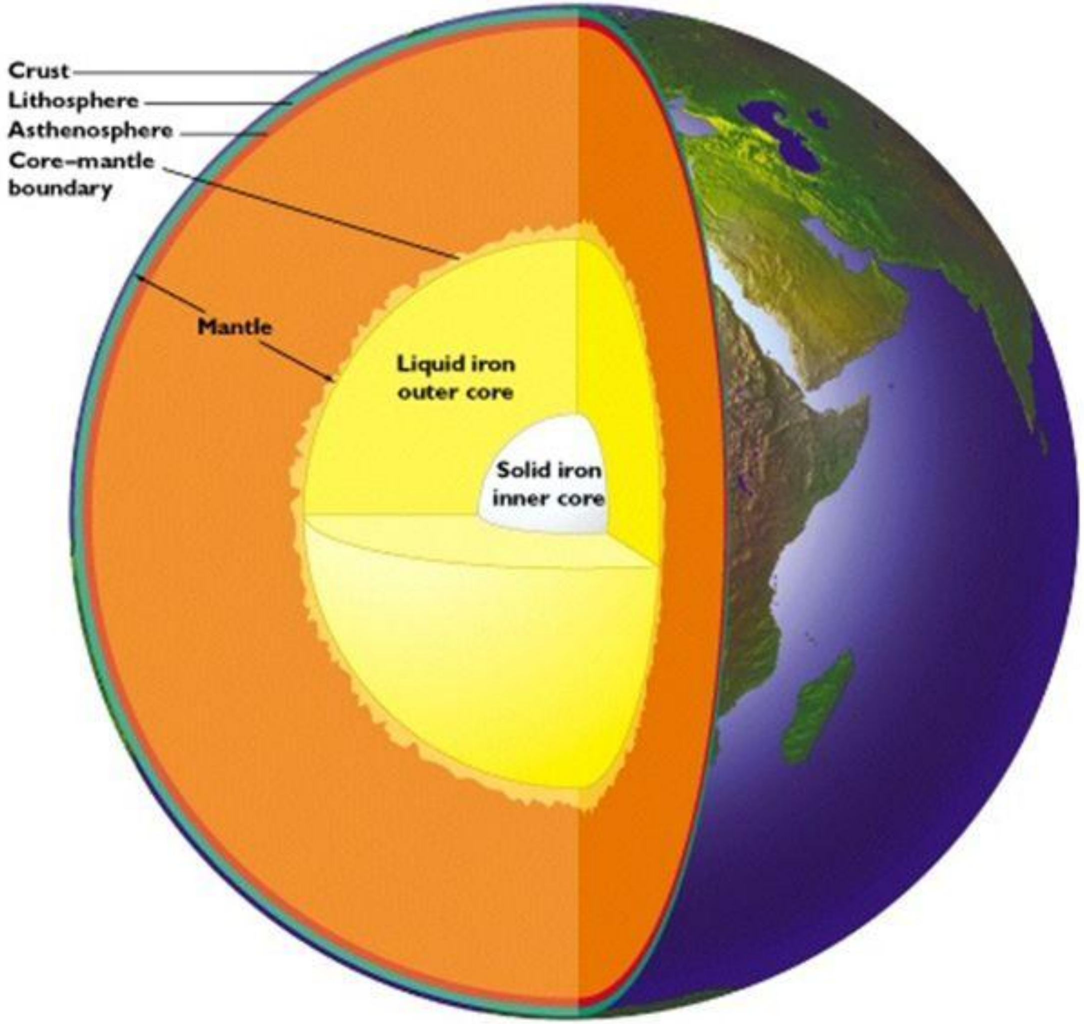
$$V(r,\theta,\phi,t) = R_{\oplus} \sum_{n=1}^{\boldsymbol{N}} \sum_{m=0}^{n} \left(\frac{R_{\oplus}}{r}\right)^{n+1} \left[g_n^m(t)\cos(m\phi) + h_n^m(t)\sin(m\phi)\, P_{n,m}(\cos\theta)\right]$$

Total Force IGRF12

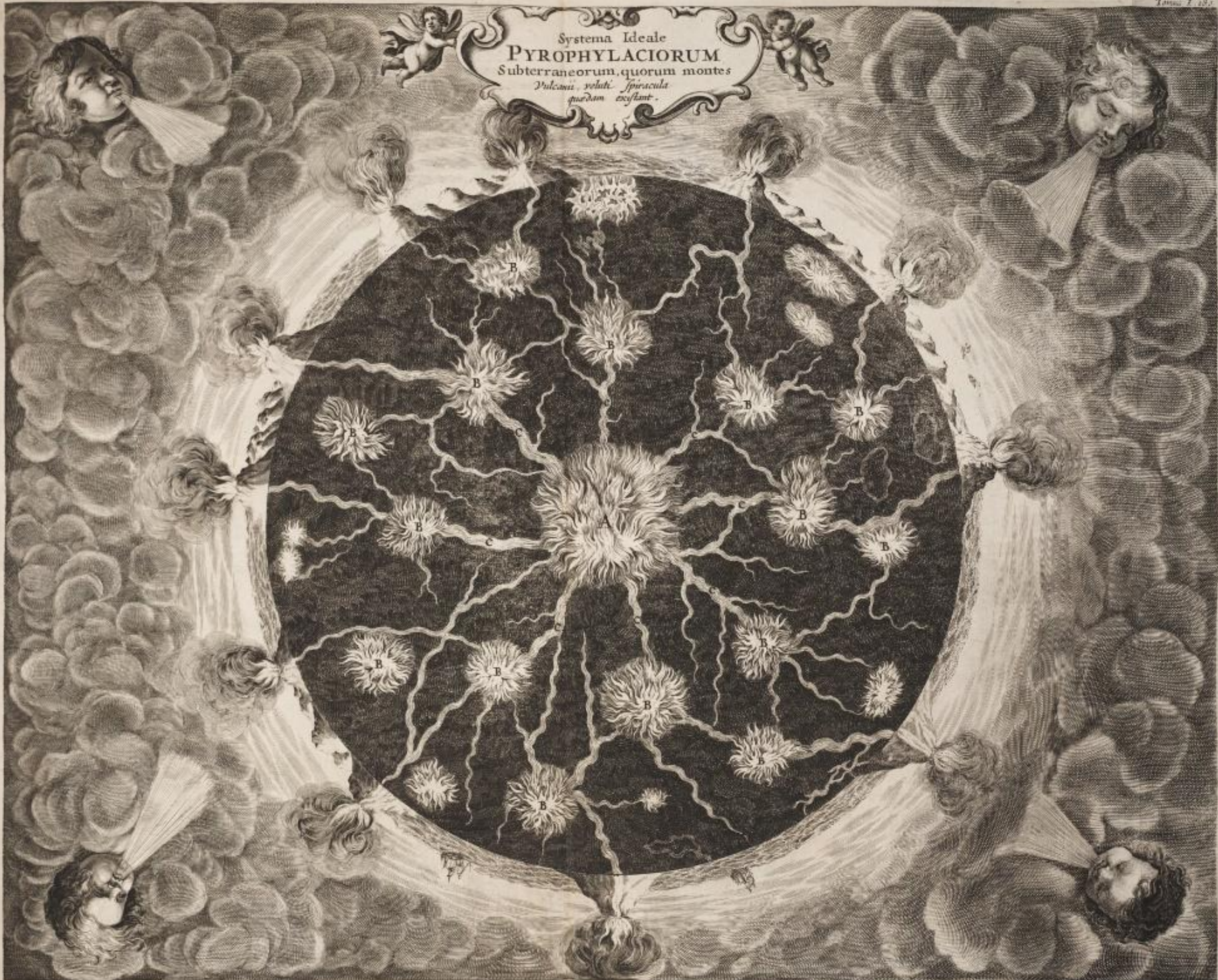



-100
-80
-60
-40
-20
0
20
40
60
80
100
nanotesla (nT)

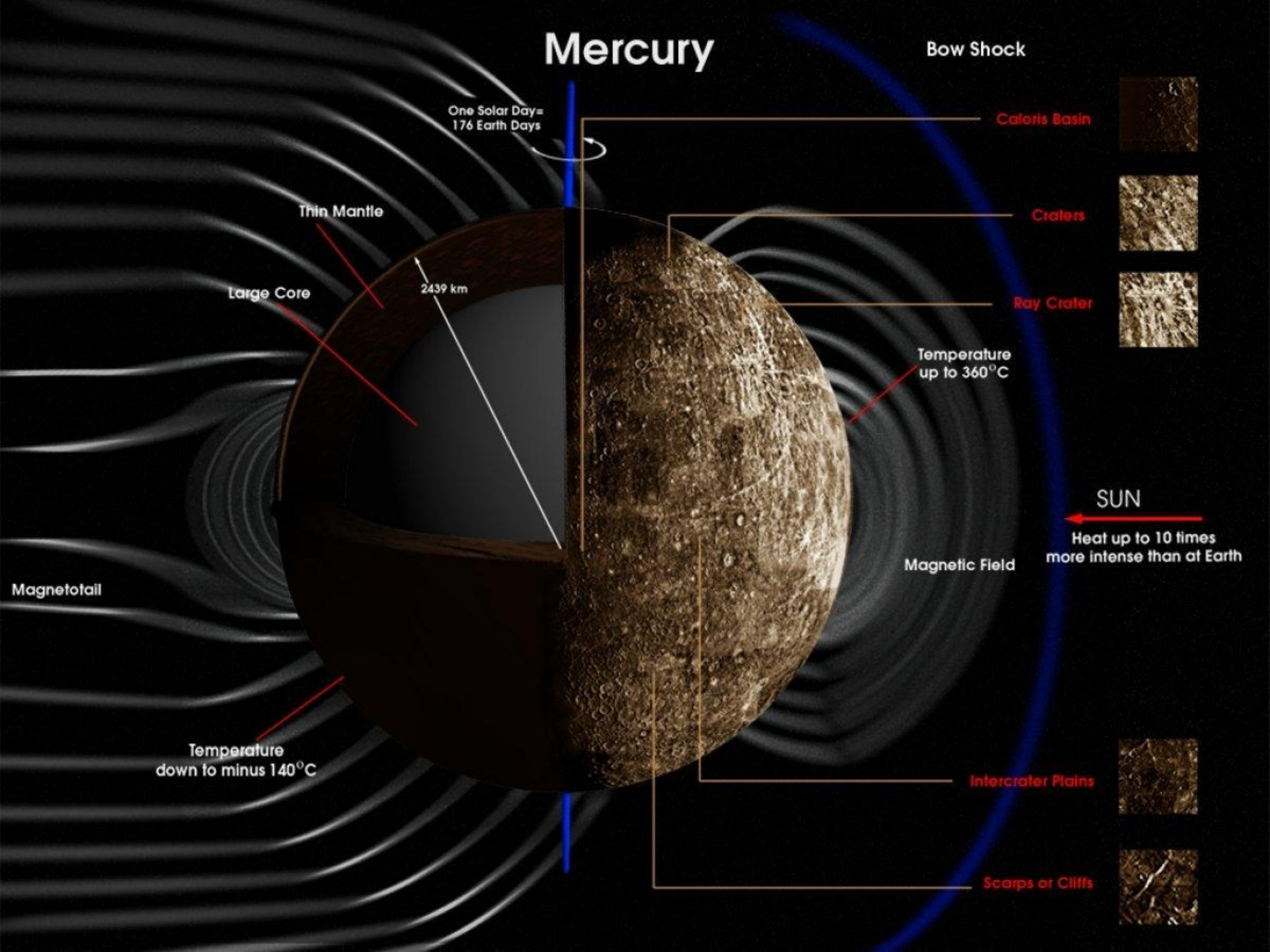
Earth's Internal Structure

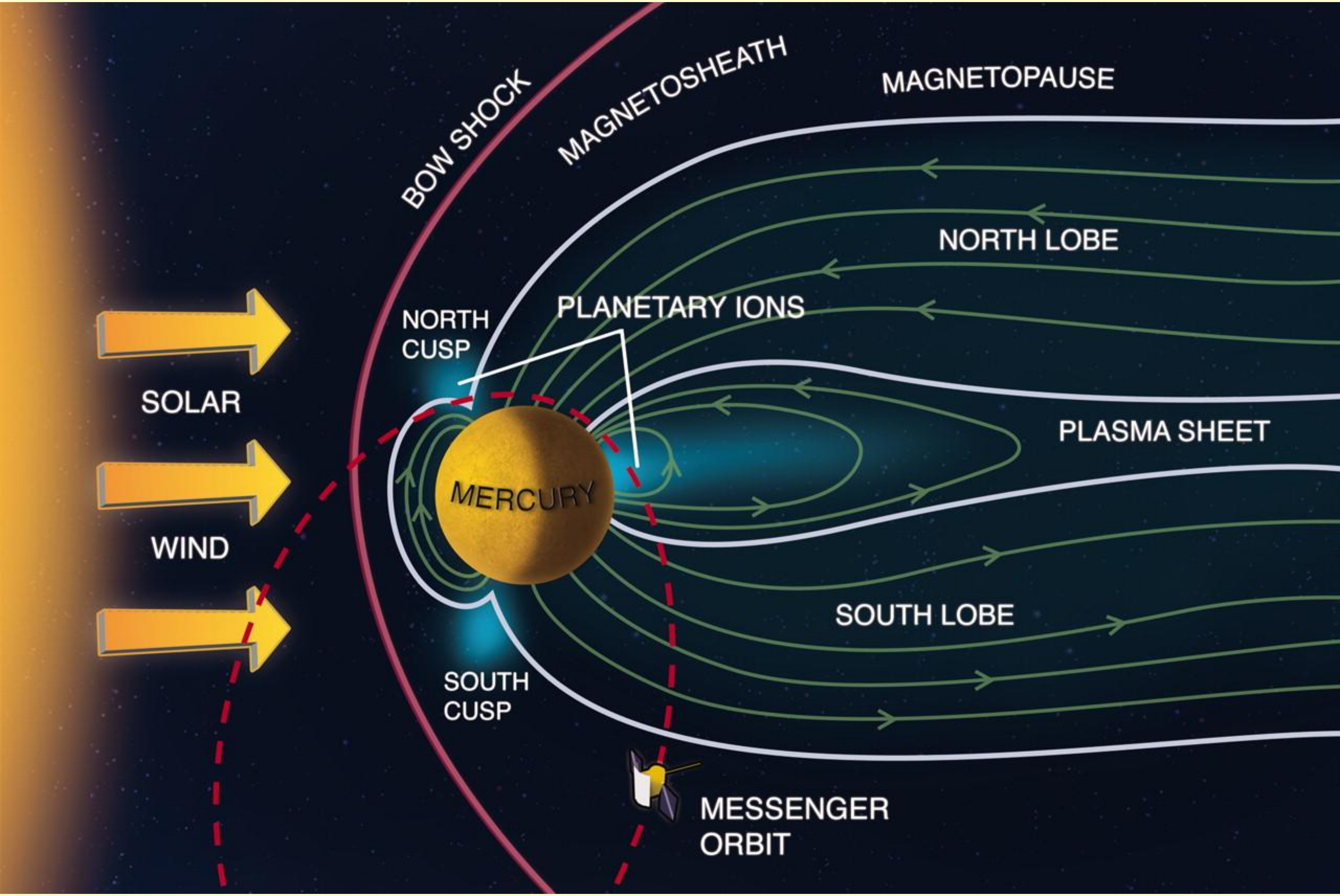


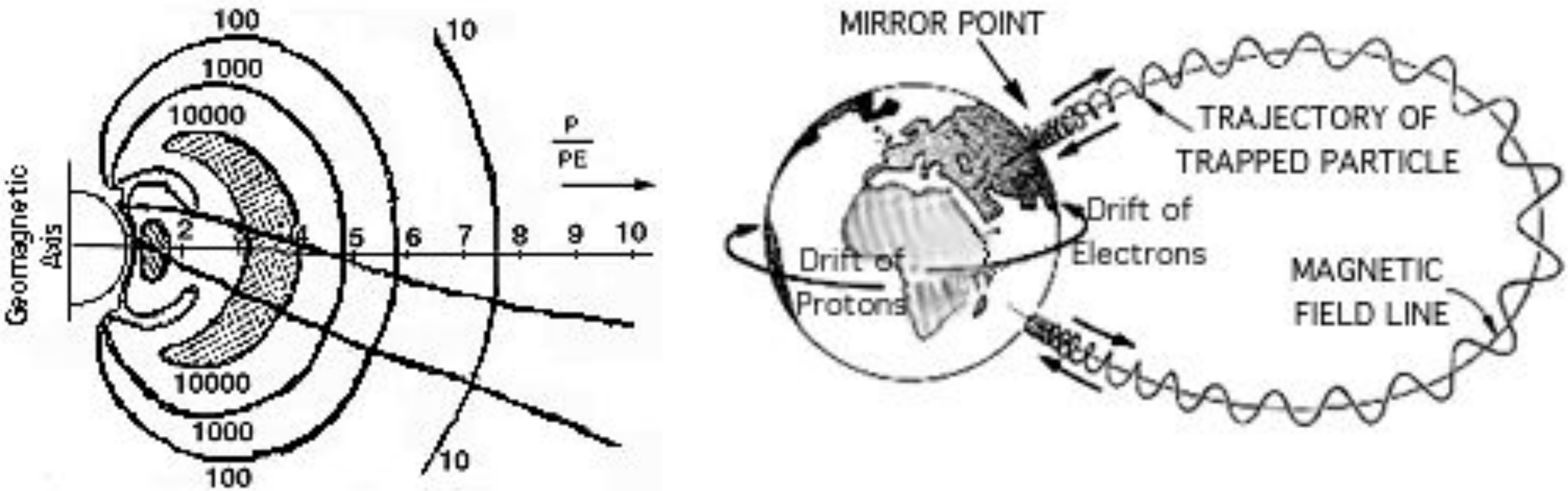
- crust
- mantle
- core



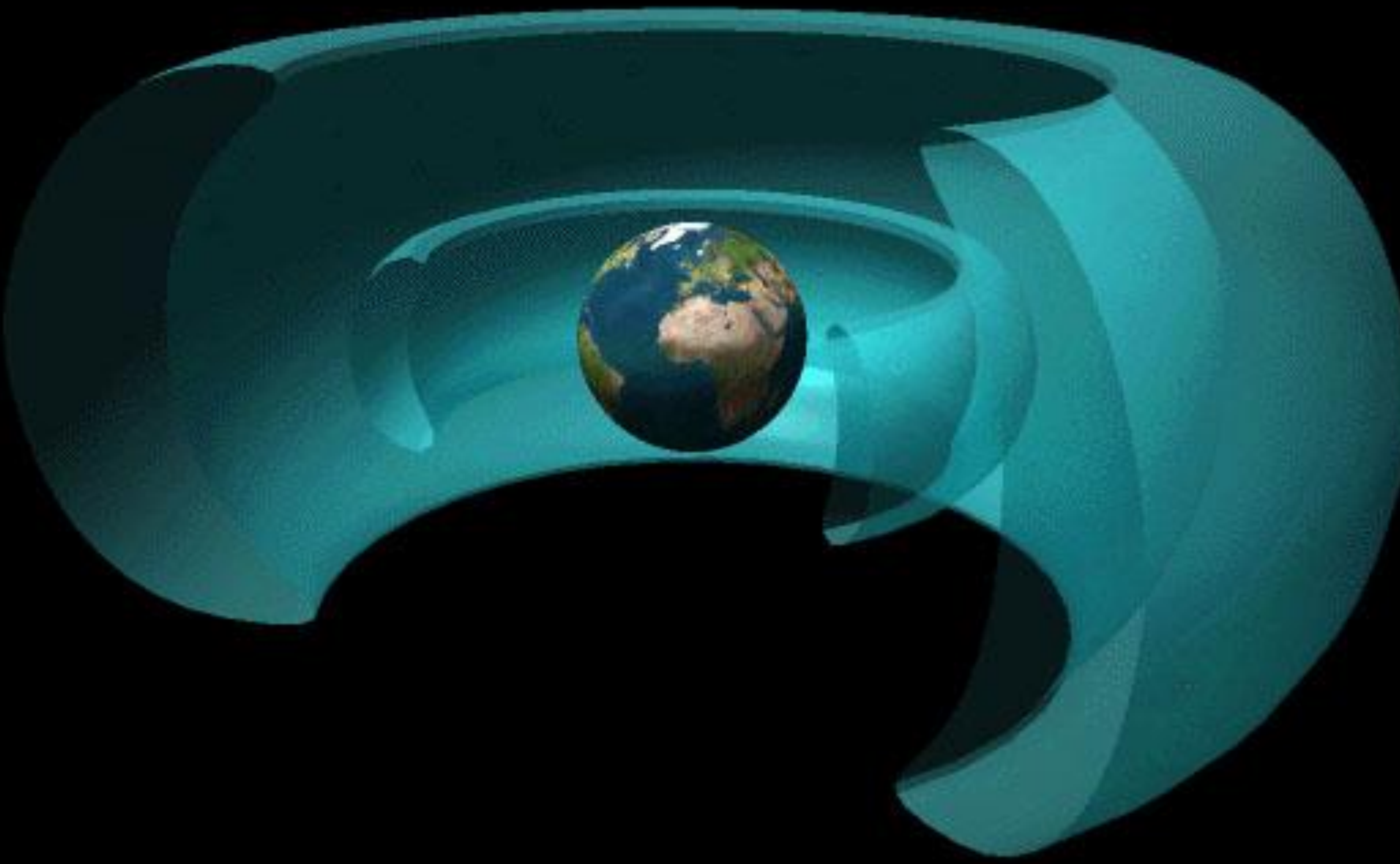
Hoc Schema exprimit Caloris sive Ignis nidos, vel quod idem est, pyrophylacia per universa Geocosmi viscera admirando DEI opificio, varie distributa ne alicubi deesset, quod conservationi Geocosmi tantopere foret necessarium; Nemo autem sibi persuadeat, Ignem revera hoc pacto quo schema refert, constitutum esse; eoq; prorsus ordine disposita æstuaria, nequaquam. Quis enim hæc observavit? quisnam illuc penetravit unquam ex hominibus? Hoc itaq; Schemate solummodo ostendere volumus, Telluris viscera plena esse æstuariis et pyrophylaciis, sive ea jam hoc modo, sive alio, disposita sint. Ex centro igitur Ignem per omnes Subterrestris mundi semitas usq; ad ipsos exterioris superficiei montes Vulcanios deduximus; Ignis Centralis signetur A litera. Reliqua sunt æstuaria Naturæ, signata B. Canales pyragogi C. minimi vero rivi sunt fissuræ Terræ, per quas Ignei spiritus pervadunt.

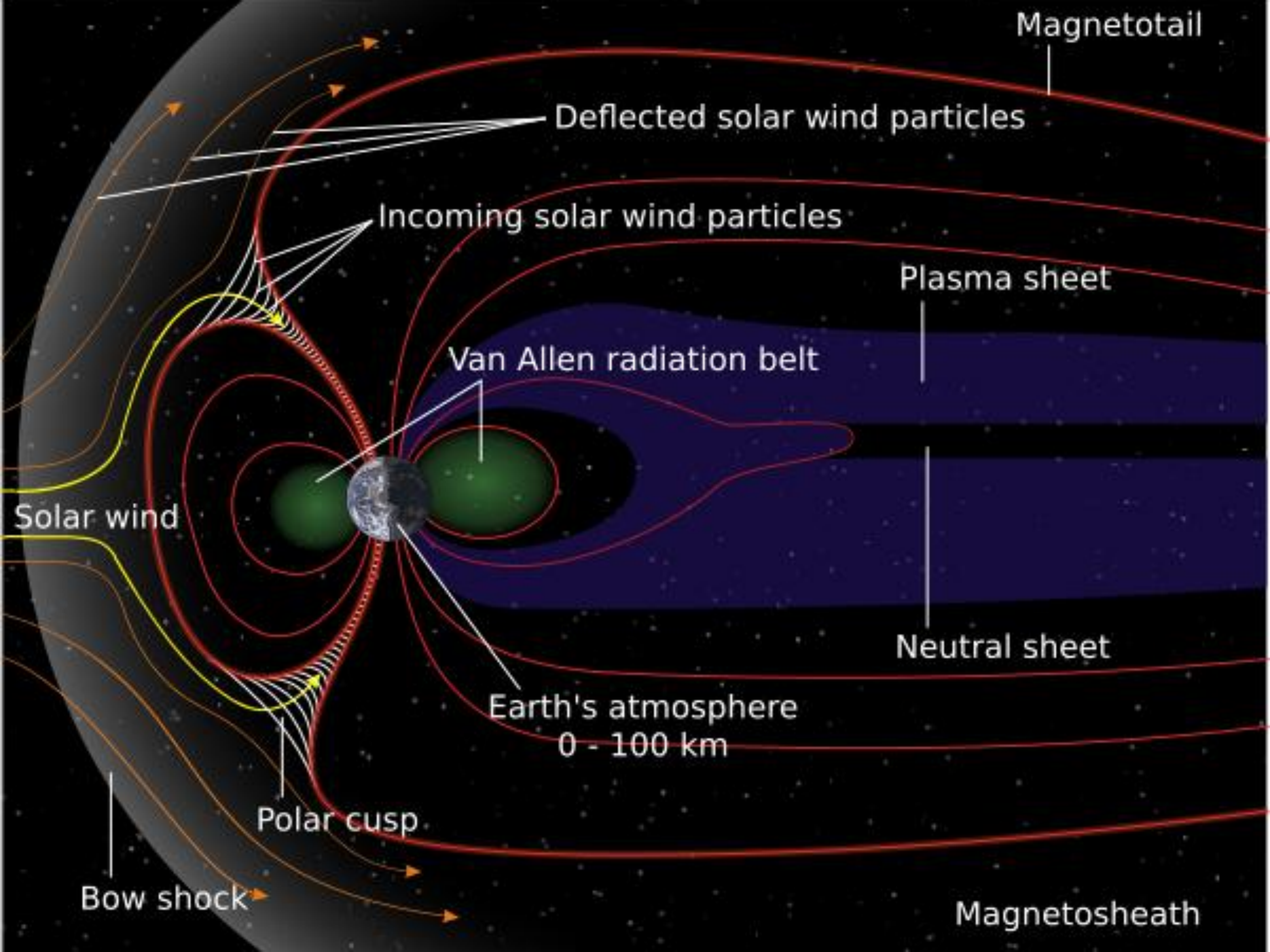

Mercury
Bow Shock
One Solar Day=
176 Earth Days
Caloris Basin
Craters
Ray Crater
Thin Mantle
Large Core
2439 km
Temperature
up to 360°C
SUN
Heat up to 10 times
more intense than at Earth
Magnetic Field
Magnetotail
Temperature
down to minus 140°C
Intercrater Plains
Scarps or Cliffs


BOW SHOCK
MAGNETOSHEATH
MAGNETOPAUSE
NORTH LOBE
PLANETARY IONS
NORTH
CUSP
SOLAR
WIND
MERCURY
PLASMA SHEET
SOUTH LOBE
SOUTH
CUSP
MESSENGER
ORBIT



Geometry and physical explanation of trapped radiation belts




Magnetotail
Deflected solar wind particles
Incoming solar wind particles
Plasma sheet
Van Allen radiation belt
Solar wind
Neutral sheet
Earth's atmosphere
0 - 100 km
Polar cusp
Bow shock
Magnetosheath

Models for radiation belts

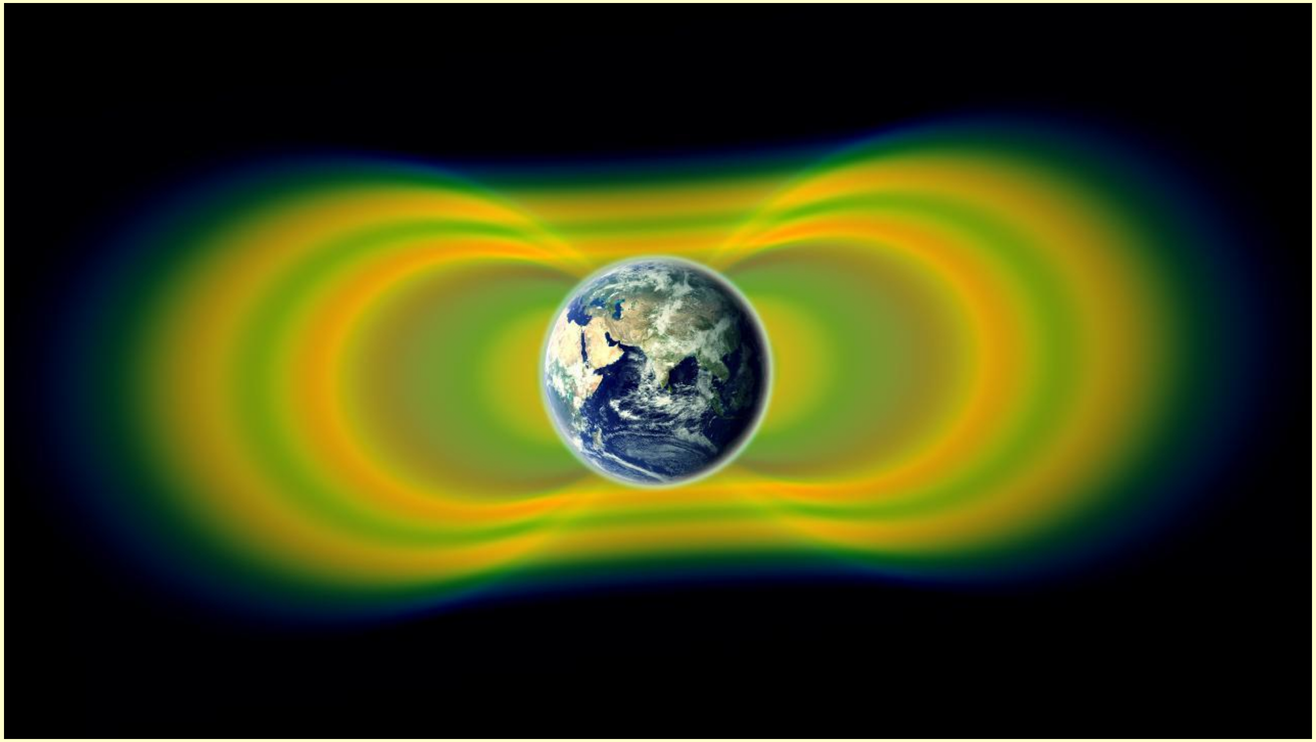
- Proton models:
  - Solar minimum: AP8MIN
  - Solar Maximum: AP8MAX
- Electron models
  - Solar minimum: AE8MIN
  - Solar maximum: AE8MAX

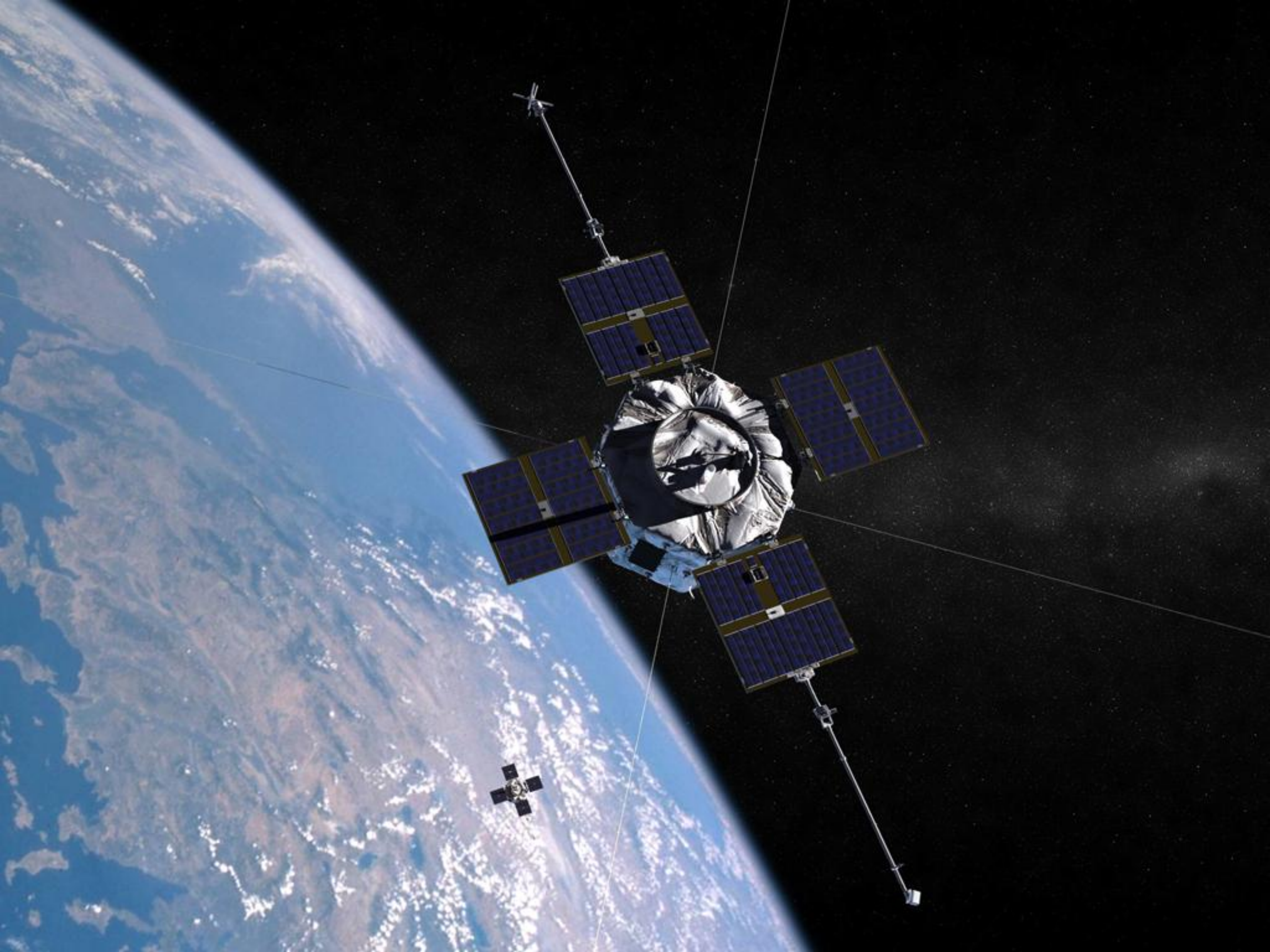
http://nssdcftp.gsfc.nasa.gov/models/radiation_belt/radbelt/

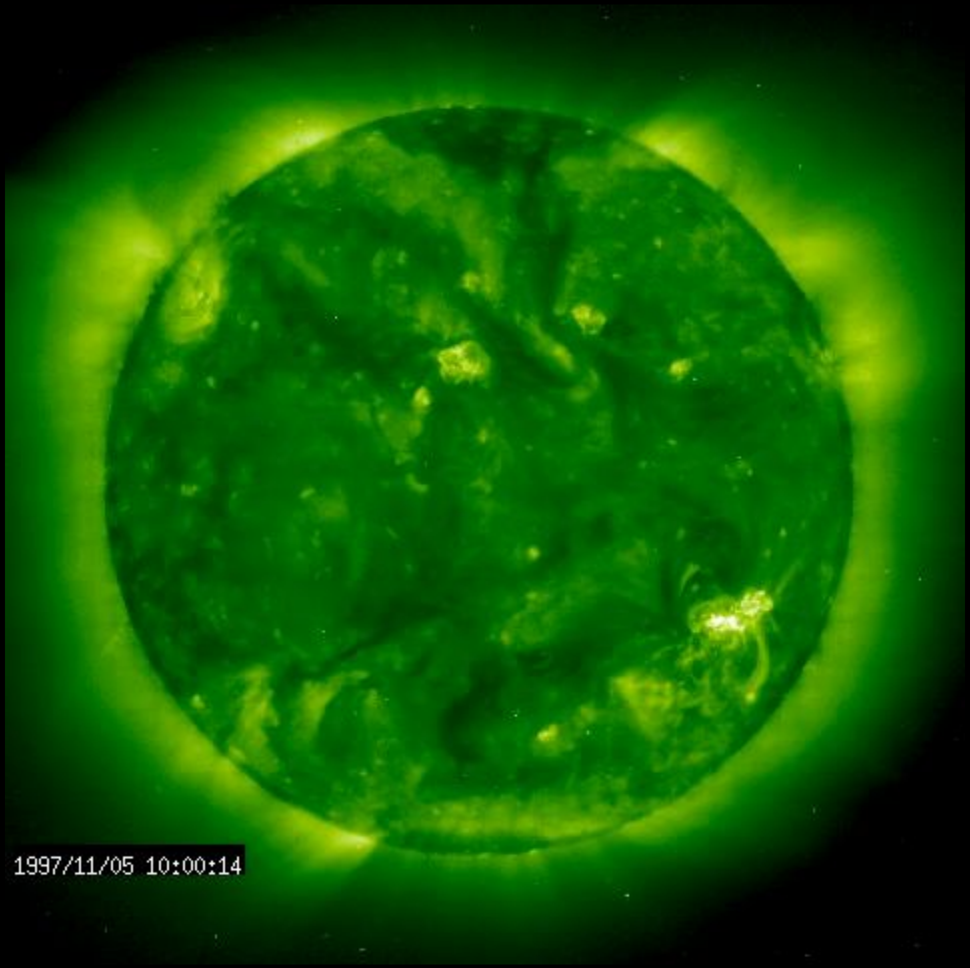
http://www.spenvis.oma.be (requires free registration)

The third van Allen belt

- Recently, the van Allen probes have discovered a third (transient) van Allen belt

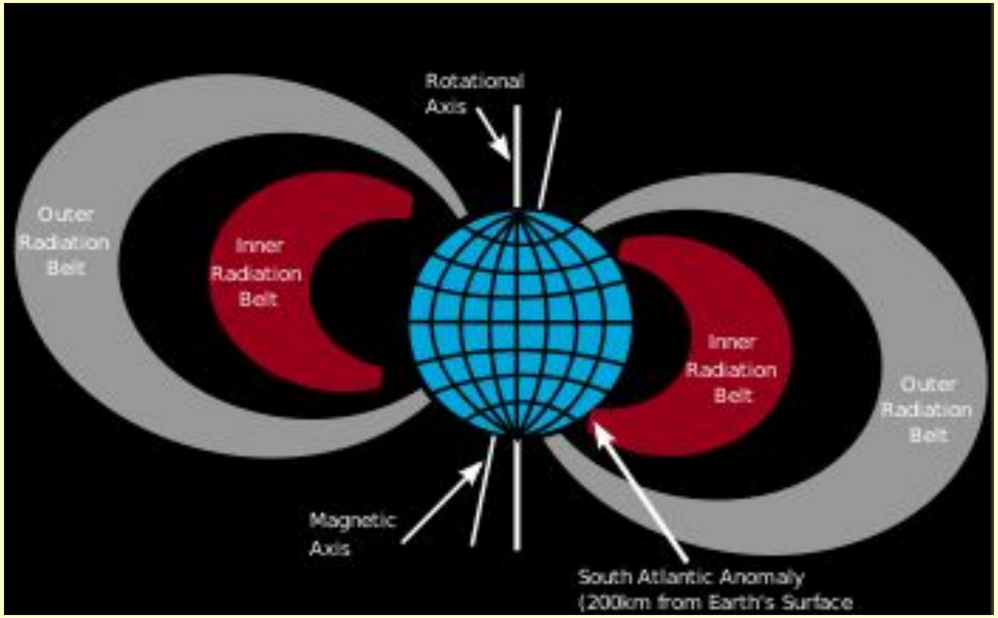





1997/11/05 10:00:14

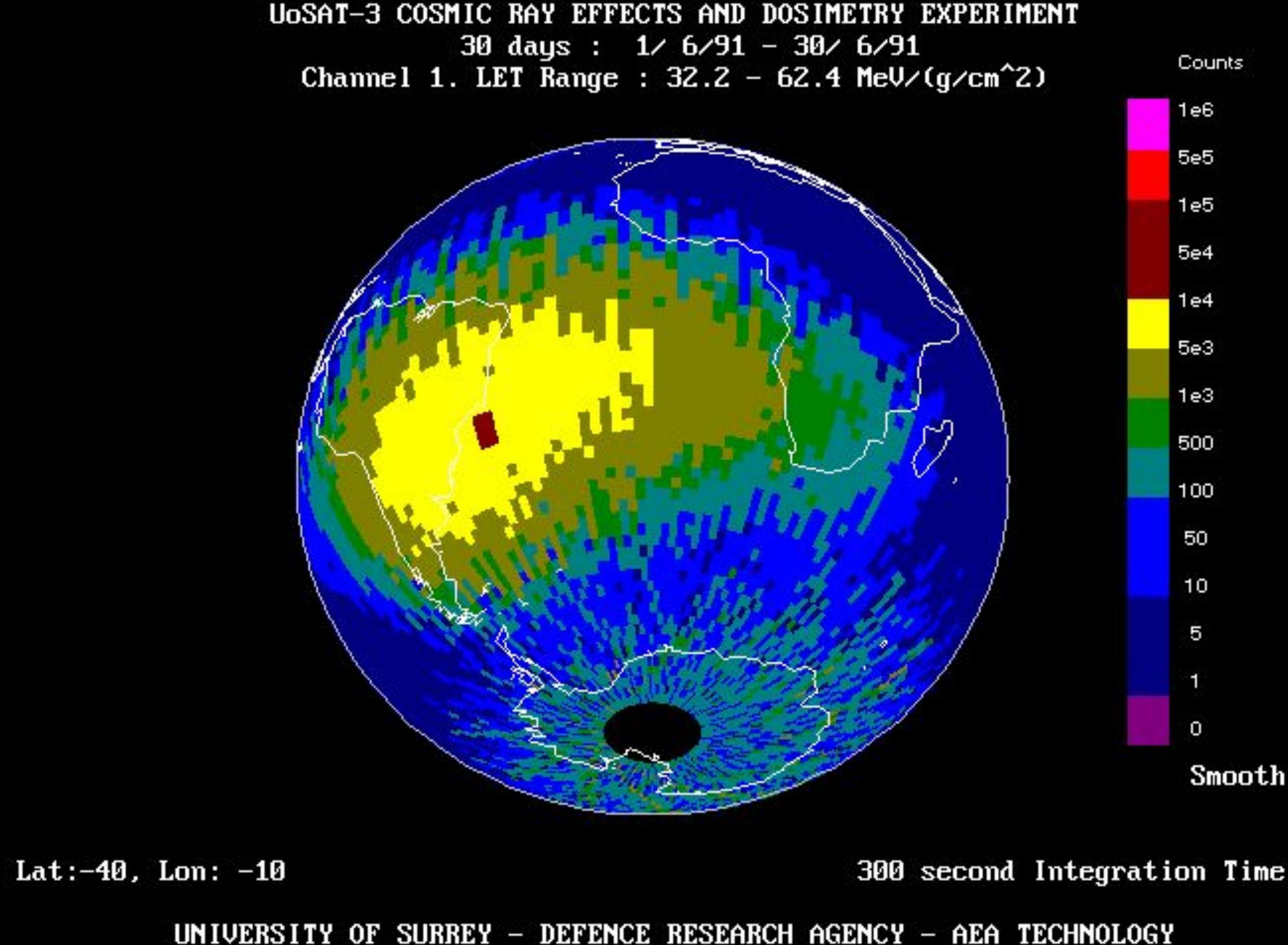
The South Atlantic Anomaly

- The South Atlantic Anomaly is due to a lack of homogeneity in the proton belt
  - The magnetic field of the Earth is off-center (by about 500 km)
  - The magnetic axis is tilted 11 deg with respect to the rotation axis of the Earth

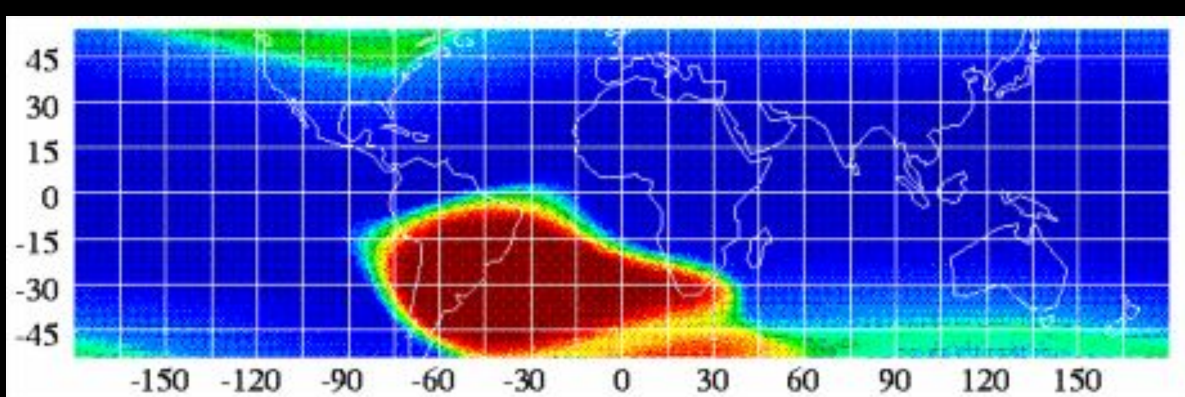


Radiation Effects

- There are several kinds of SEEs
  - Single event upsets (SEU): a change of a bit (or more) in a memory or register produced by the action of an impacting ion. They do not harm the device, but degrade its operation
  - Single event latchup (SEL): a PNPN device becomes shorted until it is power-cycled. The part may fail if the anomalous current is going on for a sufficiently long time
  - Single event transient (SET): the charge produced in an ionization event is collected and travels along the circuit
  - Single event burnout (SEB): the ionization and anomalous currents are intense enough to cause a permanent damage



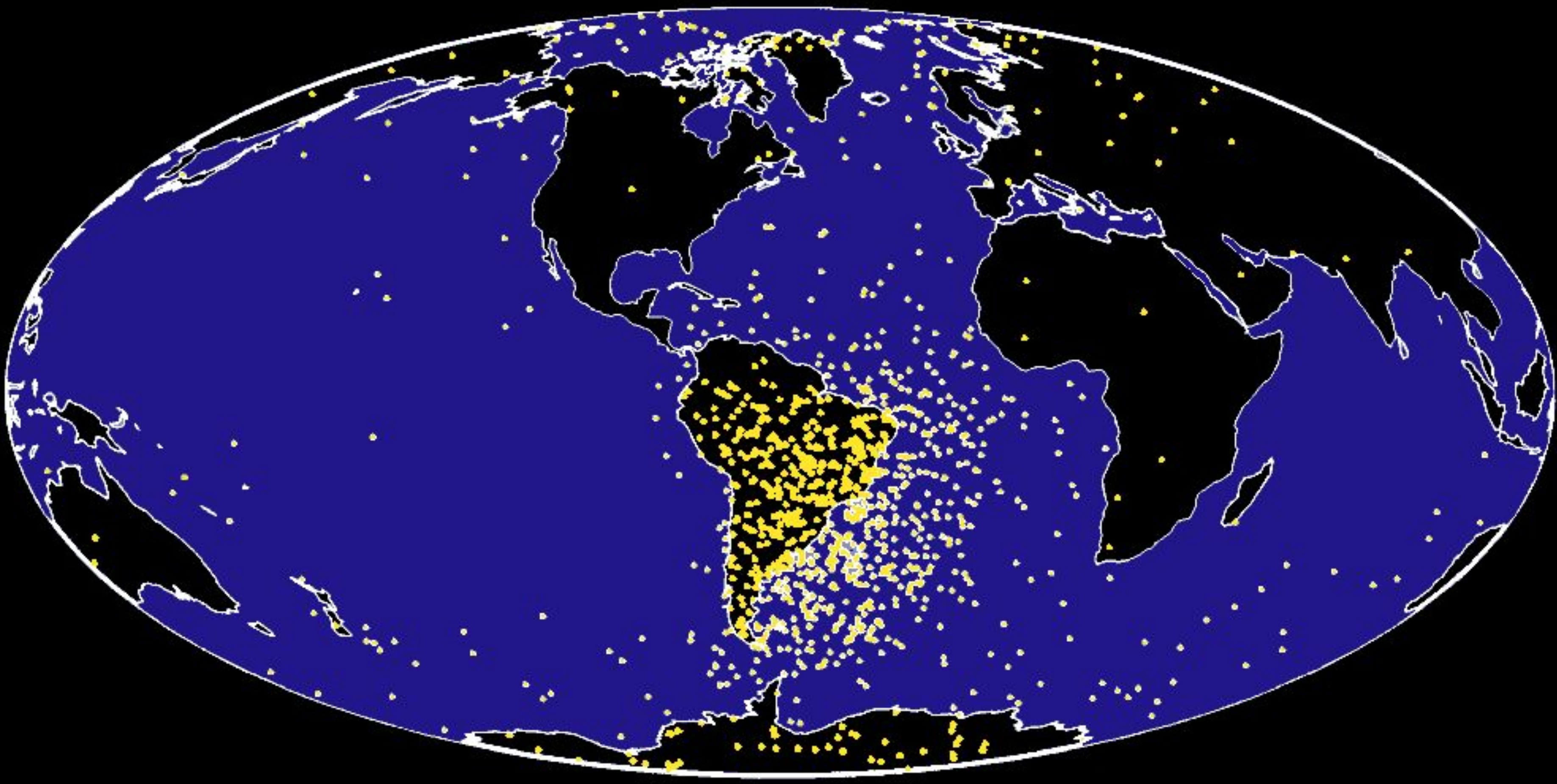
Images of the South Atlantic Anomaly



The effects of SAA

- The South Atlantic Anomaly is due to a lack of homogeneity in the proton belt
  - The magnetic field of the Earth is off-center
  - The magnetic axis is tilted with respect to the rotation axis of the Earth
- The SAA is specially relevant for satellites in low orbit with inclination between 35º and 60º
- No way to avoid the SAA
- Increased number of p have important effect of radiation doses

UOSAT-2 Memory Upsets



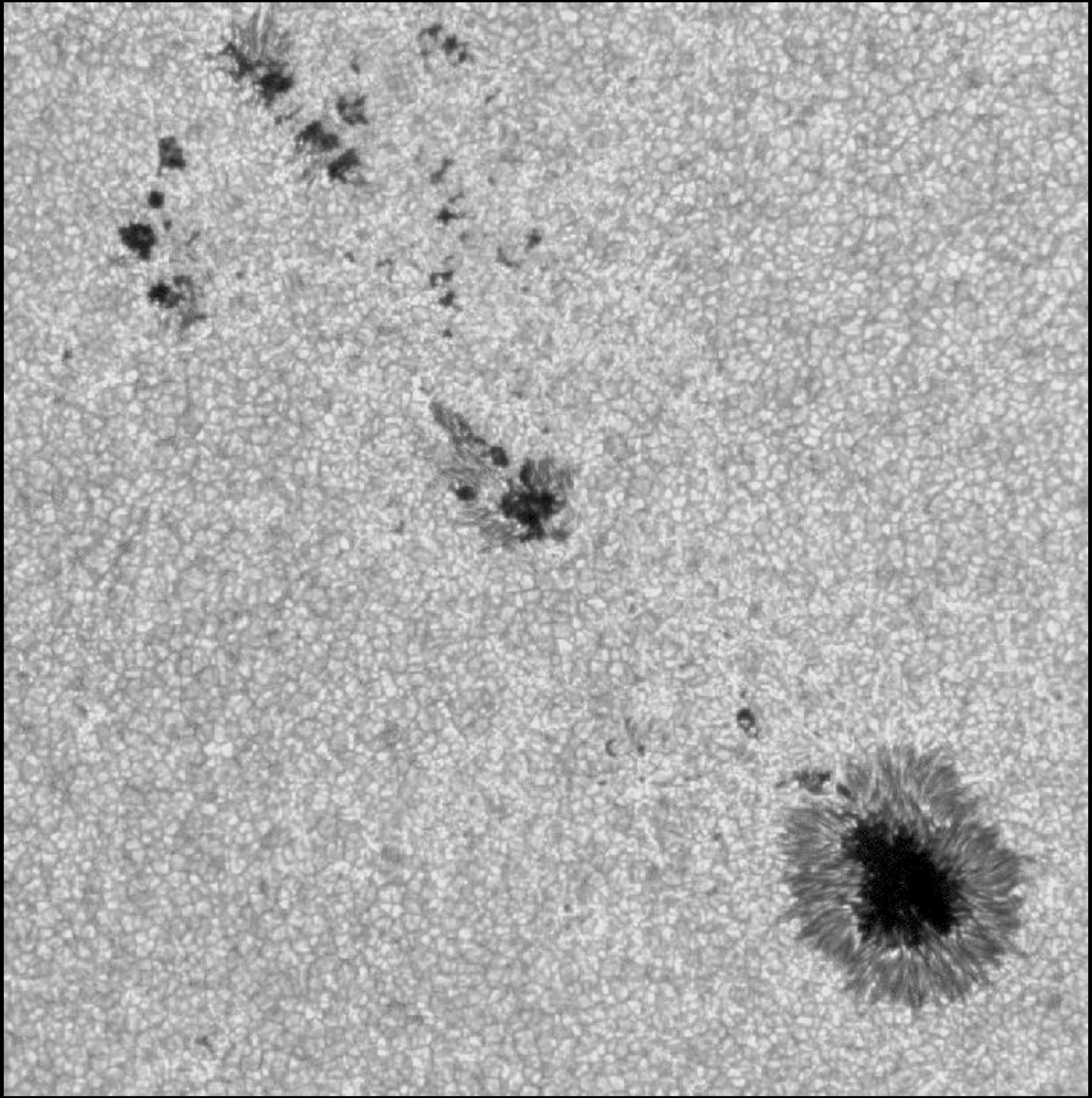
ESA/ESTEC The Netherlands

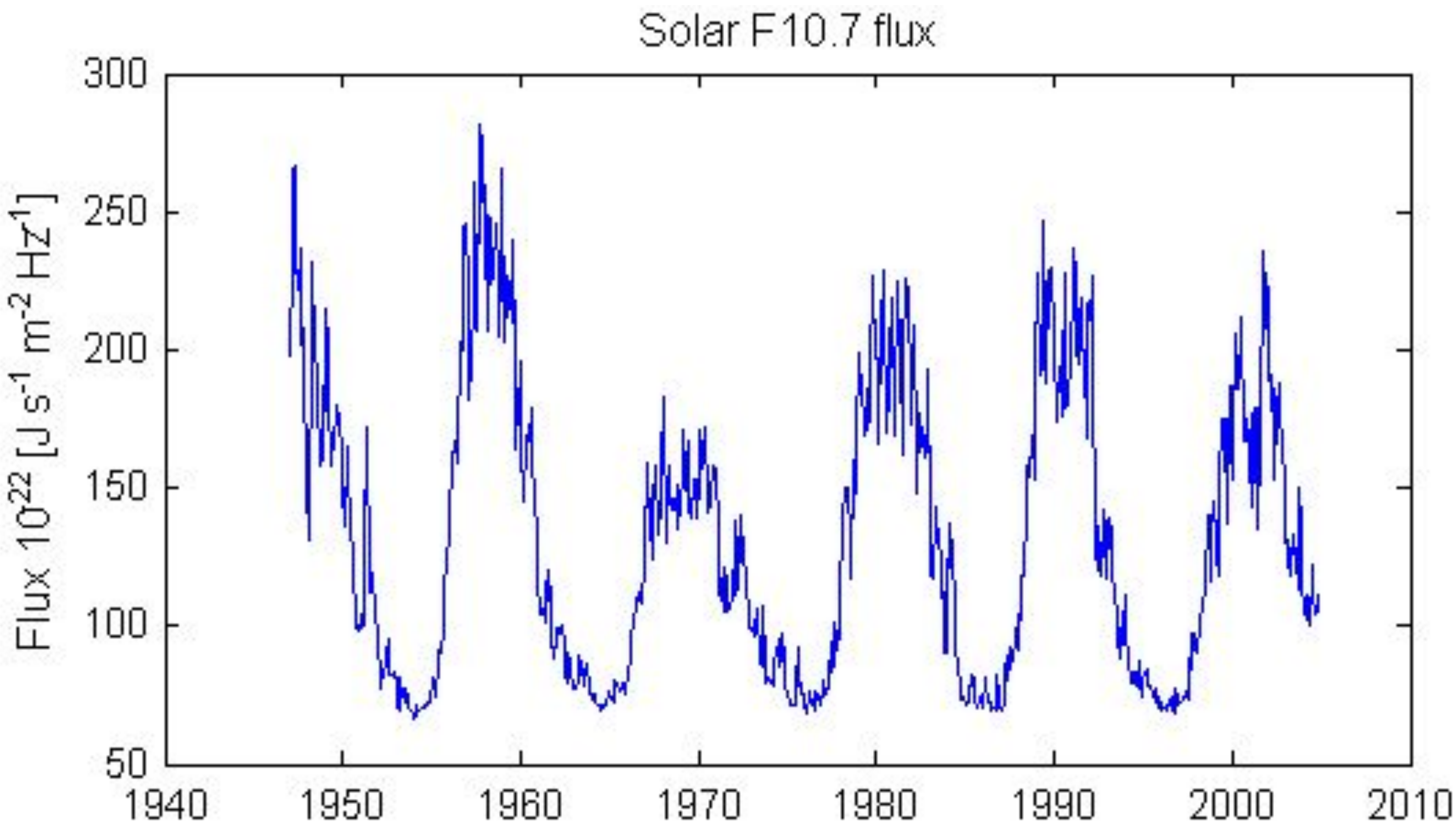
NOAA/NGDC Boulder

The Solar Cycle

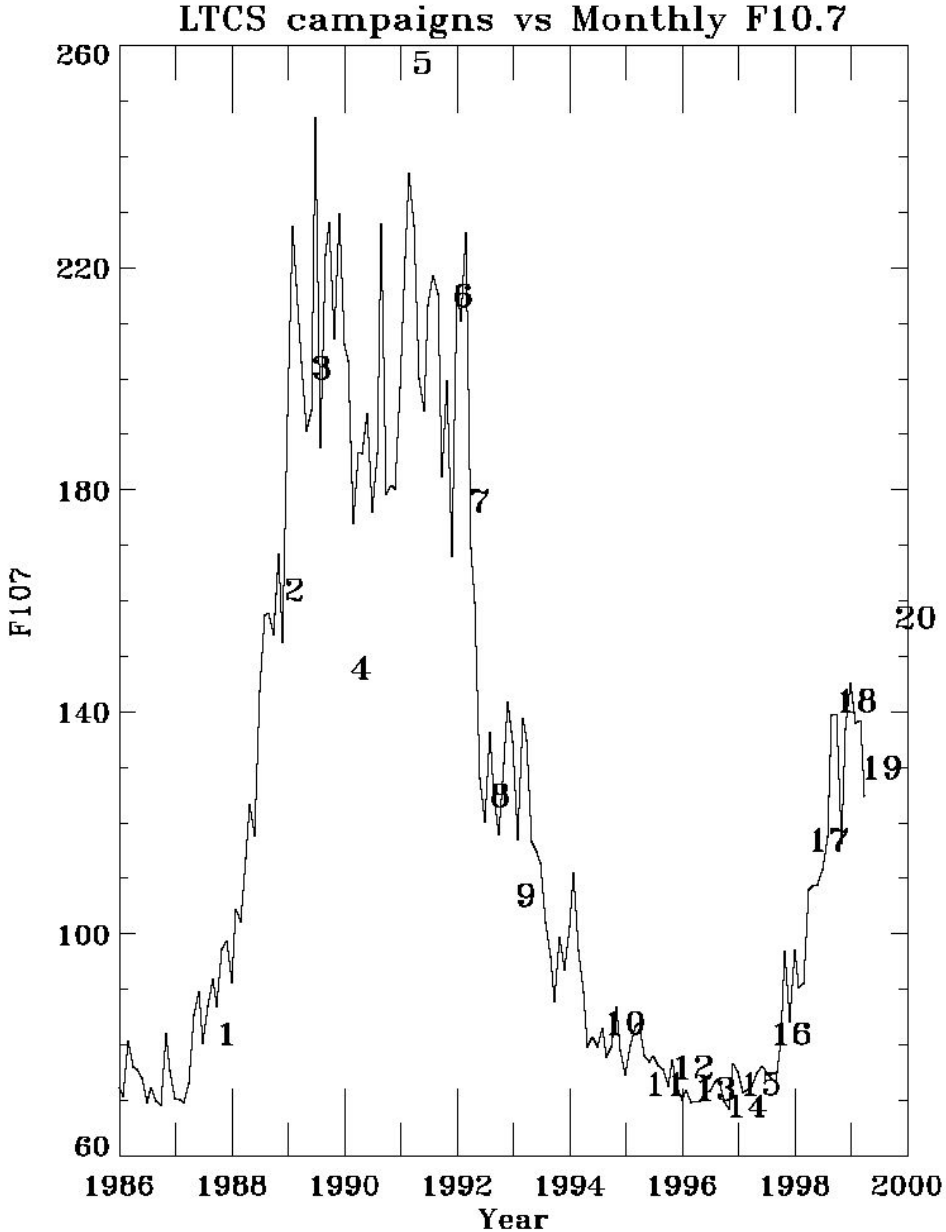
- The Sun experiences substantial changes in its activity with a period of ~11.2 years:
  - Increased number of sunspots
  - Increased number of energetic particle ejection
  - Increase in the mean energy of particles

- The activity is measured through the radiation intensity measured at a wavelength of 10.7 cm

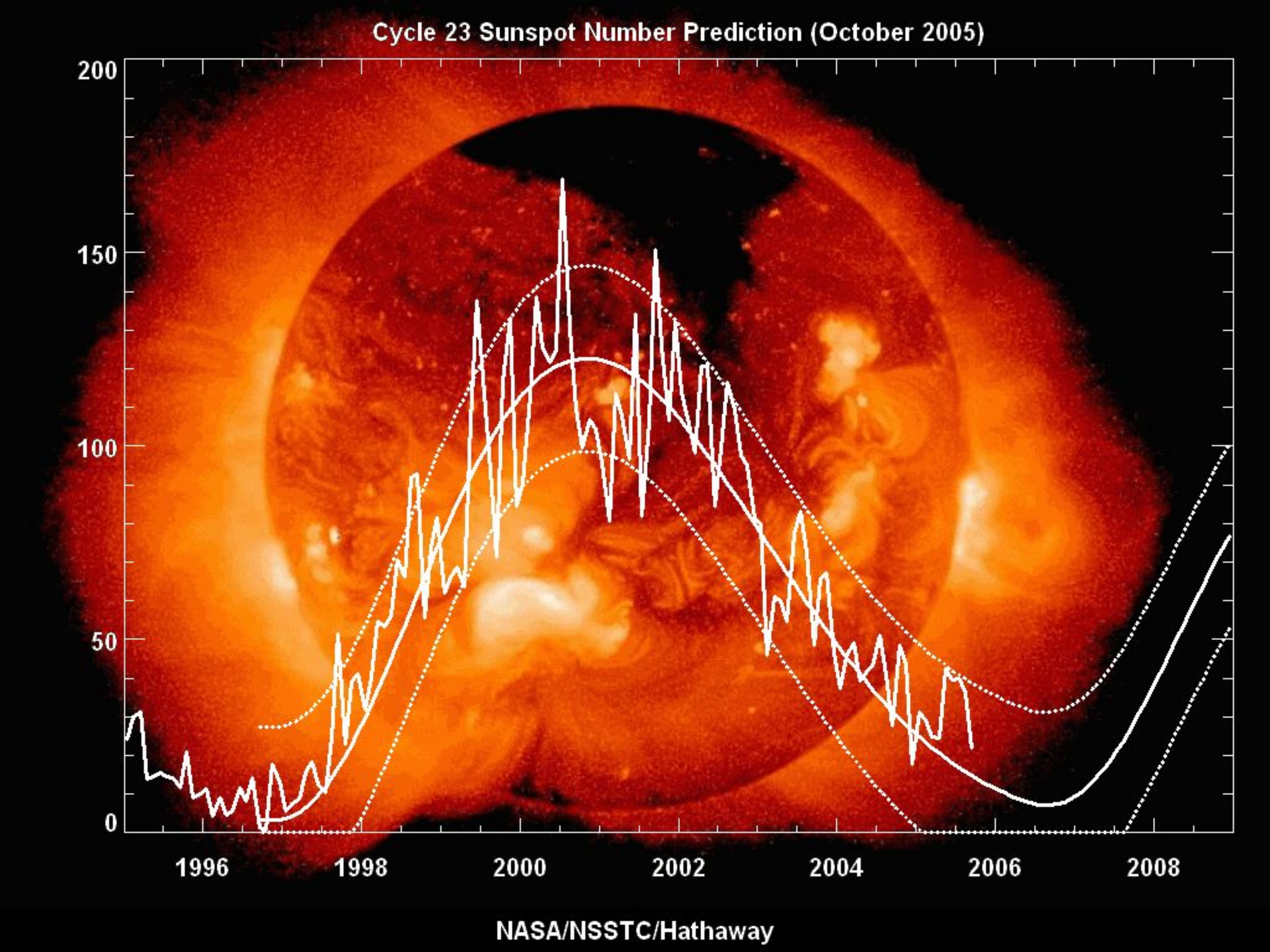


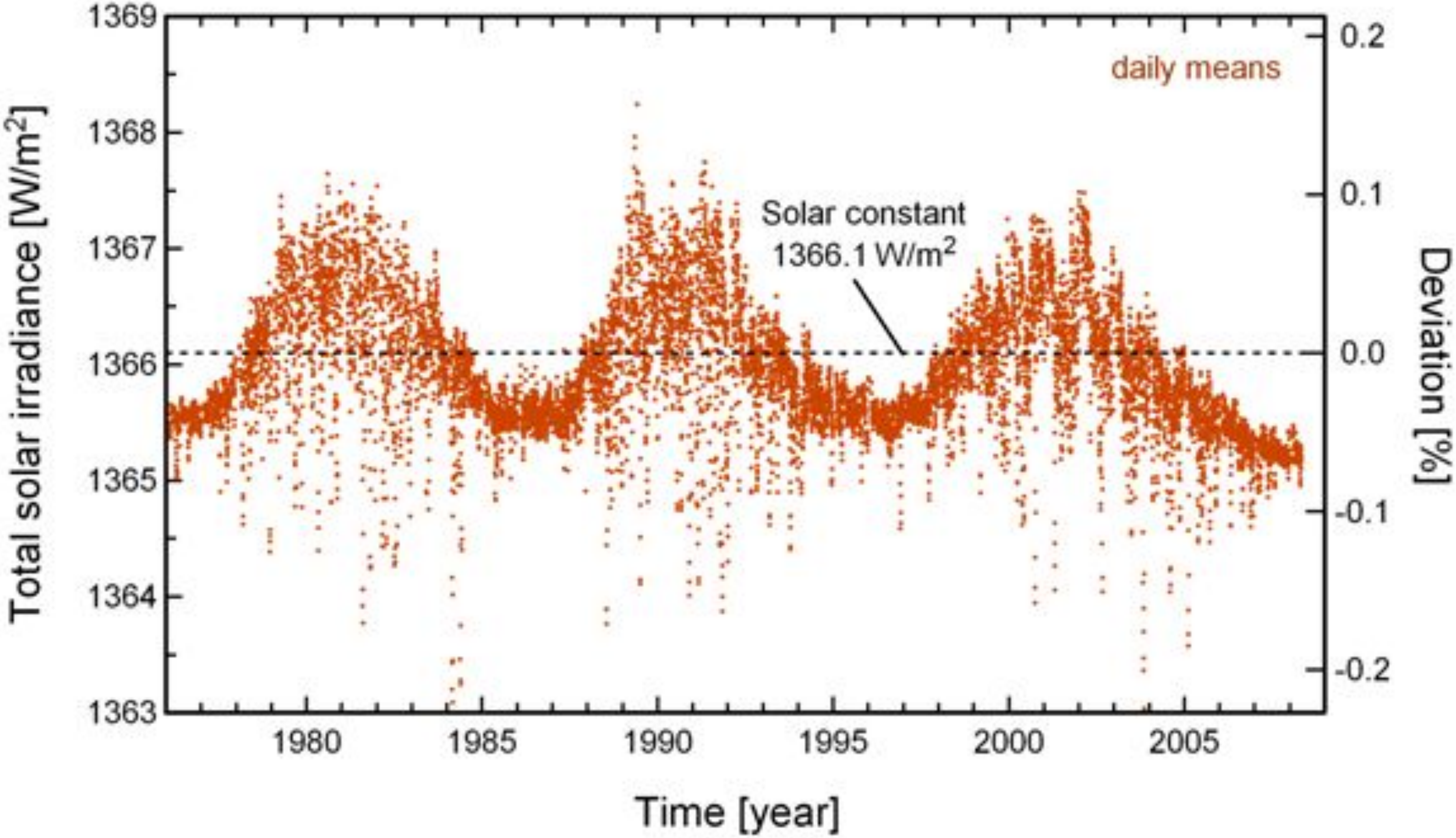


Variation of the F10.7 index throughout the last 60 years



The structure of the F10.7 peaks is highly variable and difficult to predict


Cycle 23 Sunspot Number Prediction (October 2005)
200
150
100
50
0
1996
1998
2000
2002
2004
2006
2008
NASA/NSSTC/Hathaway


daily means
Solar constant
1366.1 W/m2
Total solar irradiance [W/m2]
Deviation [%]
Time [year]
1363
1364
1365
1366
1367
1368
1369
0.2
0.1
0.0
-0.1
-0.2
1980
1985
1990
1995
2000
2005

The Upper Atmosphere

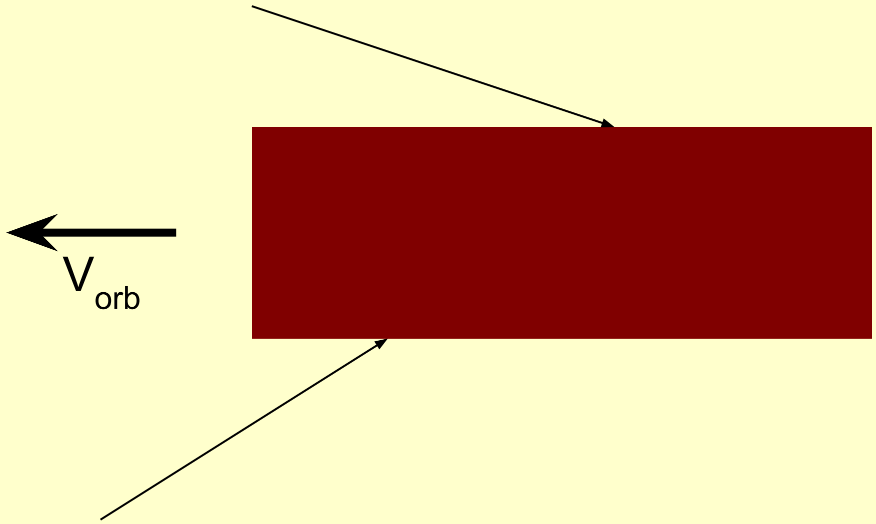
- The atmosphere has no clear limits in height (but legally ends at 100 km above Earth's surface)
- Chemical species varies with height and solar activity
- Satellites decay by atmospheric drag if initial orbit is less than 1000 km at perigee

$$a = -0.5\left(\frac{C_D A}{m}\right)\rho v^2$$

- One of the most popular models is MSISE90

The Upper Atmosphere

- For most satellites $C_D \approx 1.90 - 2.60$
- The presence of solar panels induce a lateral drag due to the thermal movement of the atmospheric constituents



Maxwell-Boltzmann Distribution

- The particles of a gas at (macroscopic) temperature T move at different speeds. These speeds follow the Maxwell-Boltzmann distribution

$$f(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right)$$

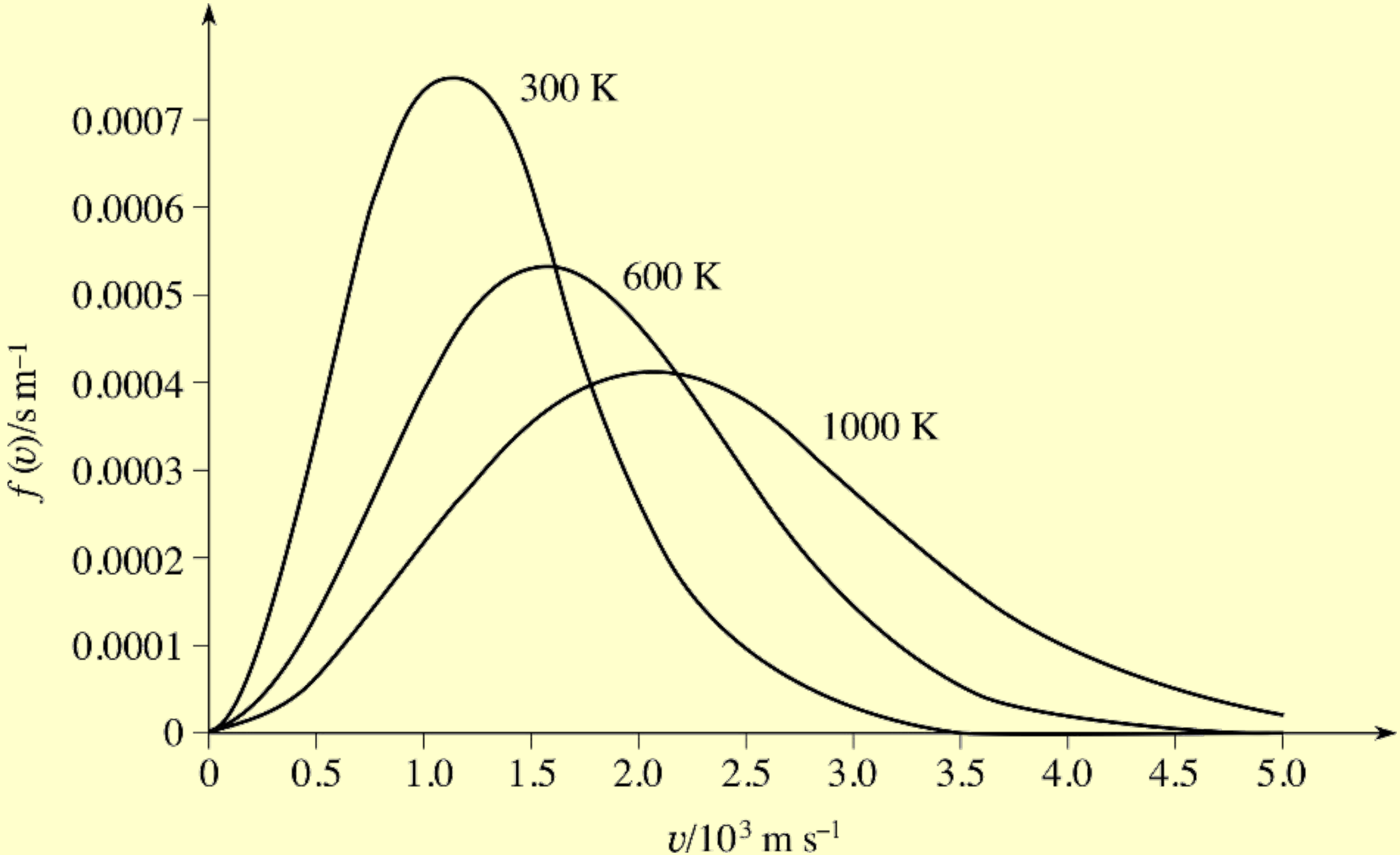
Maxwell-Boltzmann Distribution

- Then, the probable, mean, and rms velocities are

$$v_p = \left(\frac{2kT}{m}\right)^{1/2}$$

$$\langle v \rangle = \int_0^\infty v f(v) dv = \left(\frac{8kT}{\pi m}\right)^{1/2}$$

$$v_{rms} = \left(\int_0^\infty v^2 f(v) dv\right)^{1/2} = \left(\frac{3kT}{m}\right)^{1/2}$$



300 K
600 K
1000 K
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
f (v)/s m⁻¹
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
v/10³ m s⁻¹

Knudsen number

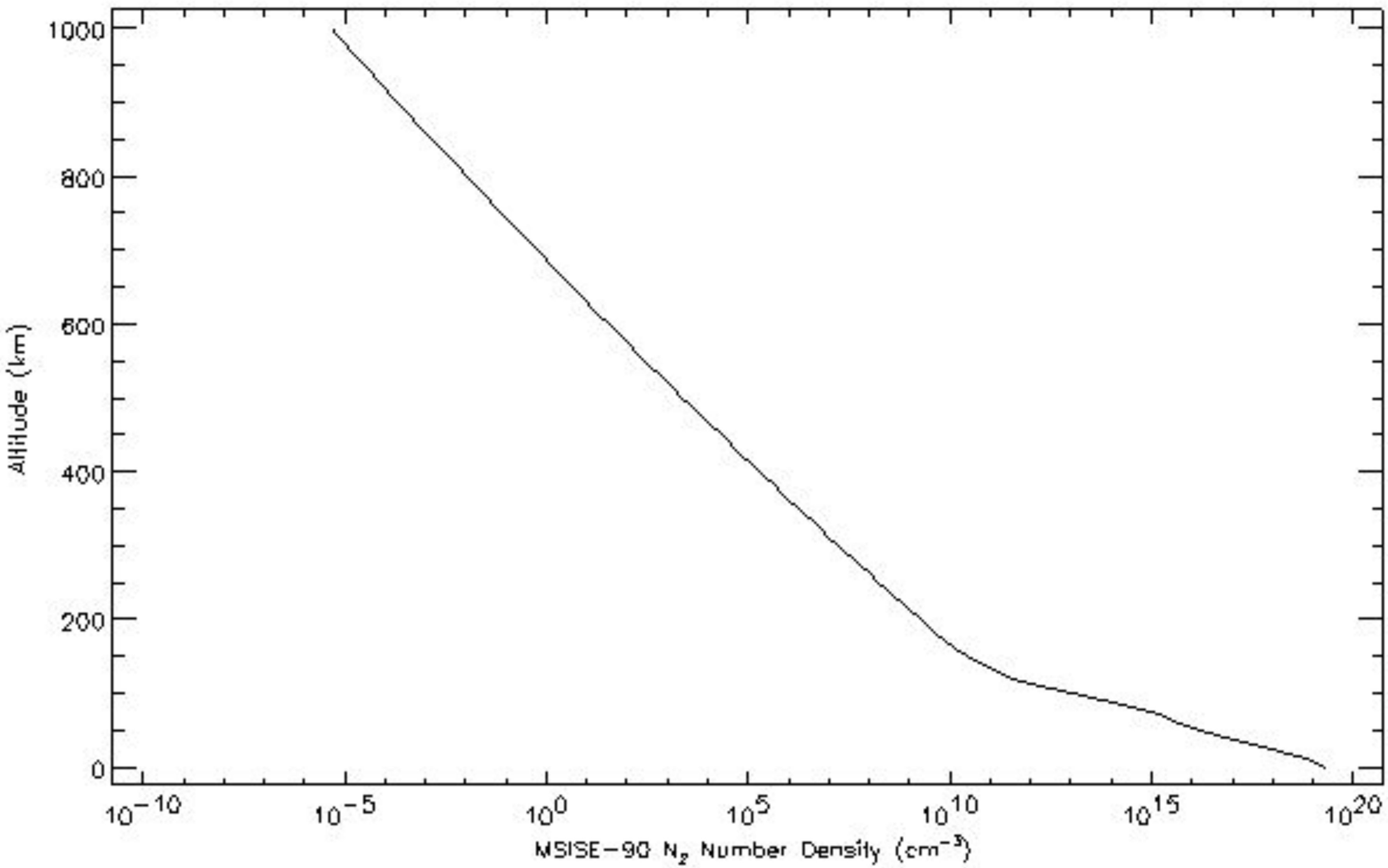
- Measures whether the satellite moves in a continuum medium (Kn < 1) or in a free molecular flow (Kn > 10)
- It is defined as

$$Kn = \frac{\lambda}{L}$$

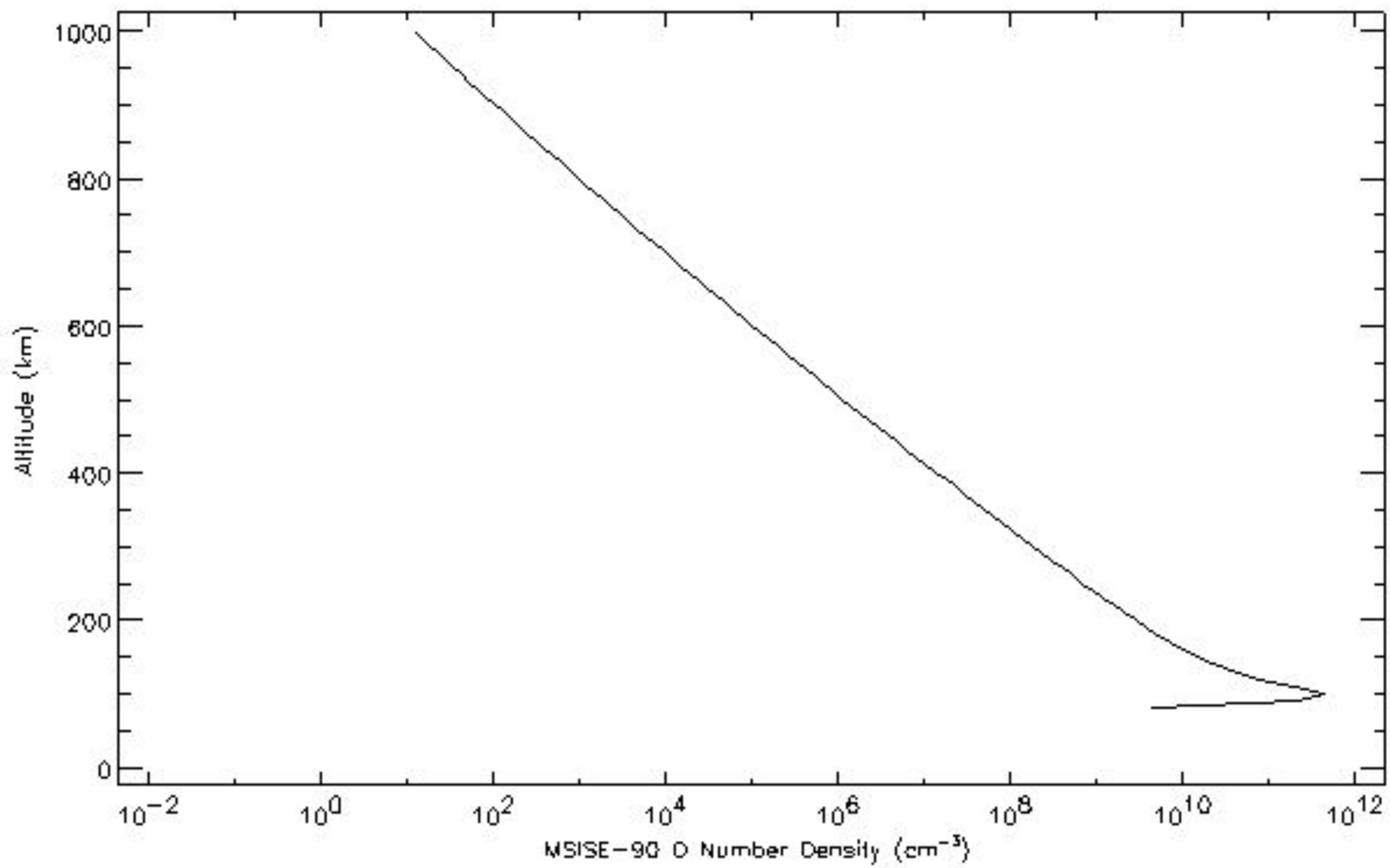
$$\lambda = \frac{k_B T}{\sqrt{2}\,\pi\,\sigma^2\,P}$$

where λ is the mean free path (given above for a Maxwell-Boltzmann distribution) and *L* is the typical dimension of the satellite.

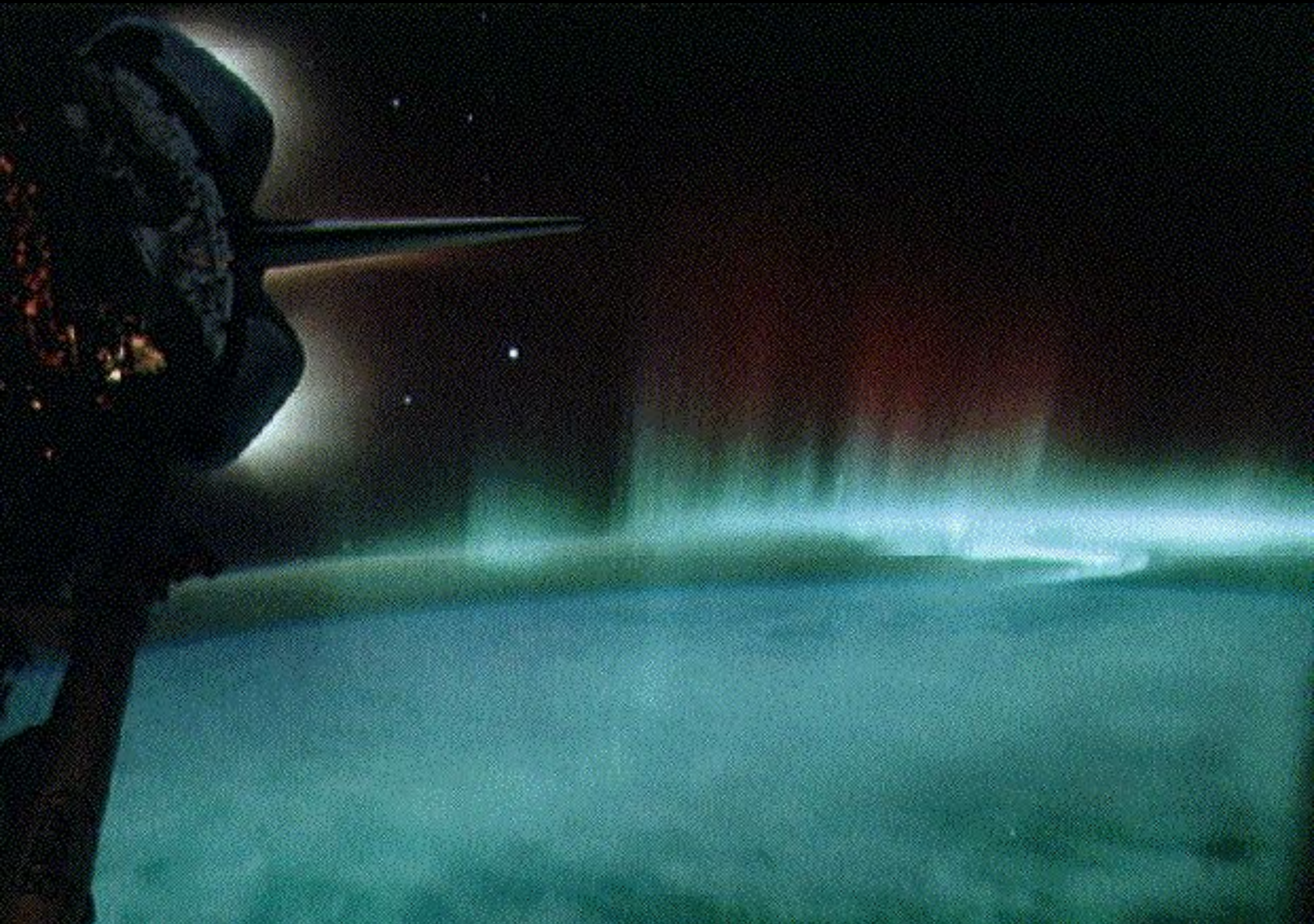
- In LEO *Kn* >> 1 always

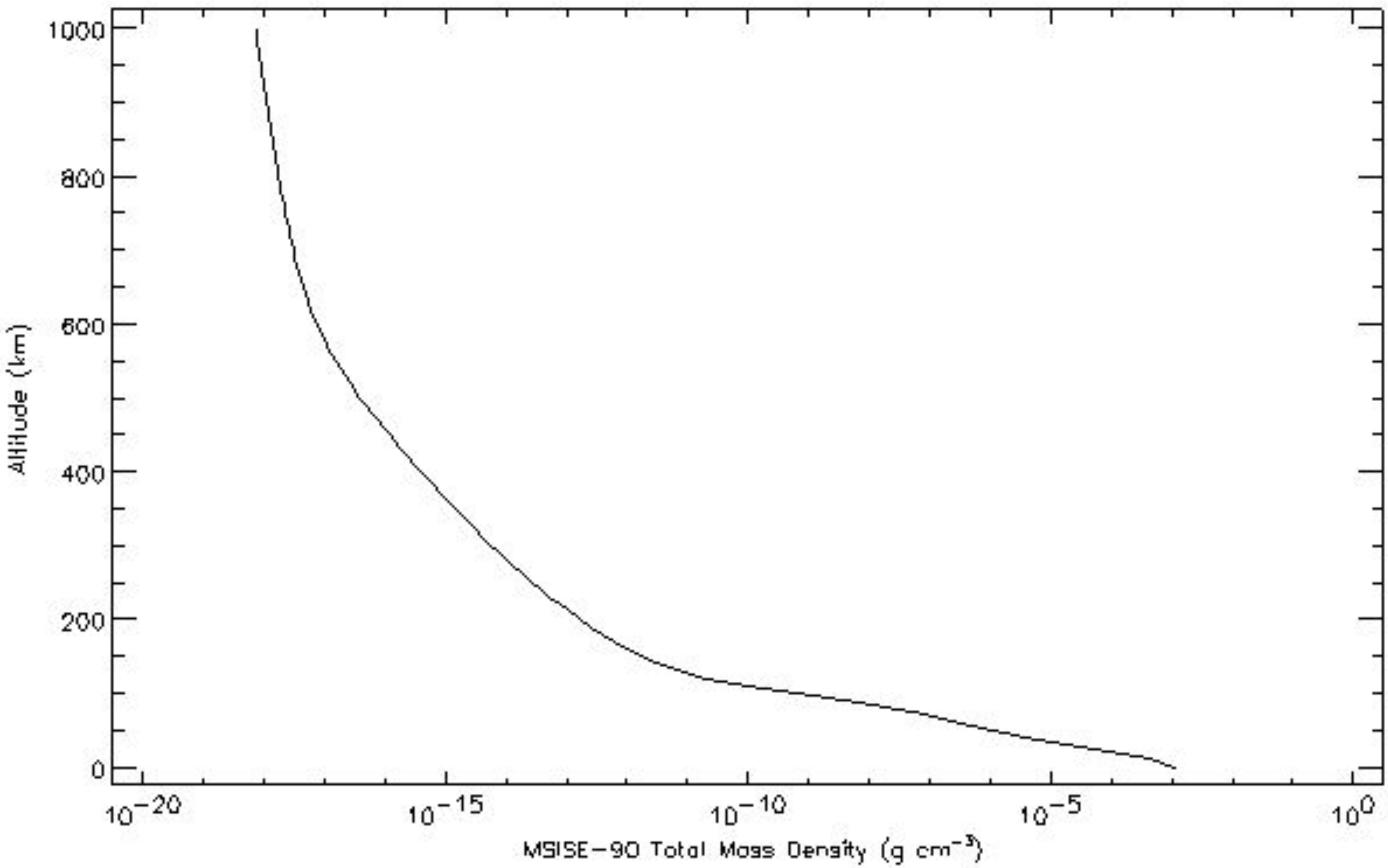


1000
800
600
400
200
0
Altitude (km)
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
MSISE-90 N_2 Number Density (cm^{-3})



1000
800
600
400
200
0
Altitude (km)
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
MSISE-90 O Number Density (cm^{-3})





1000
800
600
400
200
0
Altitude (km)
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
MSISE-90 Total Mass Density (g cm^{-3})

The Upper Atmosphere

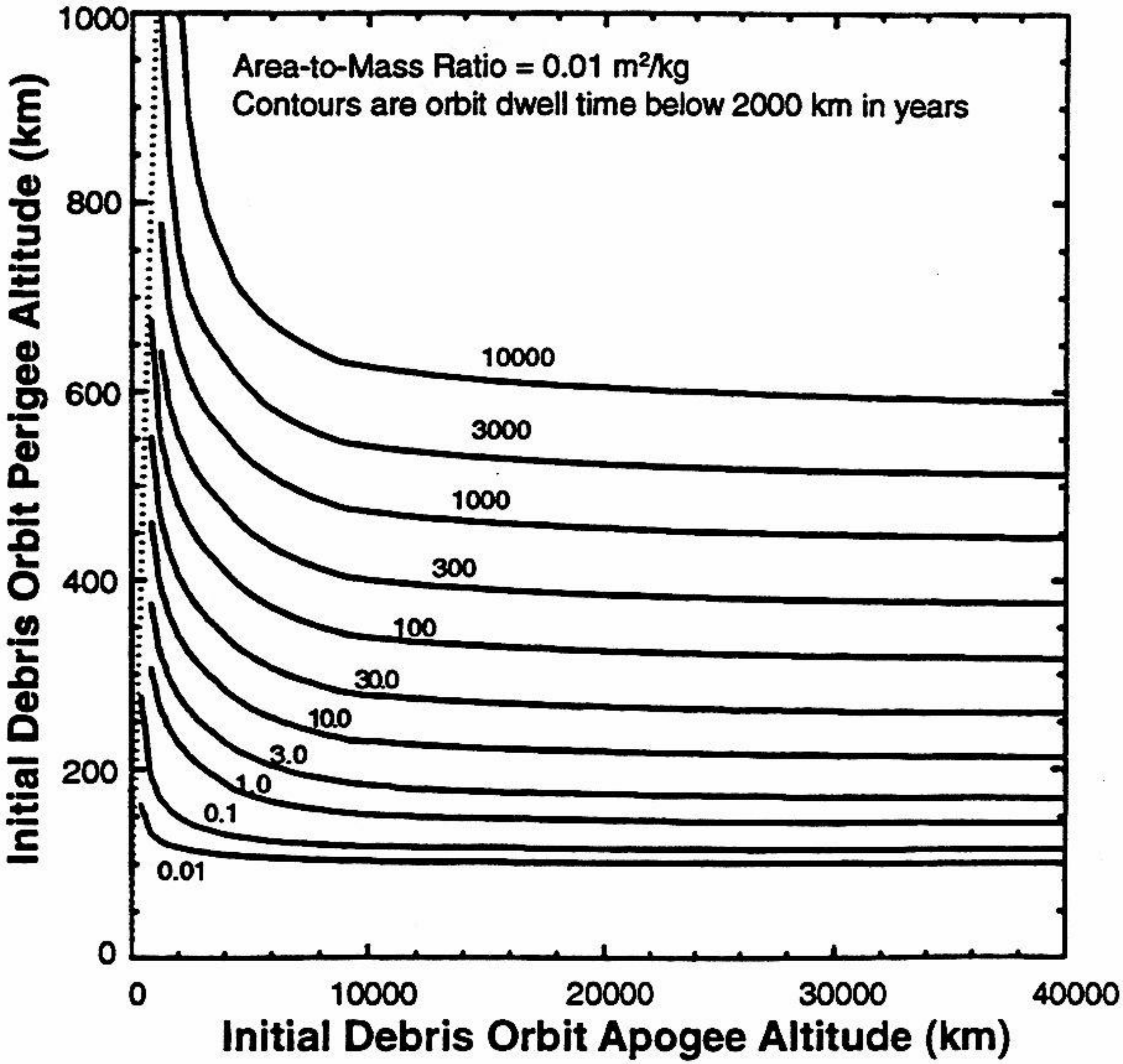
- The Upper atmosphere is affected by the intensity of solar and geomagnetic activity
  - Density variations at heights of 500 to 800 km can be of a factor of 2 due to changes in solar activity
  - Geomagnetic activity is too short to be of much impact on satellites orbital lifetimes
- The region between 120 km and 600 km belongs to the thermosphere (with T in the range 600 K to 1200 K)
  - Heated by XUV

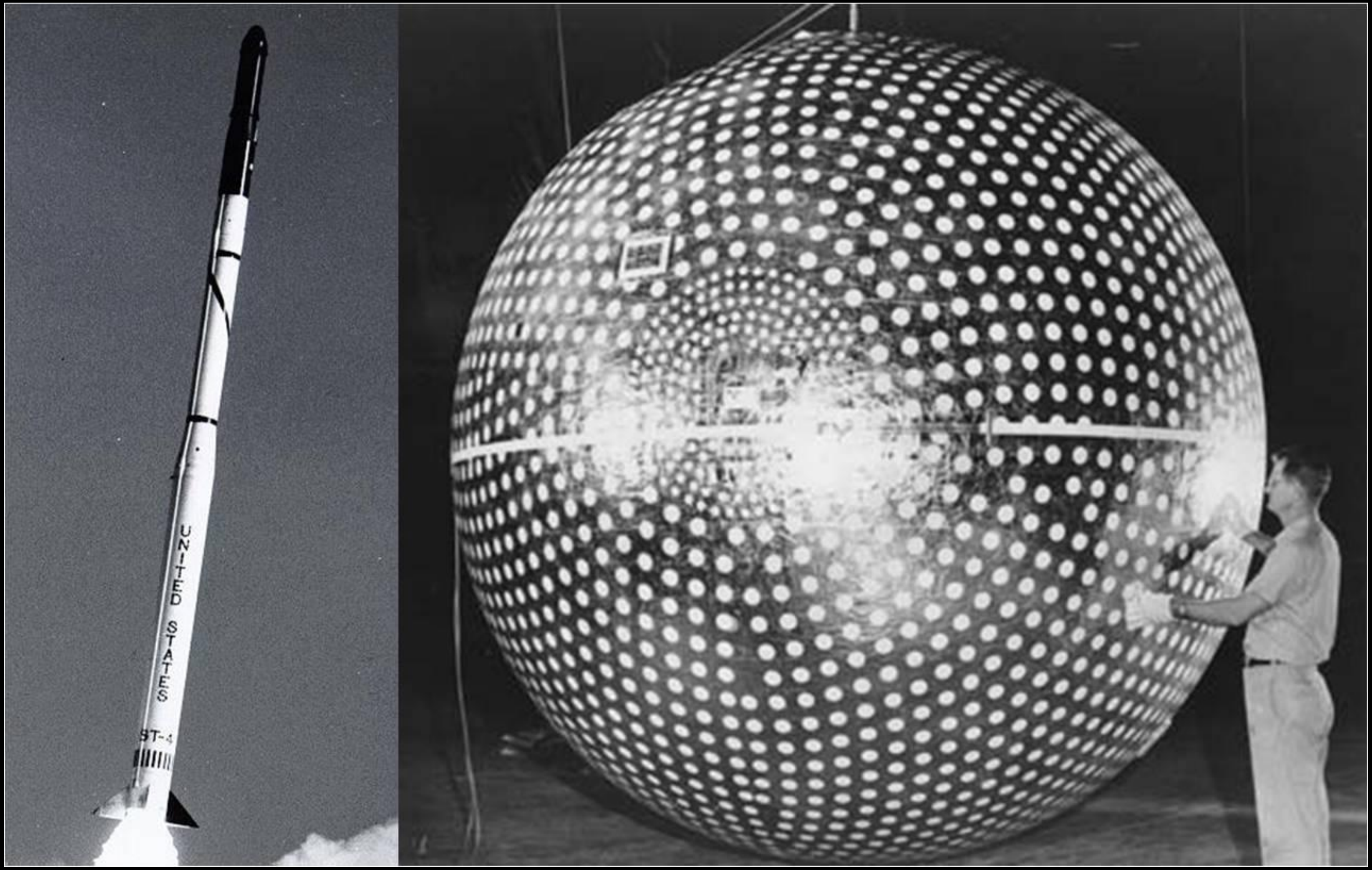
Effects of the Upper Atmosphere

- Aerodynamic drag which can lead to orbit decay
  - Depends of ballistic coefficient

$$BC = \frac{m}{C_D A}$$

- Aerodynamic lift, that can interact with attitude control
- Aerodynamic heating, with impact on thermal control and damages to the spacecraft at very low orbits
- Chemical interactions with exposed surfaces (particularly true for the reaction of atomic oxygen with organic polymers)


Area-to-Mass Ratio = 0.01 m²/kg
Contours are orbit dwell time below 2000 km in years
10000
3000
1000
300
100
30.0
10.0
3.0
1.0
0.1
0.01
Initial Debris Orbit Perigee Altitude (km)
Initial Debris Orbit Apogee Altitude (km)
0
200
400
600
800
1000
10000
20000
30000
40000



Mass = 7 kg | Apogee = 2581 km

Diameter = 3.7 m | Perigee = 635 km

BC = 0.326 kg/m^2 (C_D=2.0) | inclination = 38.8º

Effects of the Upper Atmosphere

- Aerodynamic drag which can lead to orbit decay
  - Depends of ballistic coefficient

$$BC = \frac{m}{C_D A}$$

- When solar panels have large surface, lateral drag represents a significant contribution to C_D
- Aerodynamic lift, that can interact with attitude control
- Aerodynamic heating, with impact on thermal control and damages to the spacecraft at very low orbits
- Chemical interactions with exposed surfaces (particularly true for the reaction of atomic oxygen with organic polymers)
- Sputtering reactions degrade optical properties of exposed surfaces

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

A Swarm of Femtosatellites to Determine the Density of the Lower Thermosphere

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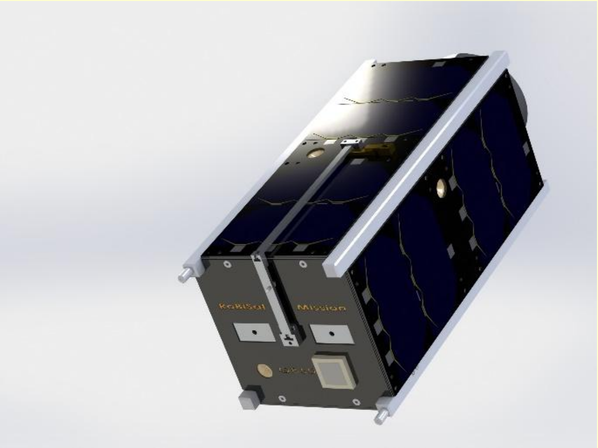
Why study the thermosphere?

- The thermosphere extends from 90 to approximately 600 km
- The region of interest for this mission is the lower thermosphere, between 100 and 250 km
  - It is badly known, as there are (almost) no satellites there
- The thermospheric density shows some trends difficult to understand
  - Secular decrease of average density (Emmert, Lean, & Picone, 2010)
  - The chemical composition may be changing
- In the thermosphere there are fast winds (up to several hundreds of meters per second)
- This region controls to a high degree the uncertainties of satellite re-entry predictions

Similar missions

- POPACS (Polar Orbiting Passive Atmospheric Calibration Spheres)
  - Three 0.1 m spheres of 1.0, 1.5, and 2.0 kg
  - Observed from the ground (TLE). Orbital elements changes give the density
  - Initial orbit: perigee at 355 km, apogee at 1455 km
- QB50: in-situ measurements of the lower thermosphere by means of 50 2U and 3U CubeSats (36 launched so far)
  - Ion neutral mass spectrometer
  - Flux-φ-probe experiment
  - Multi-needle Langmuir probe



Direct density determination

- Our plan is to measure the deceleration of a spherical femtosatellite due to drag

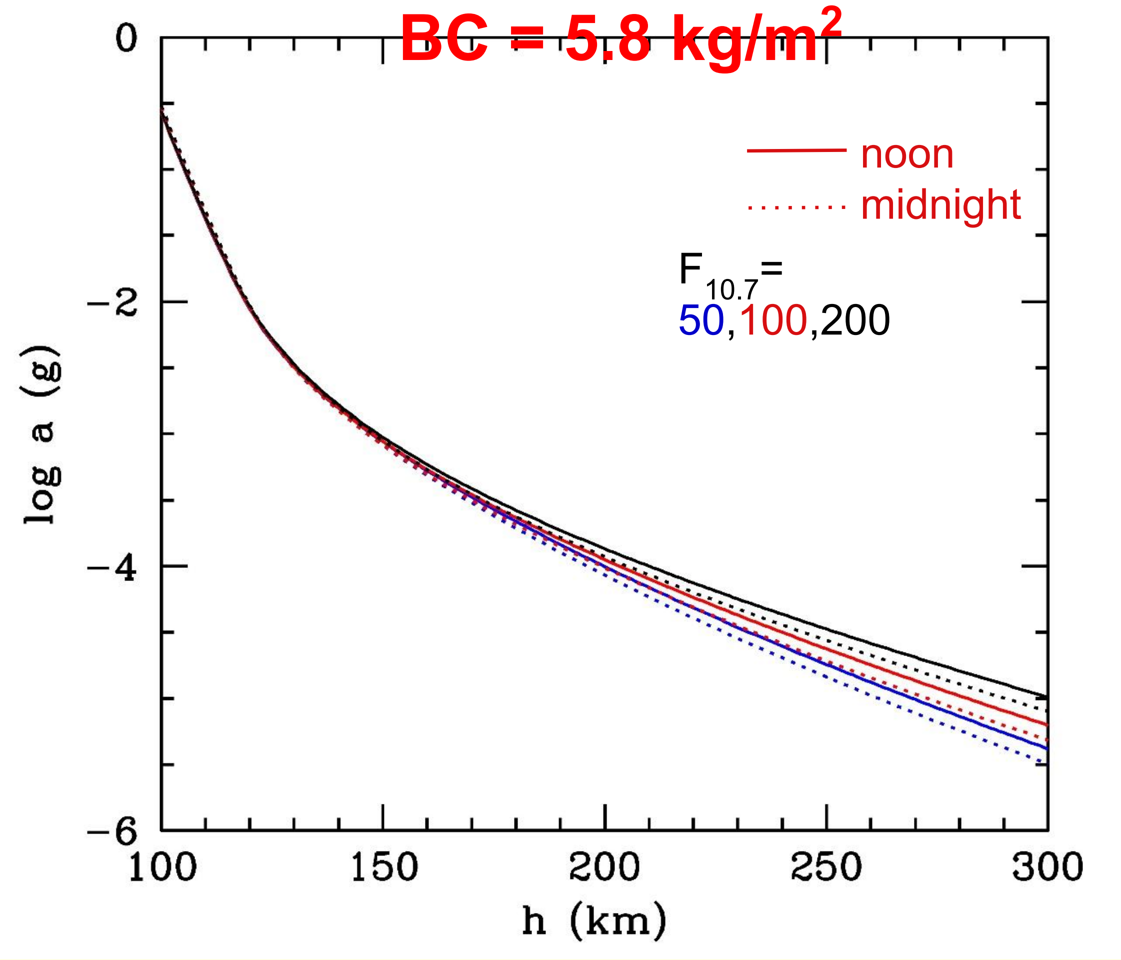
$$\vec{a} = \frac{1}{2}\rho v_{\mathrm{rel}}^2 \frac{SC_{\mathrm{D}}}{m} \hat{v}_{\mathrm{rel}}$$

where v_{rel} is the velocity of the satellite relative to the air; the rest of symbols have their usual meaning

- The acceleration will be measured by a MEMS accelerometer
- Position and time tags will be provided by a MEMS GPS

m=0.1 kg, C_D=2.2 d=5 cm

BC = 5.8 kg/m^2



NRL-MSISE00 model

Our project

- Our plan is to set up a swarm of tens to hundreds of spherical femtosatellites to **simultaneously** determine the **density** of the lower thermosphere in **multiple locations**
- The swarm should be spread along many different orbital planes, and evenly distributed over each orbital plane (pearl necklace)
- Given the high density of the lower thermosphere, the swarm would survive approximately for one week

The femtosatellite (1)

- Spherical shape
  - mass of 100 grams (maximum)
  - Centre of mass in the geometric centre
  - Diagonal inertia tensor with equal principal moments

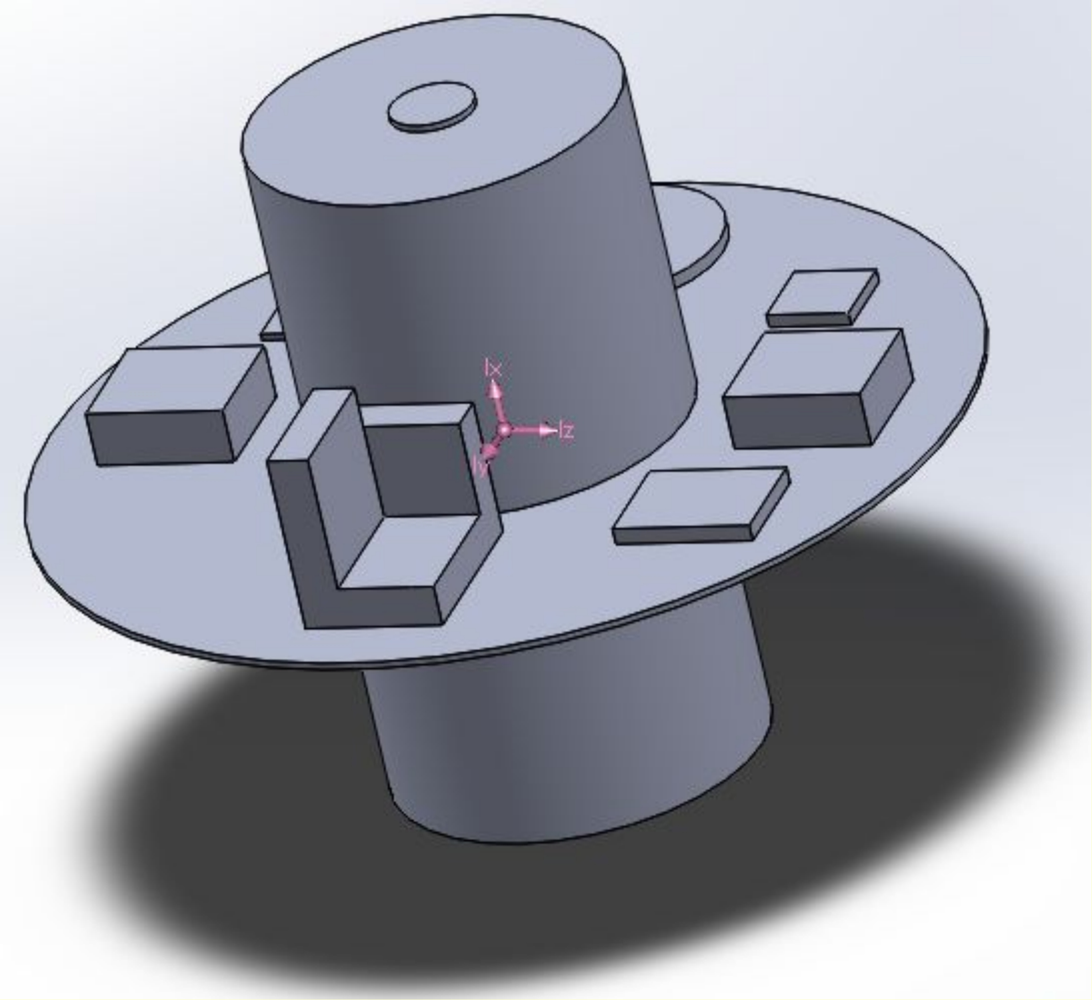
$$I = \begin{pmatrix} K & 0 & 0 \\ 0 & K & 0 \\ 0 & 0 & K \end{pmatrix} = K\,\mathbb{I} \qquad I = \begin{pmatrix} 37971.2 & -17.4 & -15.7 \\ -17.4 & 37596.6 & 238.8 \\ -15.7 & 238.8 & 37727.4 \end{pmatrix} \mathrm{g}\, mm^2$$

  - Electronics embedded in a spherical aerogel
- Sub-µg noise density MEMS accelerometer (1D)
- MEMS GPS
- Primary battery (one week endurance)

The femtosatellite (2)

- Omnidirectional antenna
- Only Tx mode
- No ADCS subsystem
- Passive thermal control + aerogel
- Very low ballistic coefficient: about 6 kg/m^2

Electronics layout of the femtosatellite



The accelerometers

- The accelerometers are the heart of the mission.
- We have identified two very sensitive MEMS accelerometers

Property	Units	ServoK-Beam (Kistler)	SF1500S.A (Colybris)
Accel. range	g	±2.5	±3.0
Sensitivity	V/g	1.5	1.2±0.1
T coefficient	μg/K	100	-200
Noise density	μg/√Hz	0.8	0.3
Op. Temperature	K	233 – 358	233 – 358

Accelerometer's noise

- The noise (N) is given by the noise density (N_0) and the bandwidth (BW):

$$N = N_0 \sqrt{1.6 \times BW}$$

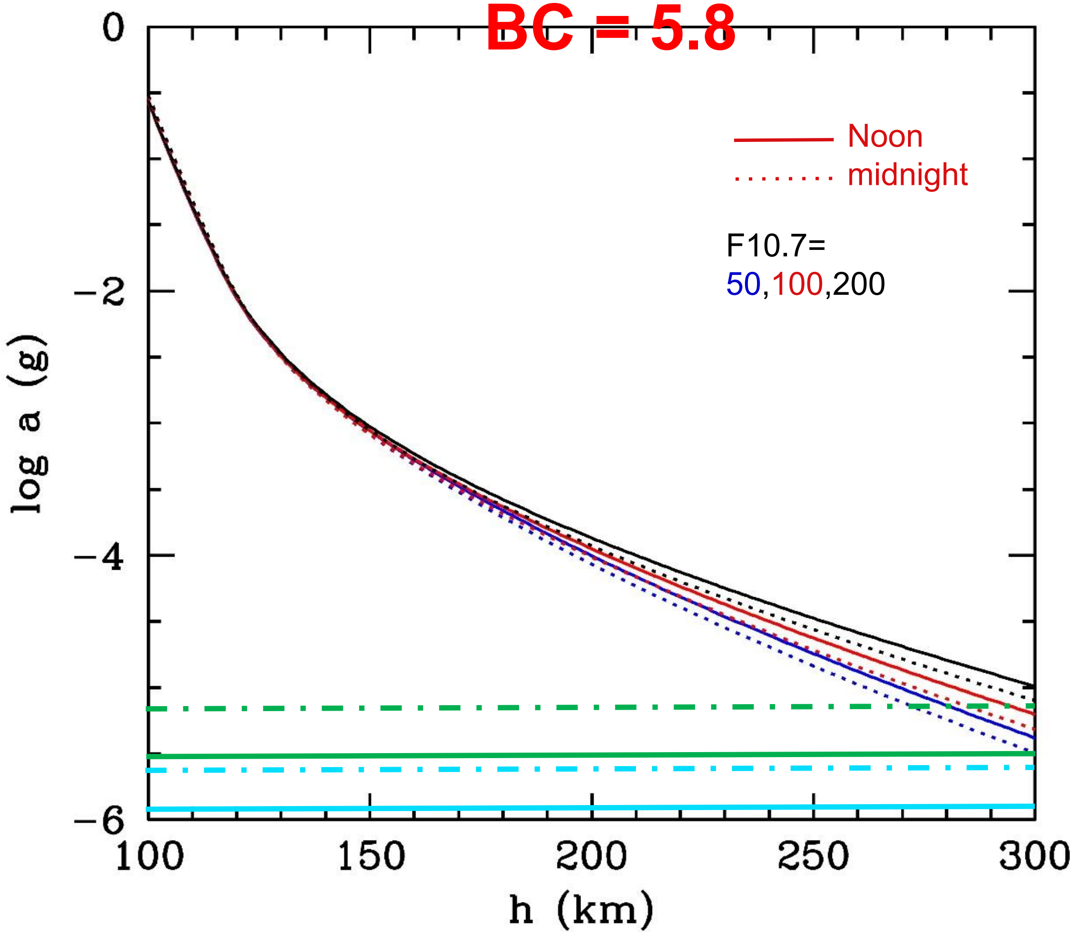
Then, the accelerometers proposed for this mission have noise floors of 3.2 and 1.2 μg (BW=10 Hz), which allow their use up to heights over 300 km (we assume significant measures down to a level equal to twice the noise floor), which is above our maximum desired altitude

m=0.1 kg, C_D=2.2 d=5 cm

BC = 5.8

Kistler

Colybris



Continuous line: noise floor
dot-dashed line: twice noise floor

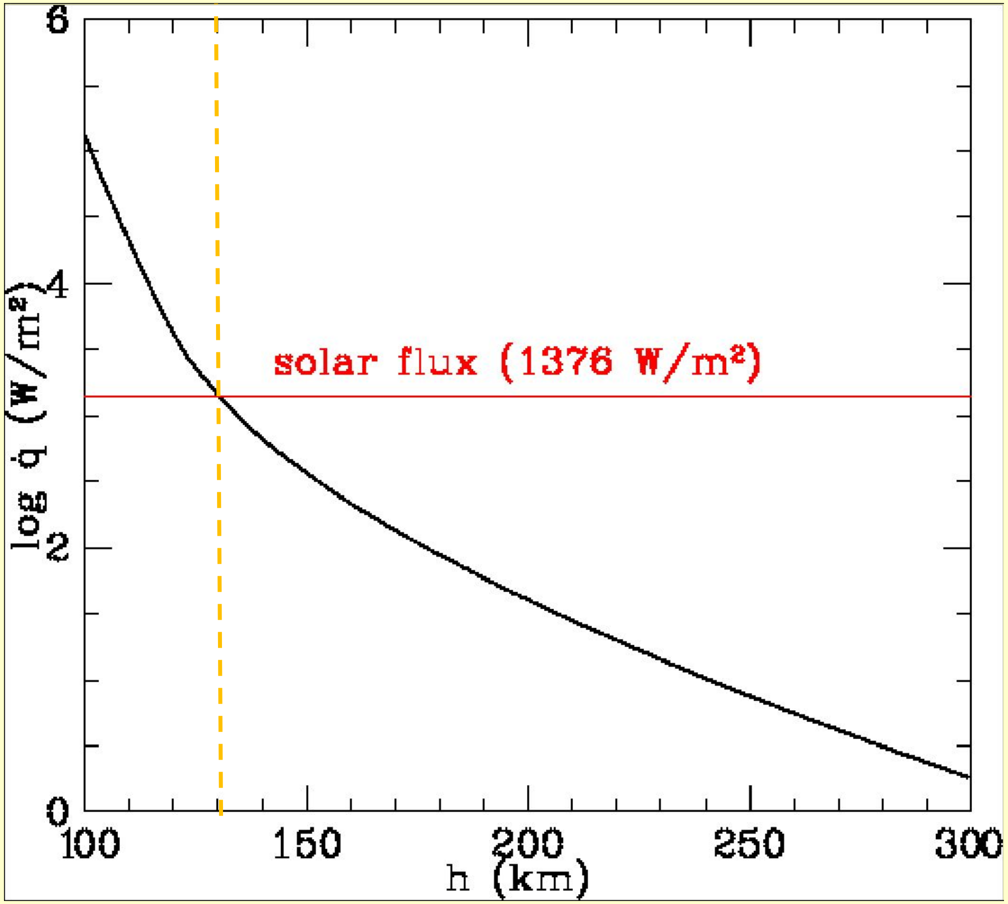
Data gathering

- Each femtosatellite would determine its deceleration once per second (locations 8 km apart)
- The data would also include position and time (both obtained through the GPS)
- GPS positions allow a cross-checking of accelerometer-derived density data
- Approximately 400 kbit per orbit and satellite
- Data downlinked to high latitude ground stations
- Orbits would be polar (to cover the whole Earth)

Thermal control

- Passive system
- Electronics embedded in a spherical aerogel
  - Very low mass
  - Exceedingly low thermal conductivity
- Aerothermal heating does not allow orbits below around 130 km (hard limit, as the following expression is valid for stagnation points)

$$q_{\text{aero}} \leq 3.05 \times 10^{11} \sigma \left(\frac{\rho}{\rho_{sl}}\right) \left(\frac{v}{v_{\text{circ}}}\right)^3 \frac{\text{W}}{\text{m}^2}$$



solar flux (1376 W/m²)
log q̇ (W/m²)
h (km)
0
2
4
6
100
150
200
250
300

Noise sources and uncertainties

- Rotational state of the satellites
- Non-orthogonality of the 1D accelerometers (cross-linking)
- Drag coefficient: we have taken C_D = 2.2 as a first guess, but it should be determined as a function of the thermospheric properties
- Non-circularity of the orbit: this will induce a small but detectable acceleration. It can be corrected with GPS data
- Wind velocity: the velocity and direction of thermospheric winds would affect the drag (by changing the relative velocity to the remaining atmosphere)
- Gravitational field: small noise due to non-spherically symmetric gravitational field (corrected with high-precision *Grace* data)

Open problems

- Launch and dispersion of a truly Earth-covering swarm
- Accelerometer testing
- Battery’s limited endurance (“Remove before flight” system)
- Aerogel and its protective cover

Conclusions and future work

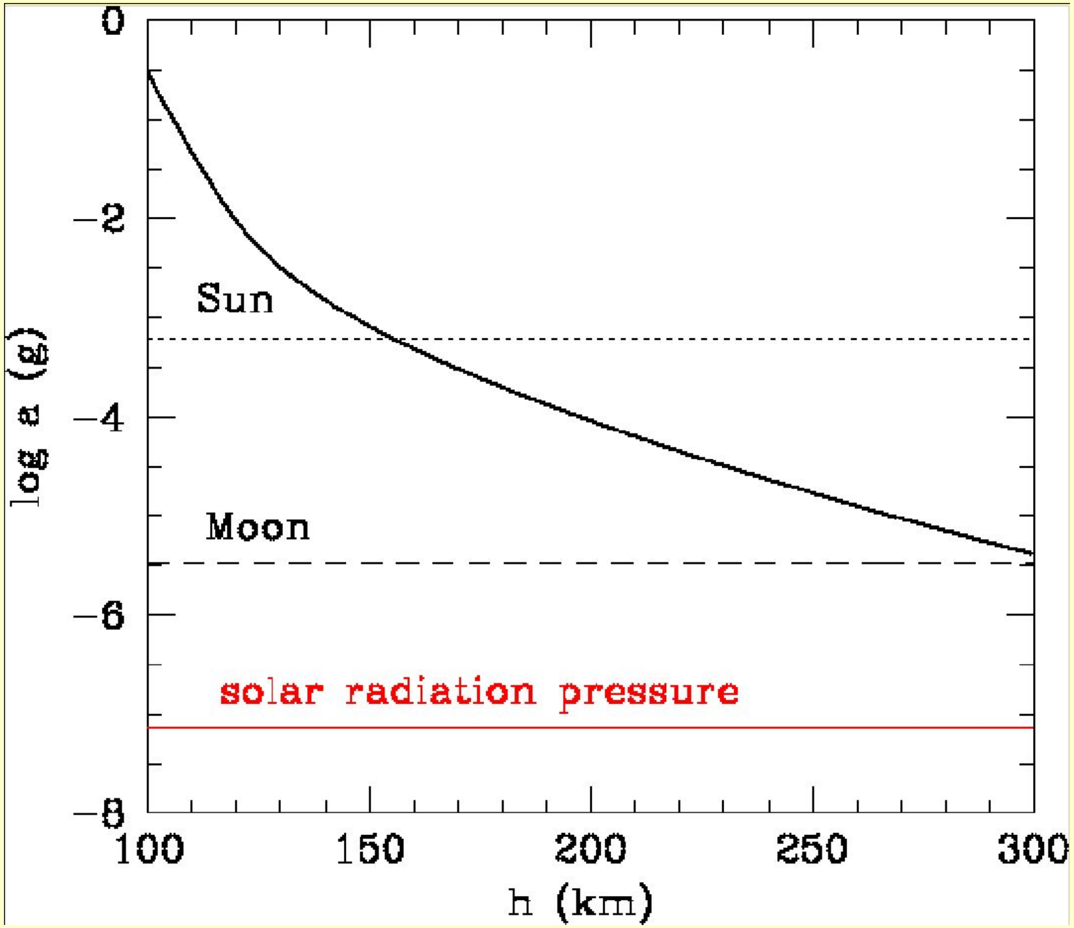
- The mission seams feasible
- Launch and dispersion still an issue

- Accelerometer testing
- Flatsat testing
- Deployer design

Mass and power budgets

System	Mass (g)	Voltage (V)	I (mA)	P (W)	Oper. T (C)
Accelerometer (3)	6	6	8.5	0.051	–40 to +85
GPS	1	2.85	10	0.029	–40 to +85
Flash memory	1	1.7	23	0.039	–30 to +85
Transmitter (on)	1	3.3	500	1.65	–40 to +85
Microcontroller	3	3	0.6	0.02	–40 to +125
Volt. Reg. (2)	4	3.6	3.5	0.026	–55 to +150
Battery	53	3.6	–	–	–55 to +85
Total (peak)	69	–	–	1.802	–30 to +85
Total (low)				0.168	

M=0.1 kg, C_D=2.2 D=5 cm



The swarm as a space debris hazard

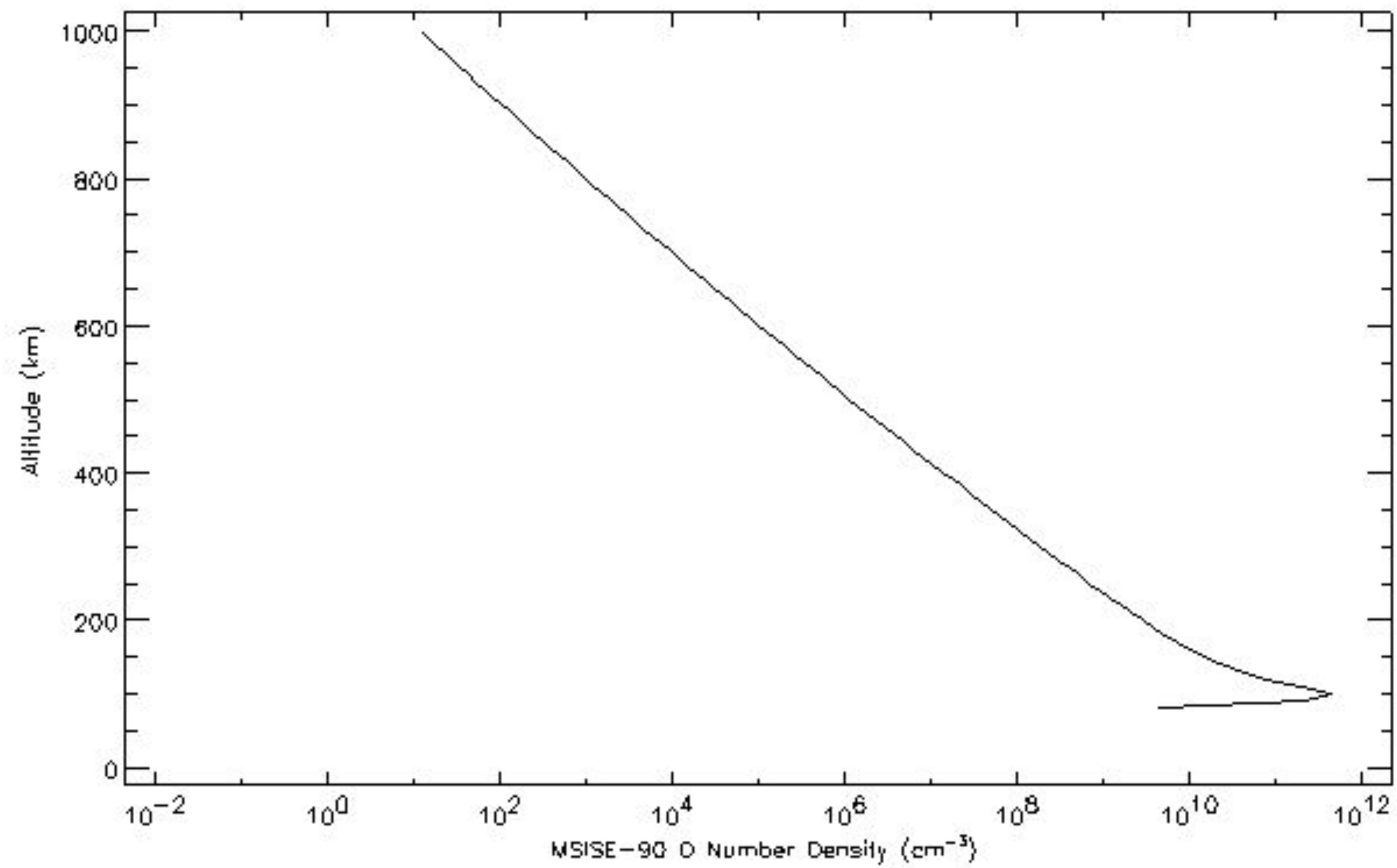
- A large swarm could be seen as a potential risk for other space agents
- The low BC and altitude warrants a lifetime of one week (perhaps 10 days) before re-entry
- At these low altitudes there are no satellites (except some intelligence ones on their perigee?)

Atomic oxygen erosion (1)

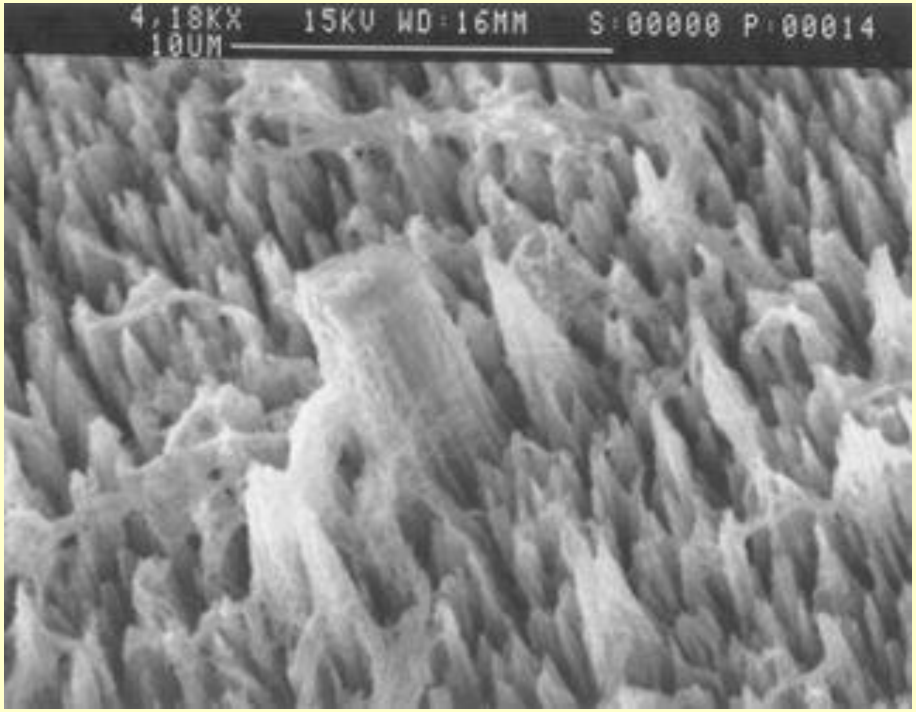
- In the height range 120–800 km, the main atmospheric constituent is atomic oxygen (AO)
- It is a highly reactive species, that can degrade in a matter of weeks several kind of surfaces (especially organic materials, like Kapton or Kevlar)
- The mass lost by AO impacts is

$$dm = \rho_t \, RE \, \phi_{AO} \, dA \, dt$$

being ρ_t the density of the target, φ_{AO} the flux (cm^{-2} s^{-1}) of atomic oxygen, and *RE* the efficiency of the reaction (in cm^3 per impacting AO).


1000
800
600
400
200
0
Altitude (km)
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
MSISE-90 O Number Density (cm^{-3})

Atomic oxygen erosion (2)



The surfaces exposed to AO erosion change substantially its surface roughness, and with it its thermal and optical properties

Atomic oxygen erosion (3)

- The RE, which can be a function of T, impacting energy and AO flux, must be experimentally determined

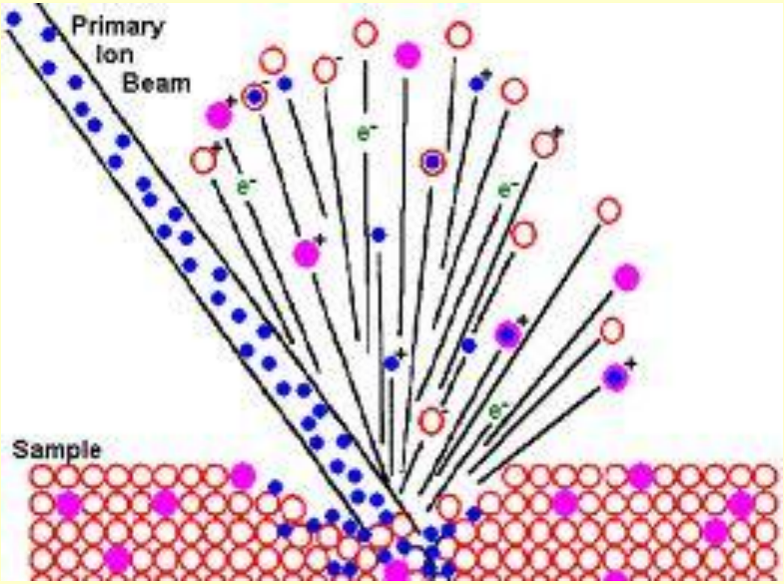
Target material	**RE** (10^{-24} cm^3/AO particle)
C	0.9 – 1.7
Teflon	0.03 – 0.50
Mylar	1.5 – 3.9
S13GLD (paint)	0.0
Kapton	1.4 – 2.5

Sputtering (1)

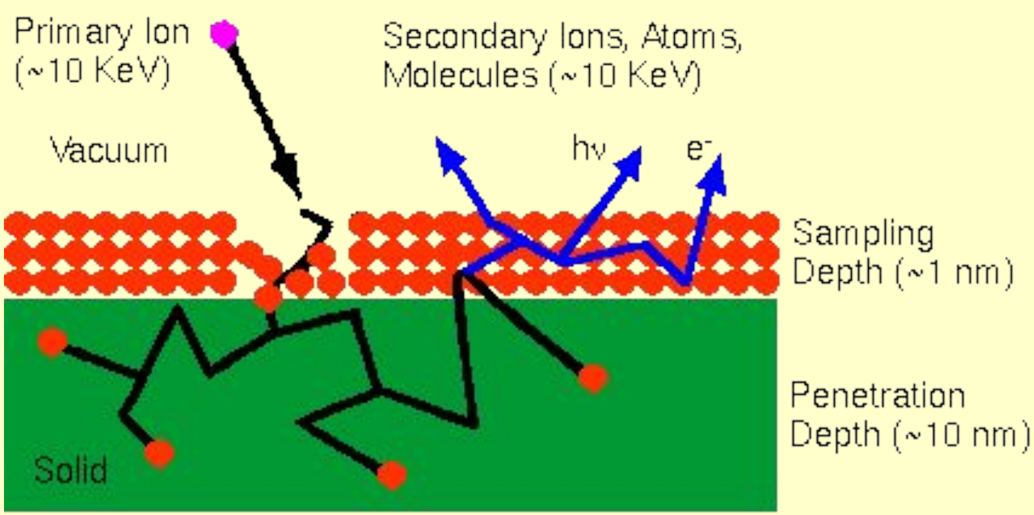
- The kinetic energy of atmospheric molecules is high enough to attack the exposed surfaces

Height (km)	**Velocity** (km/s)	**Atomic/molecular energy** (eV/particle)					
		H	He	O	N_2	O_2	Ar
200	7.8	0.3	1.3	5.0	8.8	10.1	12.6
400	7.7	0.3	1.2	4.9	8.6	9.8	12.2
600	7.6	0.3	1.1	4.7	8.3	9.5	11.8
800	7.4	0.3	1.1	4.5	7.9	9.0	11.2

Sputtering (2)



Sputtering (in the case of an intense ion beam)



Effects of sputtering on the surface of the exposed material

Sputtering (3)

- Sputtering is produced when the impacting particles has an energy over the thresholds given by

$$E_{th} = \begin{cases} 8U\left(\dfrac{m_t}{m_i}\right)^{-1/3} & m_t / m_i < 3 \\ U\left[\gamma\left(1-\gamma\right)\right] & m_t / m_i > 3 \end{cases}$$

$$\gamma = \frac{4\, m_t\, m_i}{\left(m_t + m_i\right)^2}$$

where U is the binding energy of the target, m_t the mass of one of its particles, and m_i the mass of the impacting molecule.

Sputtering (4)

- The total flux of sputtered material is given by

$$\phi_{sp} = \sum_i \int_{E_{th,i}}^{\infty} Y_i(E)\phi_i(E)\,dE$$

$$Y_i(E) = Q_i \left(\frac{E}{E_{th,i}}\right)^{1/4} \left(1 - \frac{E_{th,i}}{E}\right)^{7/2}$$

where φ_i is the flux of impacting particles with energies in the bin E and $E+dE$. The sum is performed upon all the i impacting species.

Sputtering (5)

Target	Threshold energy for the impacting species (eV)					
	O	O_2	N_2	Ar	He	H
Ag	12	14	13	17	25	83
Al	23	29	27	31	14	28
Au	19	15	25	15	53	192
C	65	82	79	88	40	36
Cu	15	22	21	24	20	60
Fe	20	28	27	31	23	66
Ni	20	29	27	31	24	72
Si	31	39	37	42	18	40

Sputtering (6)

Target	Sputtering yield at 100 eV per impact (atoms/particle)					
	O	O_2	N_2	Ar	He	H
Ag	0.265	0.498	0.438	0.610	0.030	-
Al	0.026	0.076	0.060	0.110	0.020	0.010
Au	0.154	0.266	0.244	0.310	-	-
C	-	-	-	-	0.008	0.008
Cu	0.385	0.130	0.499	0.600	0.053	-
Fe	0.069	0.153	0.129	0.200	0.028	-
Ni	0.120	0.247	0.239	0.270	0.029	-
Si	0.029	0.054	0.046	0.070	0.023	0.002

High vacuum

- The exposure to the hard vacuum of space has deleterious effects for some materials
- The extremely low ambient pressure leads to outgas of certain materials (with a temperature dependence)

$$P \approx P_{vapour}$$

- Organic materials are more deeply affected than metals or alloys

Element	0.1 μm/yr	10 μm/yr	1 mm/yr
Cd	38	77	122
Zn	71	127	177
Mg	110	171	233
Au	660	890	950
Ti	920	1070	1250
Mo	1380	1630	1900
W	1780	2150	2480

Temperature needed (in Celsius) for a given evaporation rate

Contamination

- The outgassed matter from hot surfaces can be deposited onto cold surfaces, thus leading to their contamination:
  - Changes in the α/ε ratio. Thermal control problems
  - Degradation of optical surfaces. Mostly star trackers and telescopes
  - In extremely charged plasma environments, contaminants can be released in a flash discharge, thus enabling plasma effects
  - Contaminants can become polymerized, increasing its stickiness

The effects of vacuum exposure

- At 100 km in height the pressure is ~0.1 Pa, and at 350 km is ~10^{-4} Pa.
- Solar UV flux: it is not filtered by the atmosphere and, due to its high energy, can degrade exposed surfaces

Molecular contamination

- All materials have a volatile component (on the surface, or dispersed on the structure).
- These molecules are emitted and travel along ballistic trajectories (Kn>>1).
- Substantial problems for optical devices, thermal control aggravated by possible polymerization by UV light

Mechanism	**Activation energy**	**Temporal dependence**
Desorption	1 – 10 kcal/mol	t^{-1} or t^{-2}
Diffusion	5 – 15 kcal/mol	$t^{-1/2}$
Decomposition	20 – 80 kcal/mol	NA

Molecular contamination

- The mass lost by diffusion (the most relevant input) can be expressed as

$$\dot{m} = \frac{q_0 \exp\left(-E_a / RT\right)}{t^{1/2}}$$

where E_a is the activation energy, R is the universal perfect gas constant, and q_0 is a reaction constant (experimentally determined)

- The total mass lost is (assuming that q_0 is time-independent)

$$\Delta m = 2 q_0 \exp\left(E_a / RT\right)\left(t_2^{1/2} - t_1^{1/2}\right)$$

Molecular contamination transport

- The amount of mass transferred to a specific point of the satellite from other surfaces of it depends on
  - The total mass outgassed
  - The geometry of the problem, expressed in terms of the visibility factor

$$VF_{1-2} = \int\int \frac{\cos\theta \cos\phi}{\pi r^2} dA_1 \, dA_2$$

being A_1 and A_2 the emitter and receiver surfaces, respectively, and θ and φ the angles between dA_1 and dA_2

- Once all the VF have been determined, the rate of deposition is

$$\Phi = \sum_s VF_s \, \dot{m}_s \frac{1}{\rho_s}$$

Molecular contamination deposition

- A molecule impacting a surface can get stuck for a characteristic time given by

$$\tau(T) = \tau_0 \exp(E_a / RT)$$

  where $\tau_0 \sim 10^{-13}$ s.

- The thickness of contaminant increases as

$$X(t,T) = \gamma(T)\phi(t,T)$$

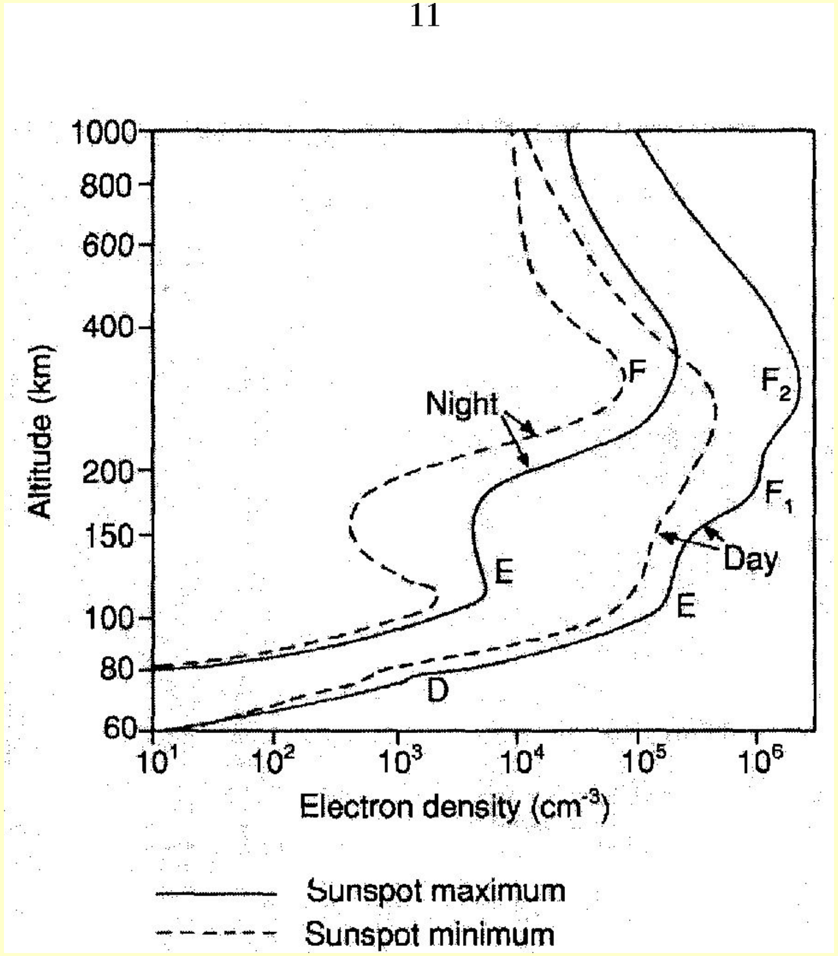
  where $\gamma(T)$ is the sticking coefficient (worst case: $\gamma = 1$, typical case, $\gamma \sim 0.1$ at 300 K), and $\varphi(t,T)$ is the arrival rate in μm/s.

ASTM E595

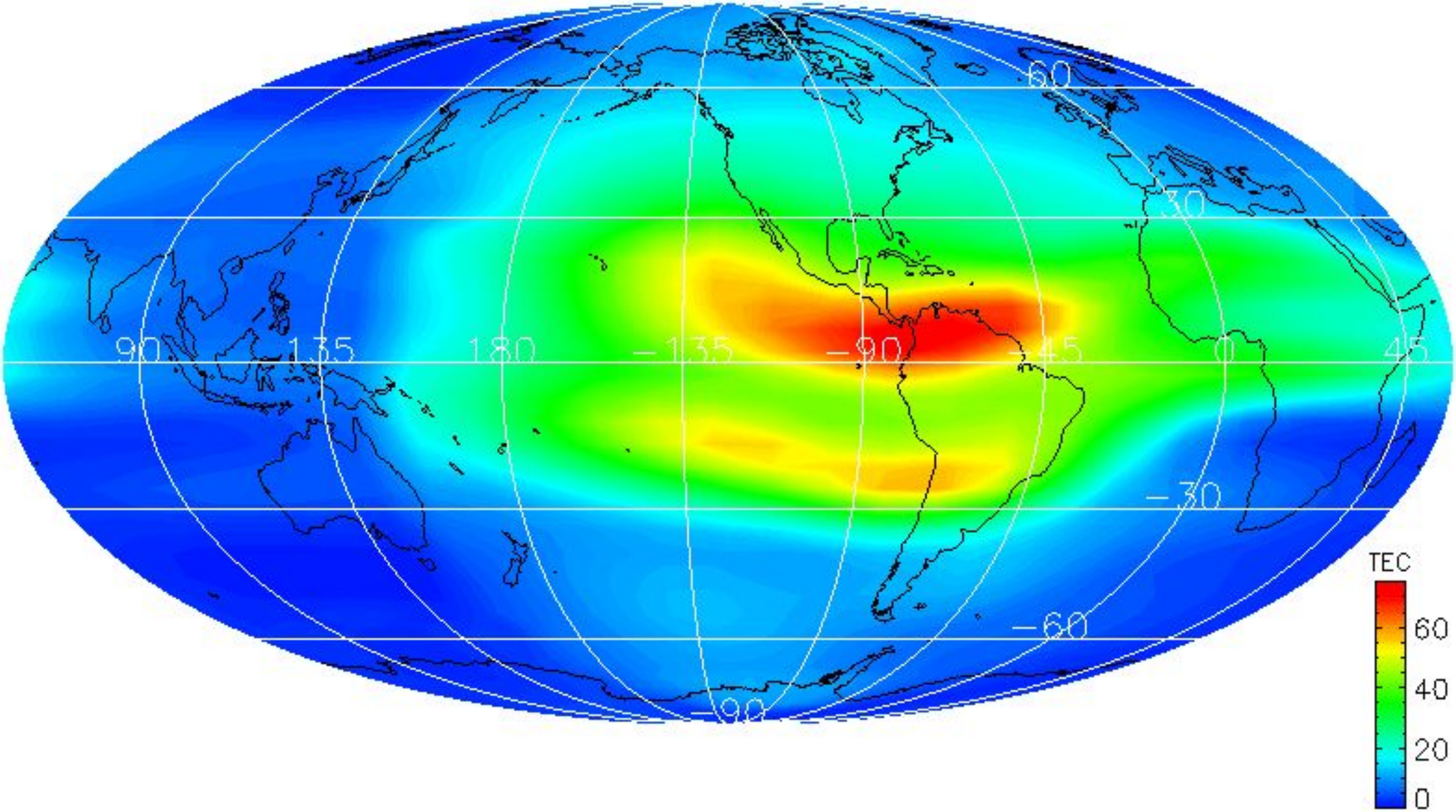
- This is a test to determine the Total Mass Loss (TML), the Collected Volatile Condensable Material (CVCM), and the Water Vapor Recovery (WVR) mass.
- A specimen is kept at 125 ºC during 24 hours, near a collector surface kept at 25 ºC. The mass lost by the specimen (TML) and the mass collected by the collector (CVCM) must comply stringent requirements for space qualification
- It is required that Kn > 1 inside the test chamber

The plasma environment

- At heights over ~100 km the radiation of the Sun ionizes the main constituents of the atmosphere, forming a neutral plasma



The plasma environment



The plasma environment

- Plasma physics is based on the Maxwell equations plus Lorentz force:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

The plasma environment

- In the presence of a plasma, the electric potential becomes screened by the polarization of opposite charges. Then, it becomes

$$V(r) = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}\exp\left(-\frac{r}{\lambda_D}\right)$$

$$\frac{1}{\lambda_D^2} = \frac{1}{\lambda_e^2} + \frac{1}{\lambda_i^2}$$

$$\lambda_{e,i} = \left(\frac{\varepsilon_0 k_B T_{e,i}}{n_0 e^2}\right)^{1/2} \approx 69\left[\frac{T_{e,i}(K)}{n_0(m^{-3})}\right]^{1/2}$$

where λ_D, λ_e, λ_i are the Debye longitude, and the Debye longitude for electrons and ions, respectively; n_0 is the plasma density.

Plasma oscillations

- This is a form of collective motion in which a small perturbation separates (at least in part) the opposite charges. There appears a restoring force, and the plasma oscillates with a frequency

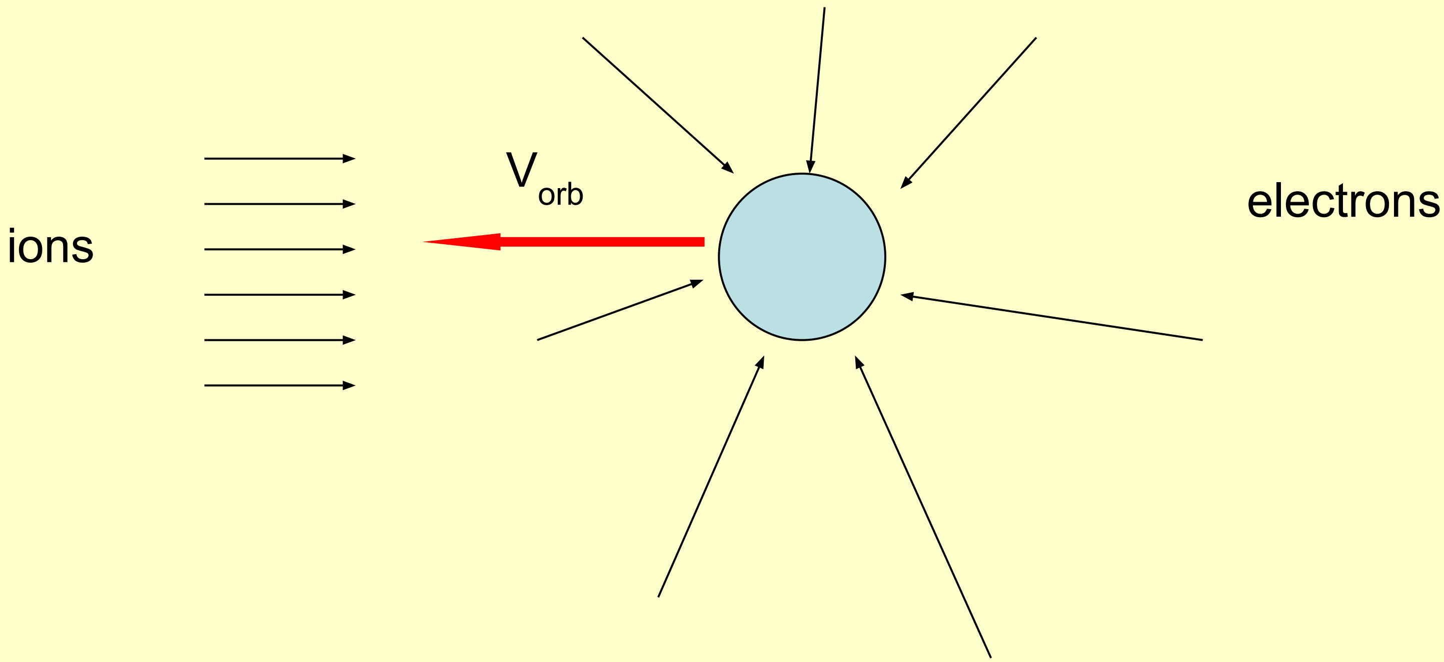
$$\nu_{p,e} = \frac{1}{2\pi}\left(\frac{n_0 e^2}{\varepsilon_0 m_e}\right)^{1/2} \approx 9\, n_0^{1/2}\left(m^{-3}\right)$$

This effect can cause electromagnetic perturbations to a satellite.

Spacecraft charging (1)

- Usually, a S/C subjected to an anisotropic flux of ions and electrons will acquire a net charge. In LEO we have

$$V_{th,i} < V_{orb} < V_{th,e}$$



Spacecraft charging (2)

- Assuming that, both electrons and ions follow a Maxwellian velocity distribution, the currents of ions and electrons are given by

$$I_i = e\,n_0\,v_{orb}\,A_i$$

$$I_e = \frac{1}{4} e\,n_0 \exp\left(\frac{eV}{k_B T}\right) v_{th,e}\,A_e$$

where $A_{e,i}$ are the cross sections of the satellite for electrons and ions, and the factor ¼ is due to the fact that half of the electrons escape from the Debye shell, and the rest have a $v \cos\theta$ towards the satellite.

- The charging process will continue until the satellite repels the incoming electrons. At this point, the satellite will be in the floating potential (in LEO, this is ~1V):

$$V_f = \frac{k_B T_e}{e} \ln\left(\frac{4\,v_{orb}\,A_i}{v_{th,e}\,A_e}\right)$$

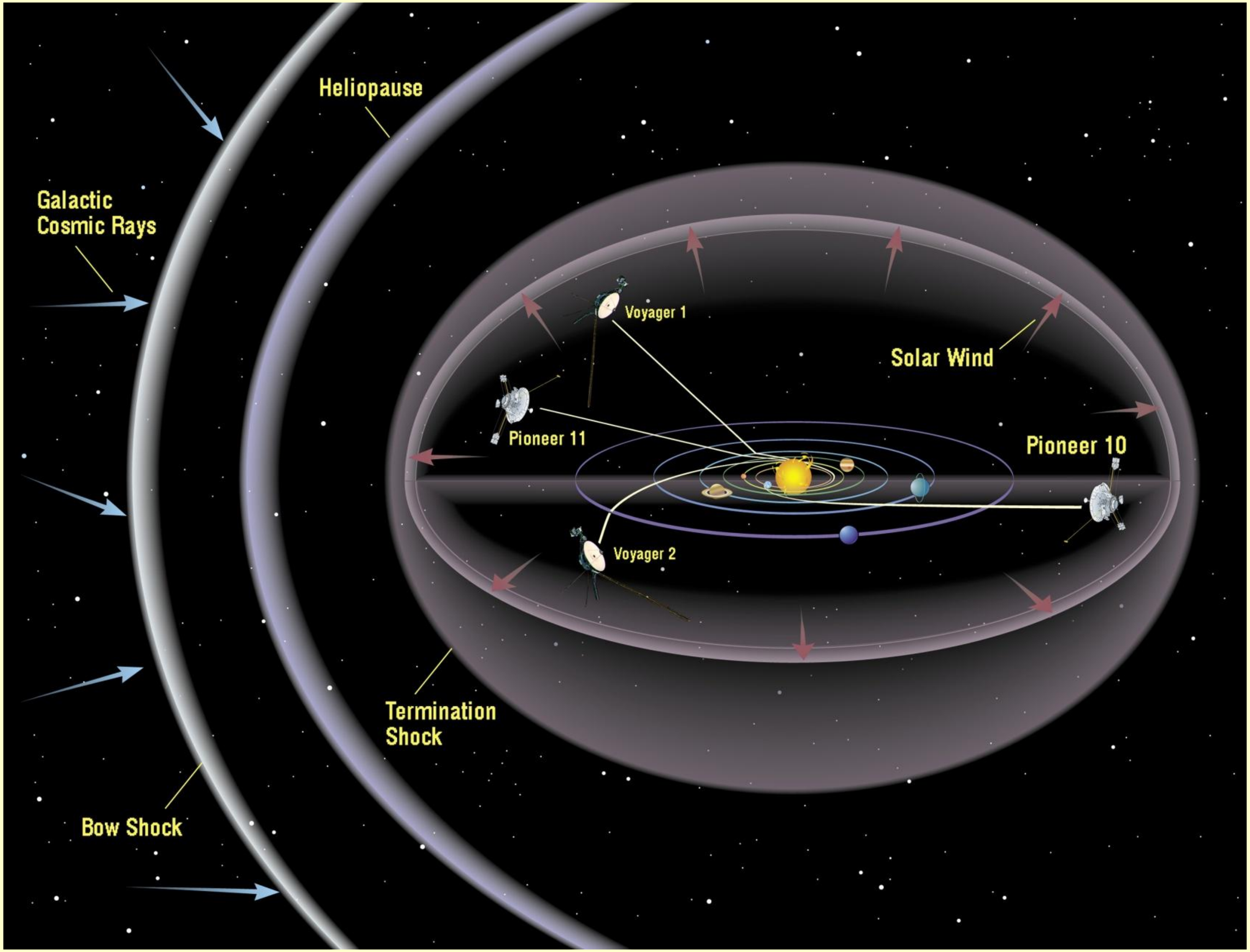
Radiation environment

- The radiation field has several components:
  - The standard solar wind plasma, formed by low energy protons, alpha particles, and electrons
  - The perturbed solar wind, with very high energy protons and electrons
  - Cosmic rays, composed of ultrahigh energy (up to 10^{15} eV) protons, alpha particles, electrons and very high energy, high Z elements (mostly iron)
  - Secondary particles resulting from then interaction of these components with the atmosphere: neutrons, muons, and pions

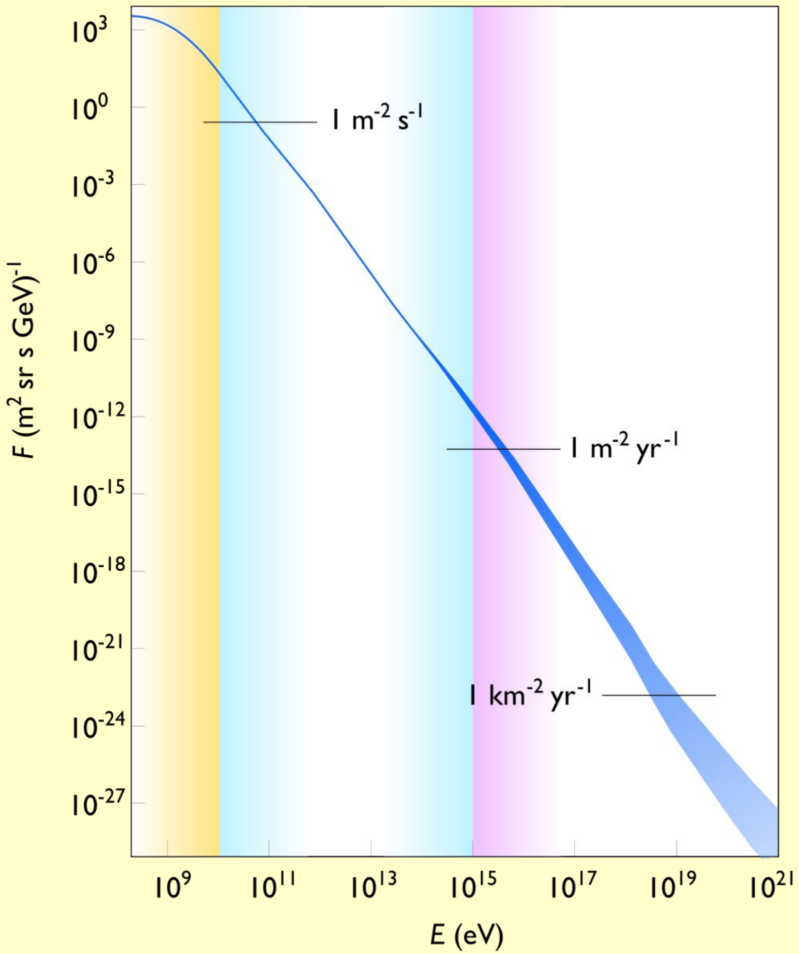
Galactic Cosmic Rays

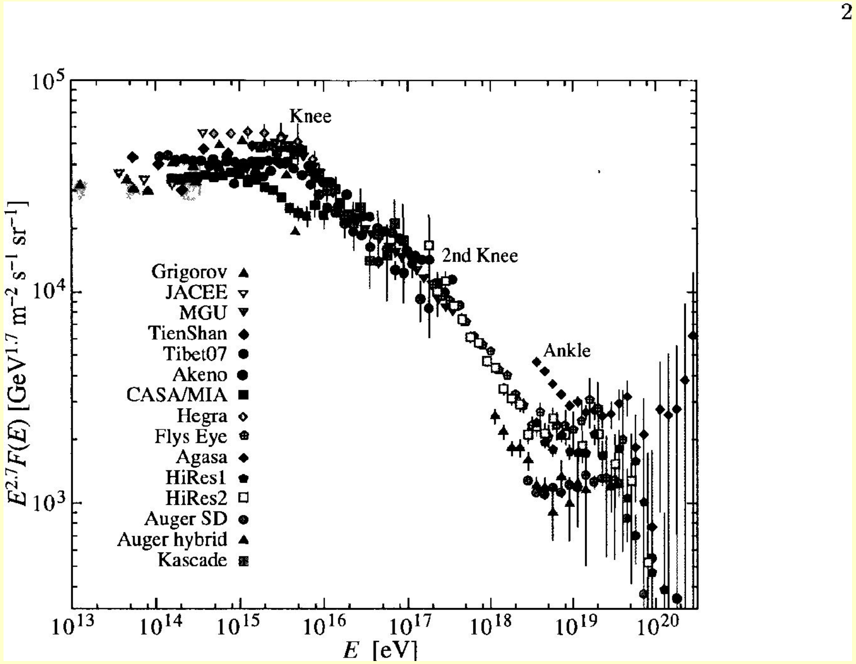
- High energy particles coming from outside the Solar System
- Composition: 85% p, 14% α, 1% heavy ions
- Hard spectrum
- Fluxes and spectra are modulated by solar activity (GCR have maximum fluxes at minimum solar activity, and viceversa)

Galactic Cosmic Rays



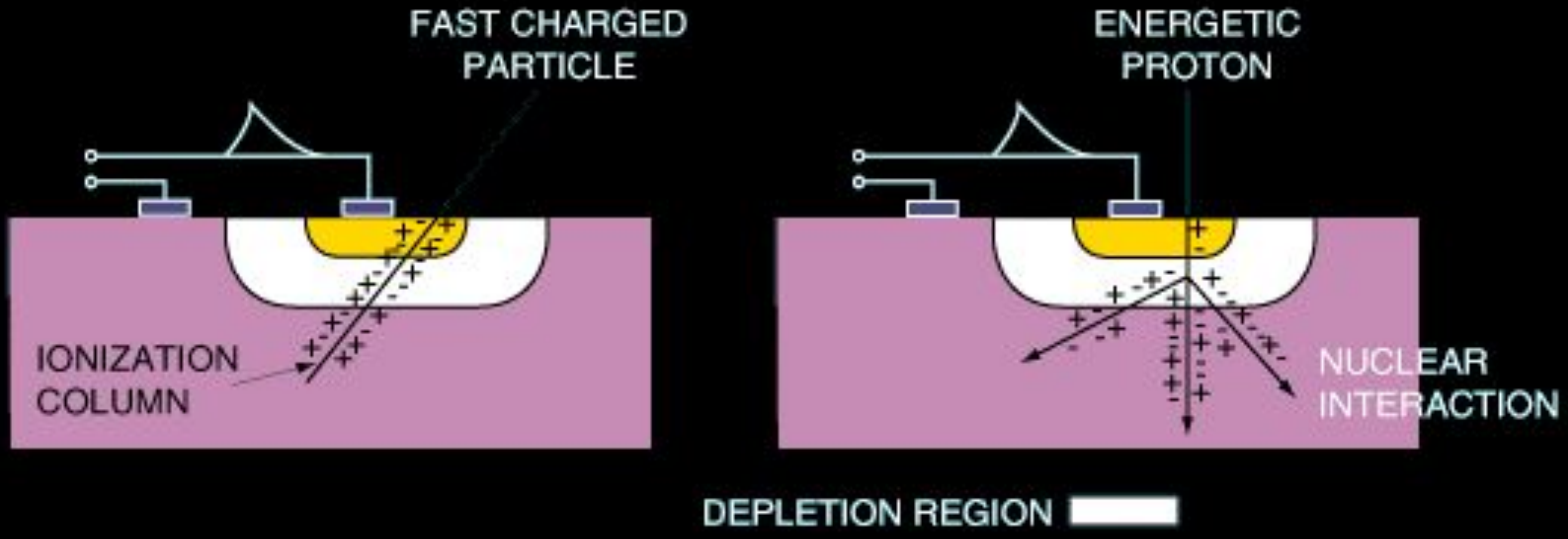
Galactic Cosmic Rays

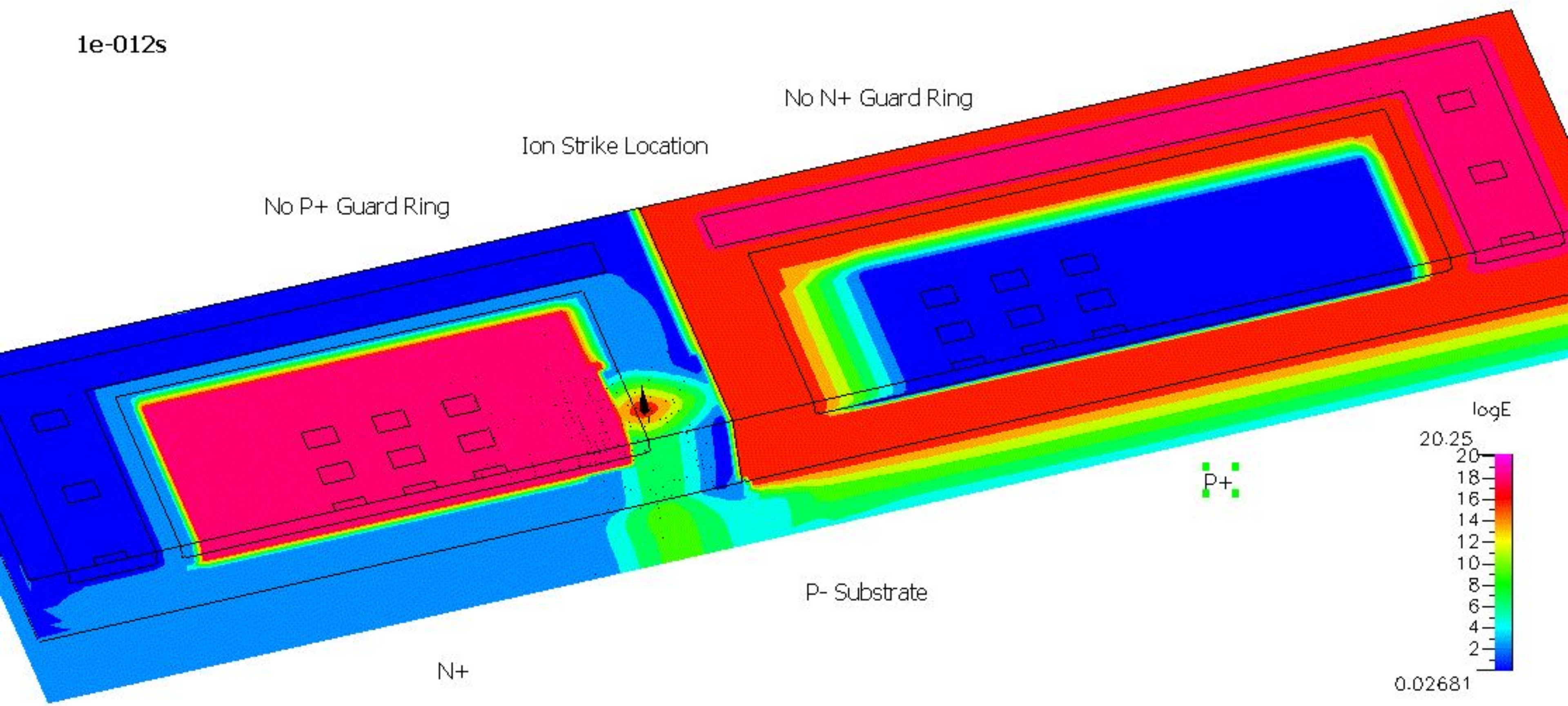


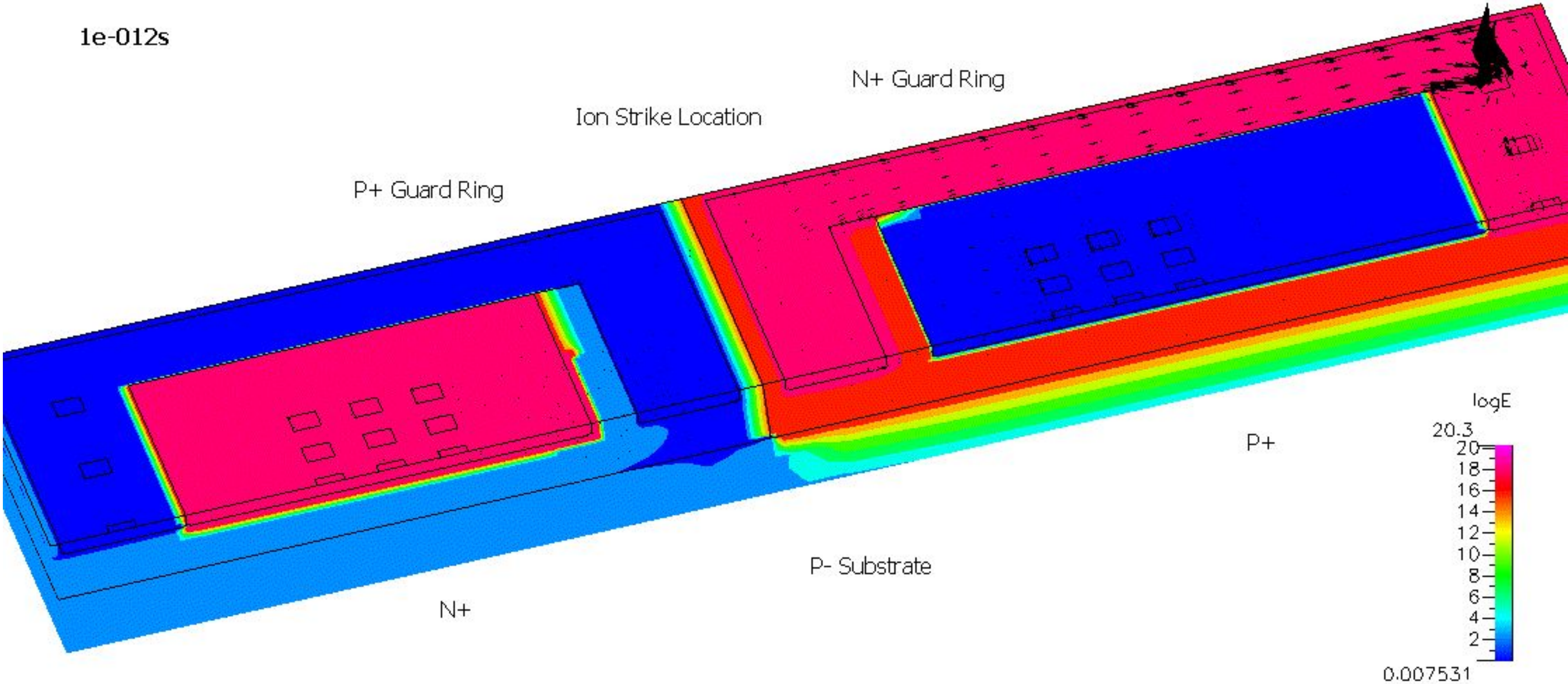


Hardness and survivability

- Single event effects: caused by the impact of a single high-energy particle.
- Single Event Upset (SEU): electron-hole pairs are formed in a sufficient number to change a logical state
  - No permanent damage to the device
  - Can generate false commands
  - Can be detected and corrected with software
- Single Event Latch-up (SEL): a conducting path establishes and anomalous current in the device
- Burn-out (SEB): reduced impedance in PNPN devices can result in burn-out (a conducting path survives long enough to irreversibly damage the device)
- SEL and SEB typical of cosmic rays


FAST CHARGED PARTICLE
IONIZATION COLUMN
ENERGETIC PROTON
NUCLEAR INTERACTION
DEPLETION REGION


1e-012s
No N+ Guard Ring
Ion Strike Location
No P+ Guard Ring
logE
20.25
20
18
16
14
12
10
8
6
4
2
0.02681
P+
P- Substrate
N+


1e-012s
N+ Guard Ring
Ion Strike Location
P+ Guard Ring
logE
20.3
20
18
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10
8
6
4
2
0.007531
P+
P- Substrate
N+

Radiation protection

- Charged particles can be readily stopped by almost any material, but they will emit most of its energy as a rain of secondary particles, including neutrons
- Neutrons and gamma rays, being neutral, are difficult to stop. They need low Z elements (Be and H are excellent choices)
- In order to avoid the high mass of the sandwiches Al/Be/Al (for example) NASA is experimenting with plastic substrates including a high amount of H. But the resistance of these organic materials to the space environment must be fully tested. This is the only possibility for small satellites

Physical Countermeasures

- Shielding with high-density material
  - Effective against primary radiation
  - Produces secondary radiation
  - Increases mass
- Chips on insulating substrates (instead of semiconductor wafers): Silicon Oxide (SOI) and Sapphire (SOI). Increase the radiation hardness by orders of magnitude
- Chips on substrates with a high bang gap: SiC and GaN
- Use of Magnetoresistive RAM (MRAM) or Static RAM (SRAM), which are more resistant to radiation

Software Countermeasures

- Error-Correcting Code (ECC):
  - Uses parity bits to identify alterations
  - Continuous reading of memory to identify altered bit chains
  - Increases processor overhead
- Redundant systems with majority voting
- Watchdog timer: it induces a hard reset if the processor does not produce a specific operation (as a write operation) at specific time intervals; if the operation is verified, the watchdog resets a time counter. It is a last resort solution.

Micrometeoroids (1)

- Micrometeoroids (and space debris) do not usually destroy a satellite, but in the long term can affect to the optical properties of their surfaces or to the efficiency of the solar cells
- Their effects can be classified as
  - Erosion
  - Penetration
  - Catastrophic effects

Micrometeoroids (2)

- The flux of micrometeoroids is given by

$$F\left(m^{-2}yr^{-1}\right)=3.156\times10^{7}\left(A^{-4.38}+B+C\right)$$

$$A=15.0+2.2\times10^{3}m^{0.306}$$

$$B=1.3\times10^{-9}\left(m+10^{11}m^{2}+10^{27}m^{4}\right)^{-0.306}$$

$$C=1.3\times10^{-16}\left(m+10^{6}m^{2}\right)^{-0.85}$$

  where *m* is the mass of the meteoroid in grams
- The Earth gravitationally focuses micrometeoroids

$$F_{grav}=1+\frac{R_{\oplus}+100\,\mathrm{km}}{R_{\oplus}+h}$$

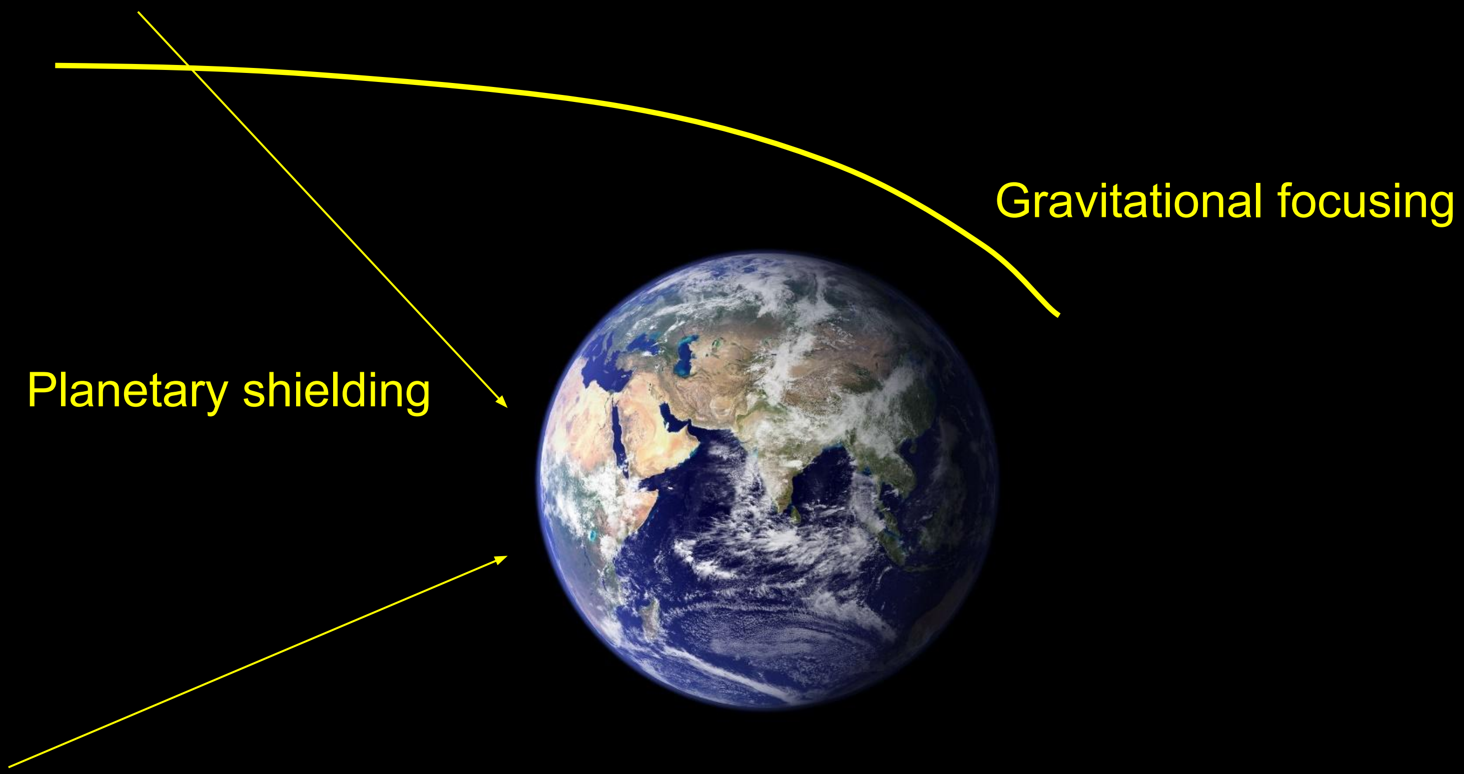
Micrometeoroids (3)

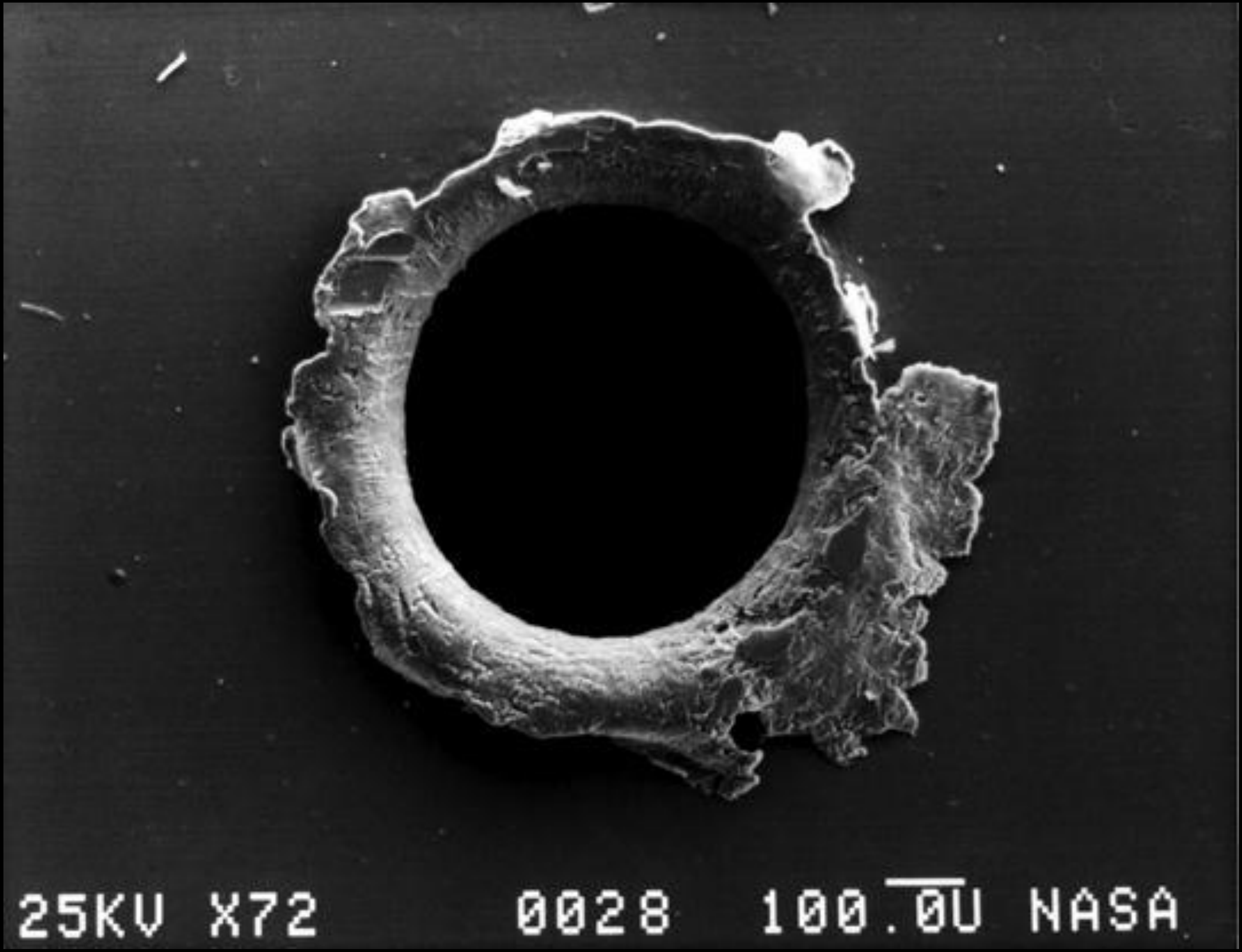
- And also acts as a shield

$$F_{shield} = \frac{1 + \cos\eta}{2}$$

$$\eta = \sin^{-1}\left(\frac{R_{\oplus} + 100\ \mathrm{km}}{R_{\oplus} + h}\right)$$

- Most impacts are produced on the space-facing surfaces

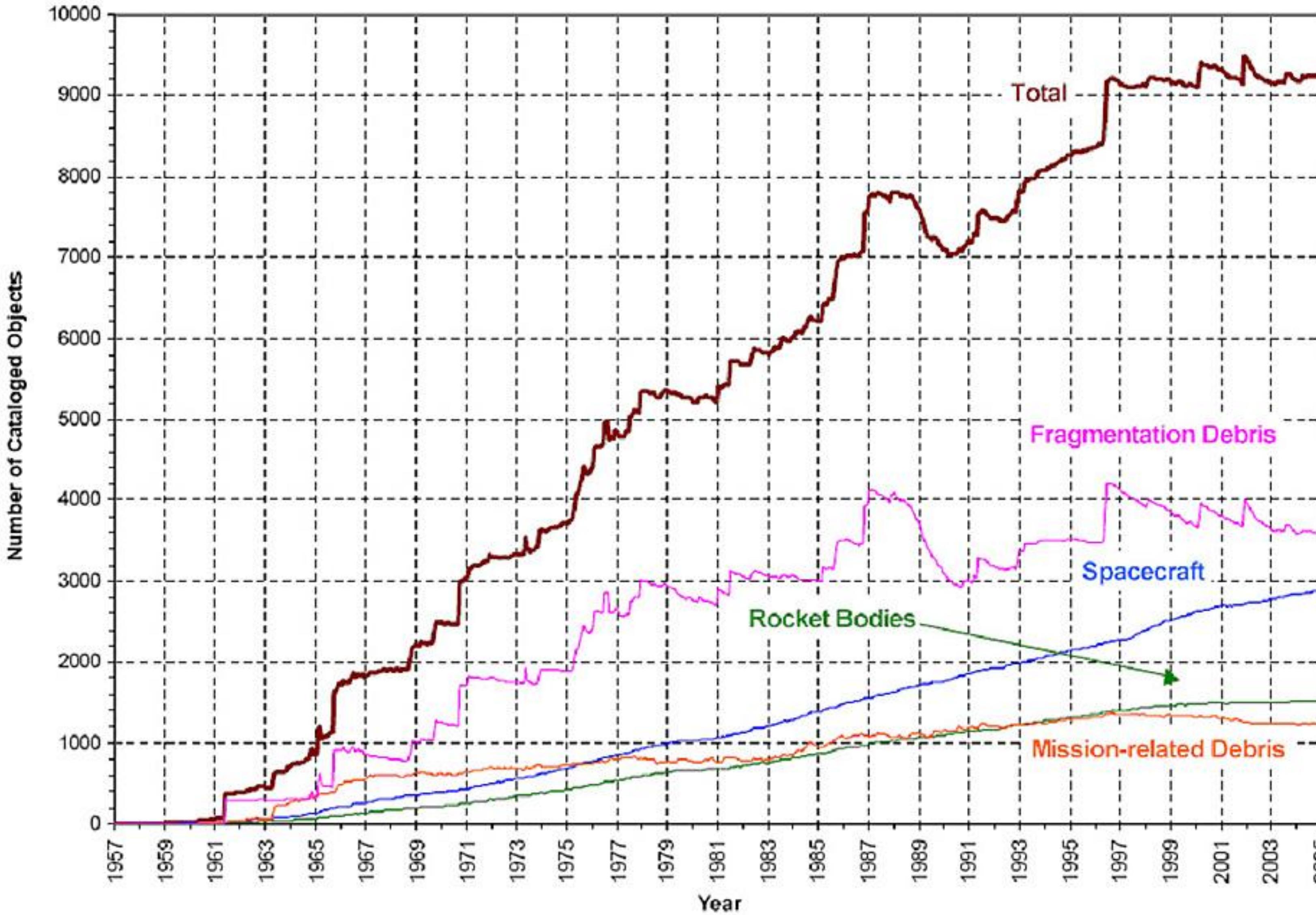

Gravitational focusing
Planetary shielding


25KV X72 0028 100.0U NASA

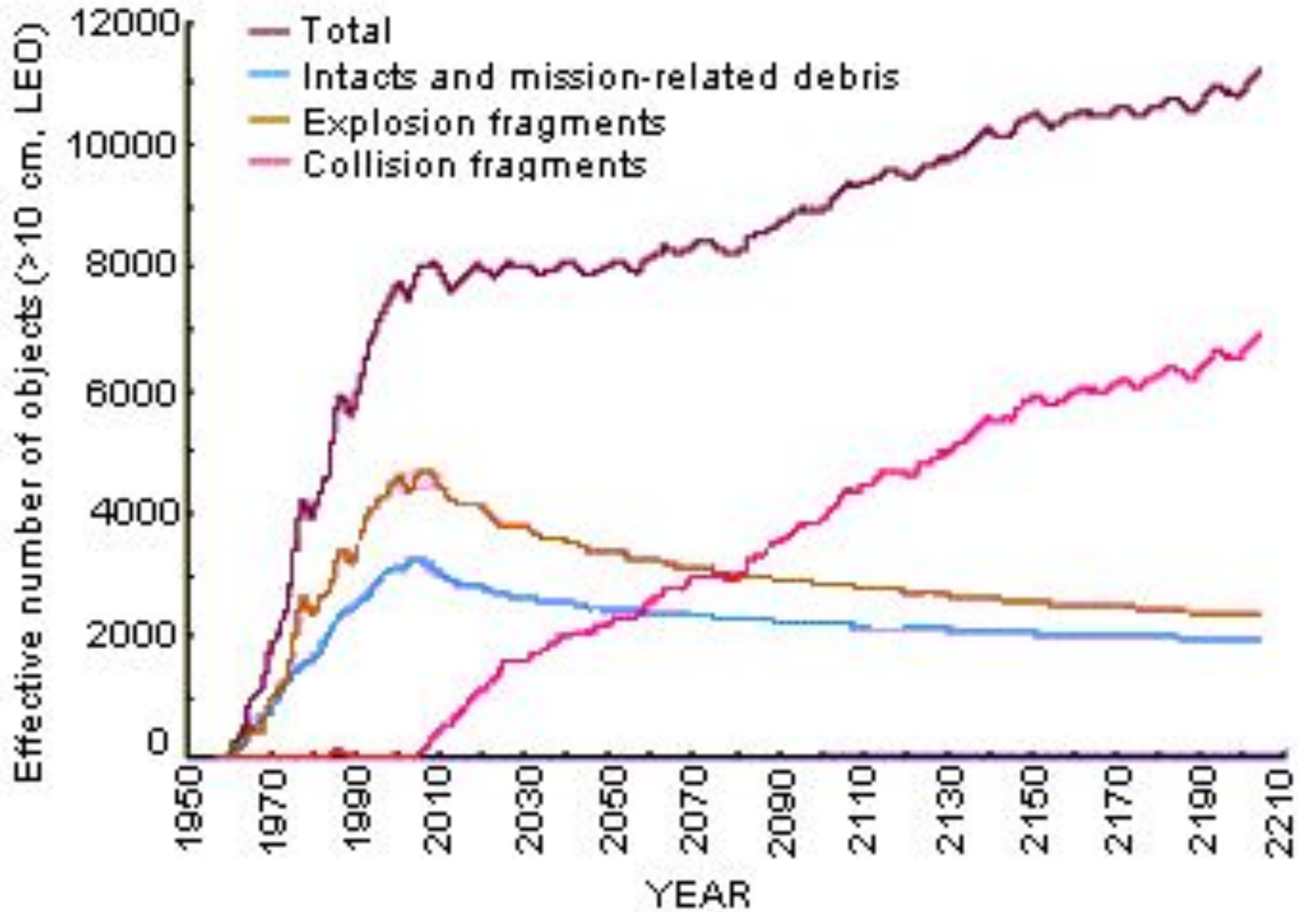
Space debris (1)

- Space debris are produced by human activities in space
- They can be (among many other possibilities)
  - Inactive satellites
  - Rocket upper stages (sometimes with some fuels)
  - Pieces resulting from explosions –accidental or intentional– and collisions
  - Paint flakes
  - Chunks of nuclear reactor coolant
  - Small parts and/or tools
- The current limit for detection and follow-up is around 5 cm

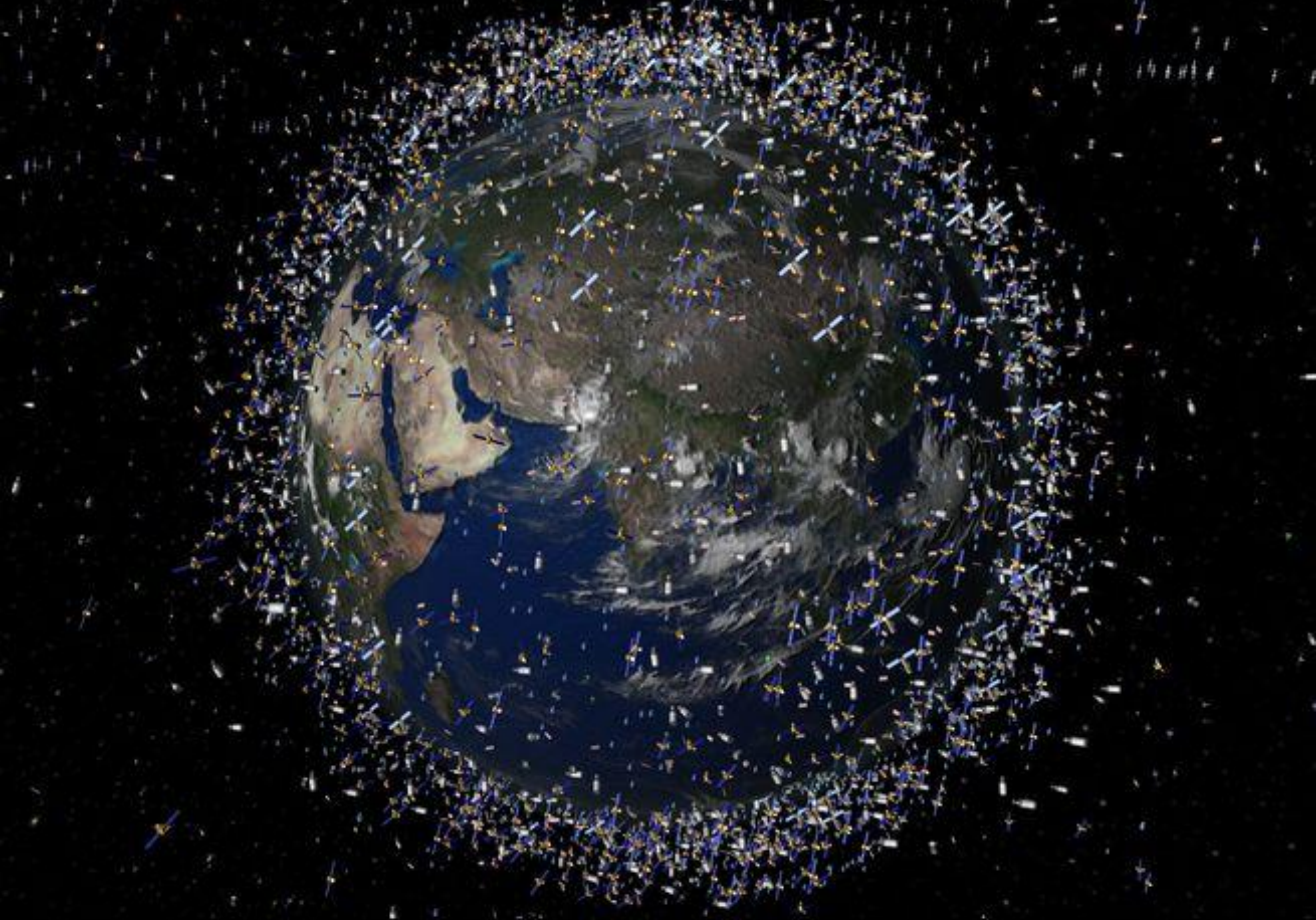
Monthly Number of Cataloged Objects in Earth Orbit by Object Type



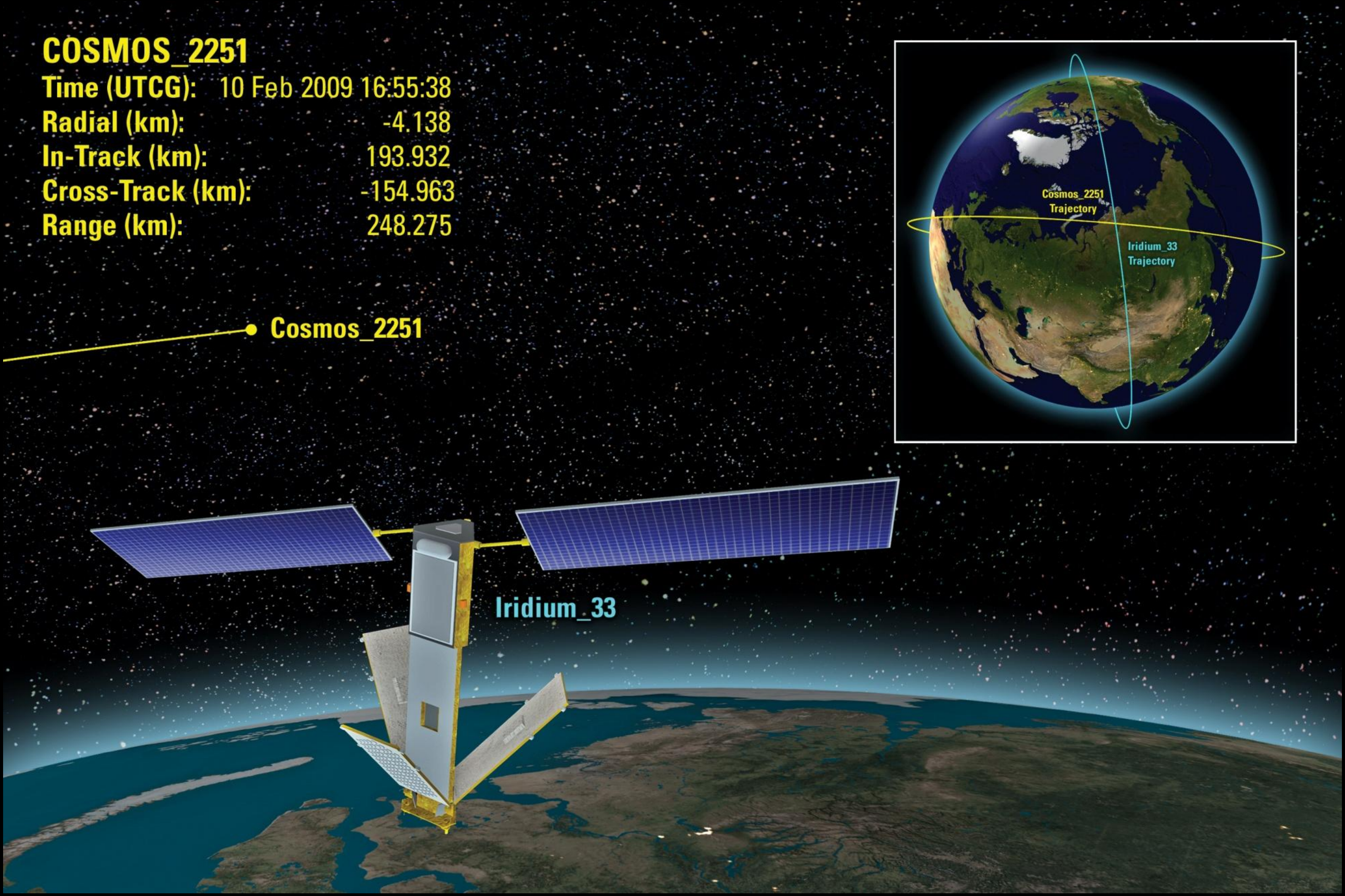
Monthly Number of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the US Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.



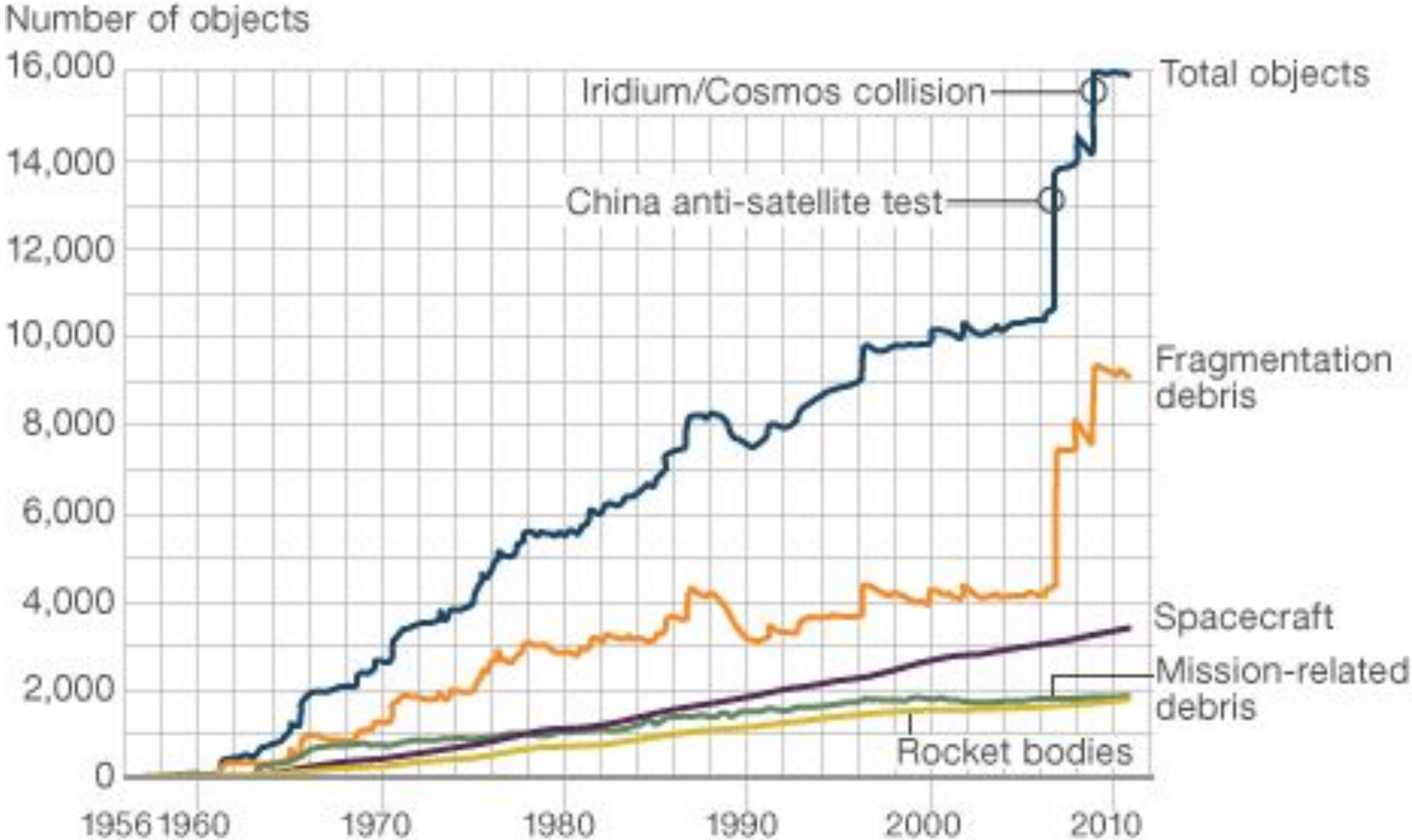
Growth of future populations. Effective number of LEO objects, 10cm and larger, from the LEGEND simulation. The effective number is defined as the fractional time, per orbital period, an object spends between 200 and 2000 km altitudes. Intacts are rocket bodies and spacecraft that have not experienced breakups.



Note: Artist's impression; size of debris exaggerated as compared to the Earth


COSMOS_2251
Time (UTCG): 10 Feb 2009 16:55:38
Radial (km): -4.138
In-Track (km): 193.932
Cross-Track (km): -154.963
Range (km): 248.275
Cosmos_2251
Cosmos_2251 Trajectory
Iridium_33 Trajectory
Iridium_33

Growth of orbital space objects including debris



Source: Nasa

Space debris (2)

- Space debris at heights of less than 600 km reenter in the atmosphere in relatively short times (less than 3 or 4 years, depending on its BC)
- This problem is specially serious in LEO and GEO
- There are no effective countermeasures against the effects of micrometoroids or space debris other than choosing low population orbits

Kessler syndrome

- It is possible that a series of collisions between space debris produces a cascade a smaller debris that would eventually cause a runaway effect on the number of debris
- This situation would be encountered if the debris density overcomes a (badly determined) threshold
- In a Kessler syndrome scenario, some orbital regions in LEO could become unusable
- Currently, the most affected orbits (and then the ones were a Kessler syndrome is more likely) include geostationary and Sun-synchronous (700 km in altitude) orbits

Our swarm as a space debris hazard

- A large swarm could be seen as a potential risk for other space agents
- The low BC and altitude warrants a lifetime of one week (perhaps 10 days) before re-entry
- At these low altitudes there are no satellites (except some intelligence ones on their perigee?)

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Debris Mitigation

The United Nations, through its Office for Outer Space Affairs, has set up a number of mitigation guidelines

1. Limit debris released during normal operations
2. Minimize the potential for break-ups during operational phases
3. Limit the probability of accidental collision in orbit
4. Avoid intentional destruction and other harmful activities
5. Minimize potential for post-mission break-ups resulting from stored energy
6. Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission
7. Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission

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