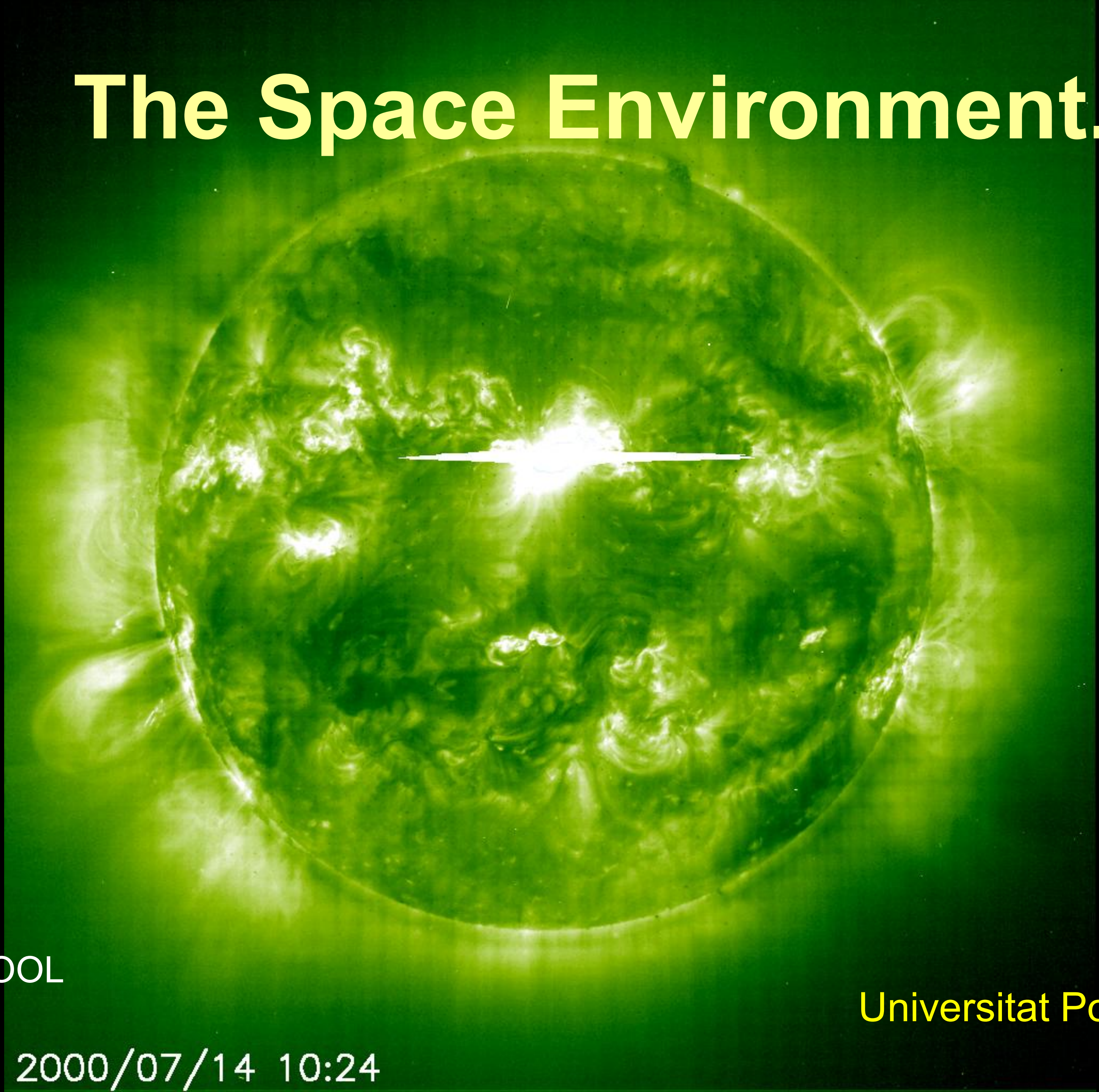
The Space Environment.



XVI INTERNATIONAL
SUMMER SPACE SCHOOL
Samara University
Summer 2021

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Department of Physics
Universitat Politècnica de Catalunya

Syllabus

- **Introduction**
- Gravitational field
- Magnetic field
- Van Allen Belts
- The upper atmosphere
- High vacuum effects
- The plasma environment
- Cosmic Rays
- Space Debris and Micrometeoroids

Satellites and the Space Environment

Standard satellites rely in S-class (space qualified) devices to ensure a long operational time in orbit

In most cases, small satellites are launched as secondary payloads, and have no saying on the final orbital parameters (besides skipping launches to overly inadequate orbits)

Furthermore, given the frequent use of COTS parts, it is very recommendable to allow ample margins, making necessary a fairly good idea of the expected environmental conditions

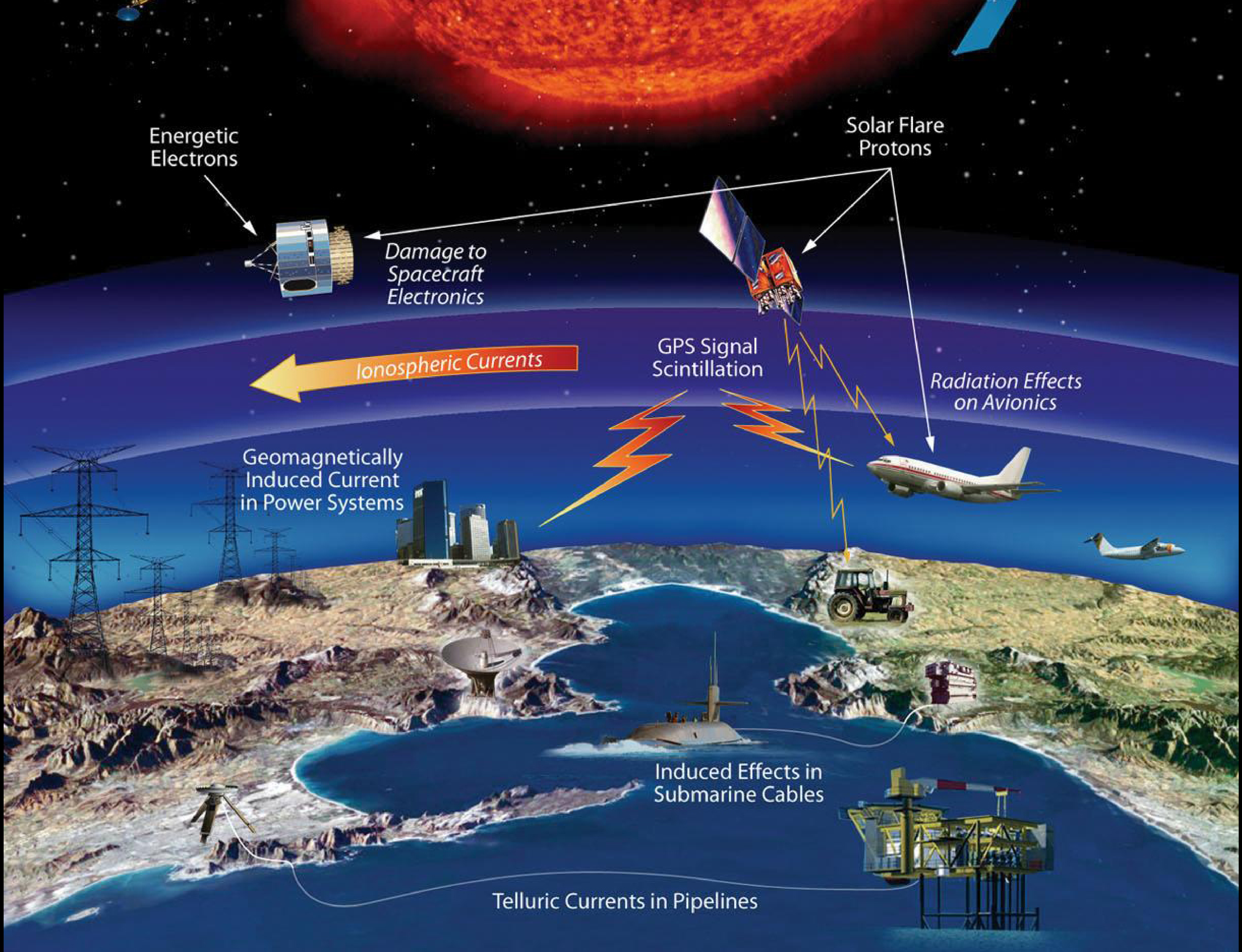
The space environment is rather harsh, and varies with time (often in very short timescales)

Effects of the Space Environment

There are several phenomena that have a significant impact on satellite design

- 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


Energetic
Electrons
Solar Flare
Protons
Damage to
Spacecraft
Electronics
GPS Signal
Scintillation
Ionospheric Currents
Radiation Effects
on Avionics
Geomagnetically
Induced Current
in Power Systems
Induced Effects in
Submarine Cables
Telluric Currents in Pipelines

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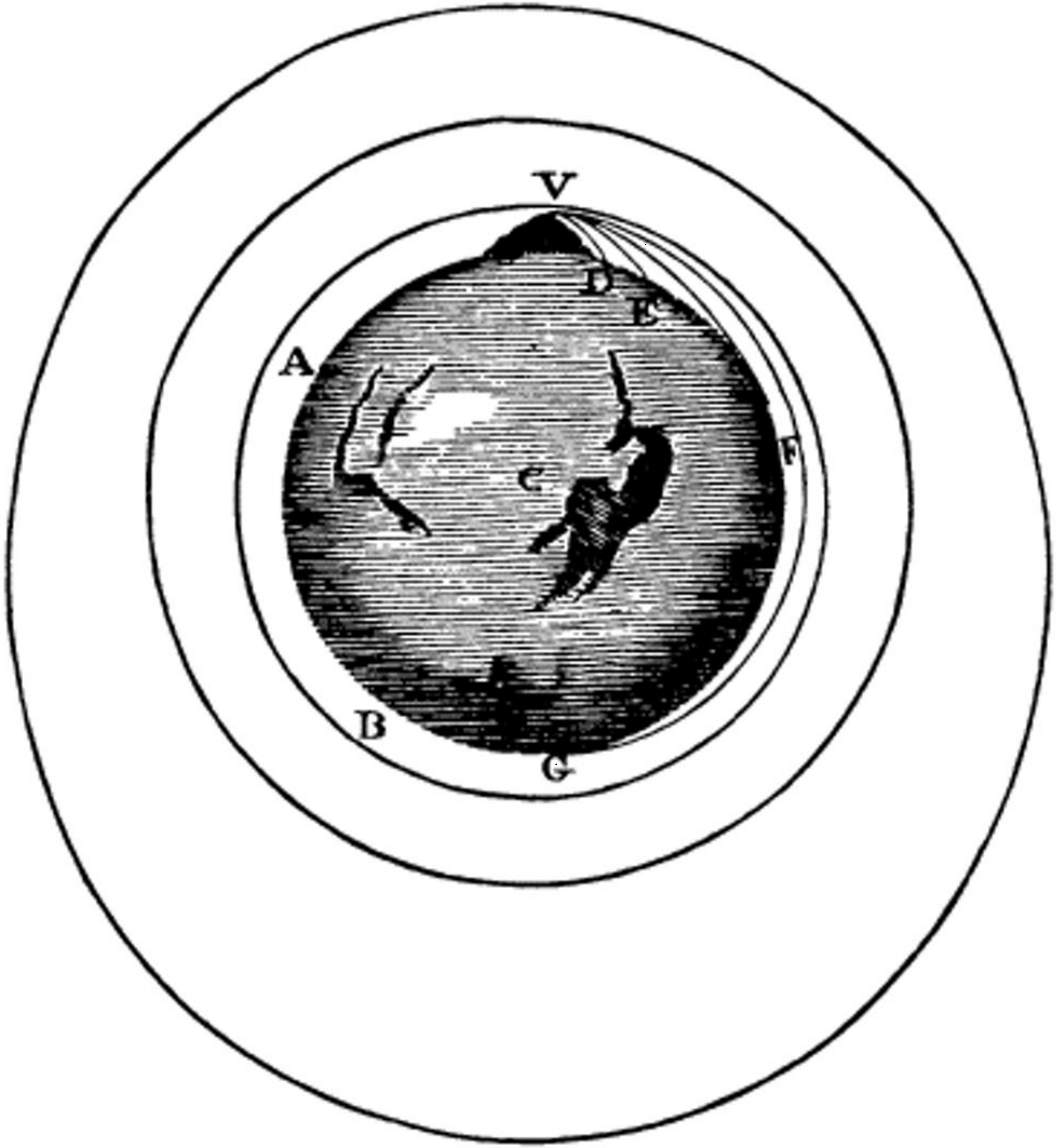
The gravitational field

- 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

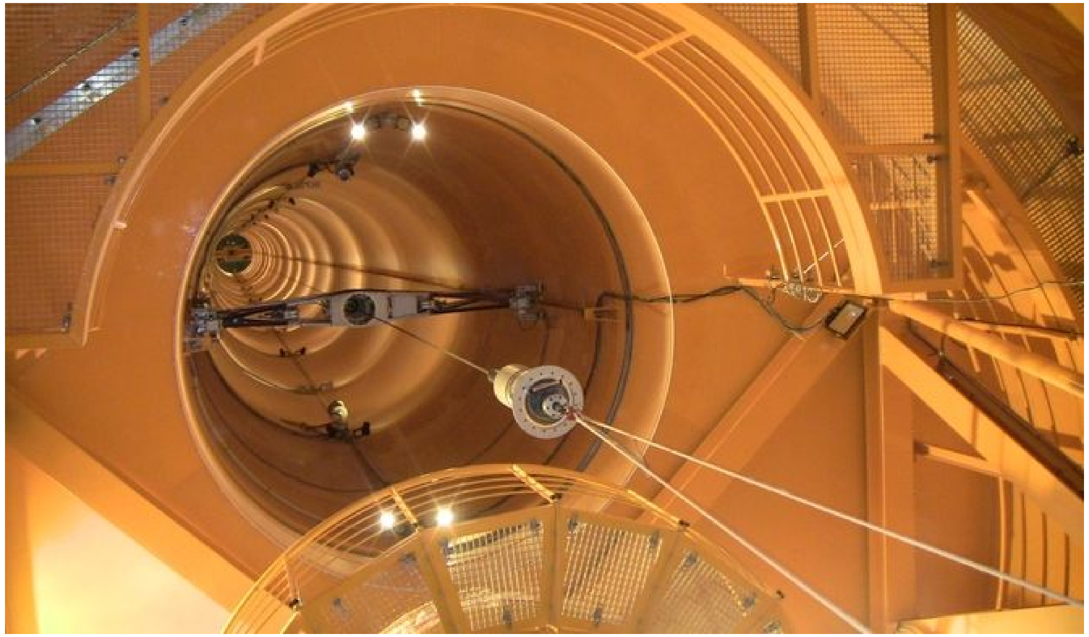
$$\sum \vec{F} = \vec{0} \rightarrow$$

$$\vec{g}_{ISS}\,(h = 420\ \text{km}) \simeq 8.5\ \text{m/s}^2$$


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)

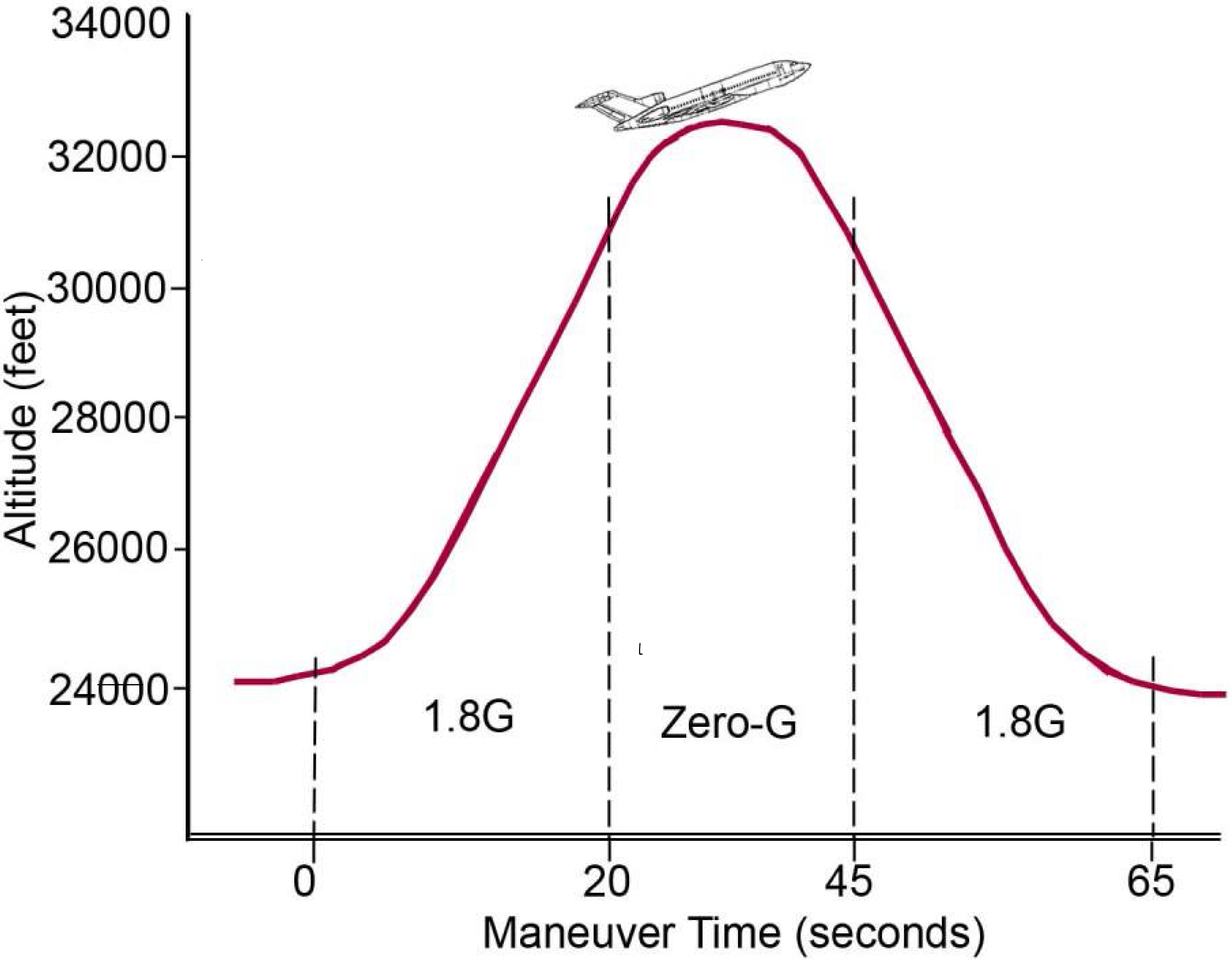


Interior of the Bremen test tower


РОСКОСМОС
RF-75353


ZERO-G


NASA
930



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

REXUS/BEXUS
Student Experiment Programme

ESA’s REXUS rocket

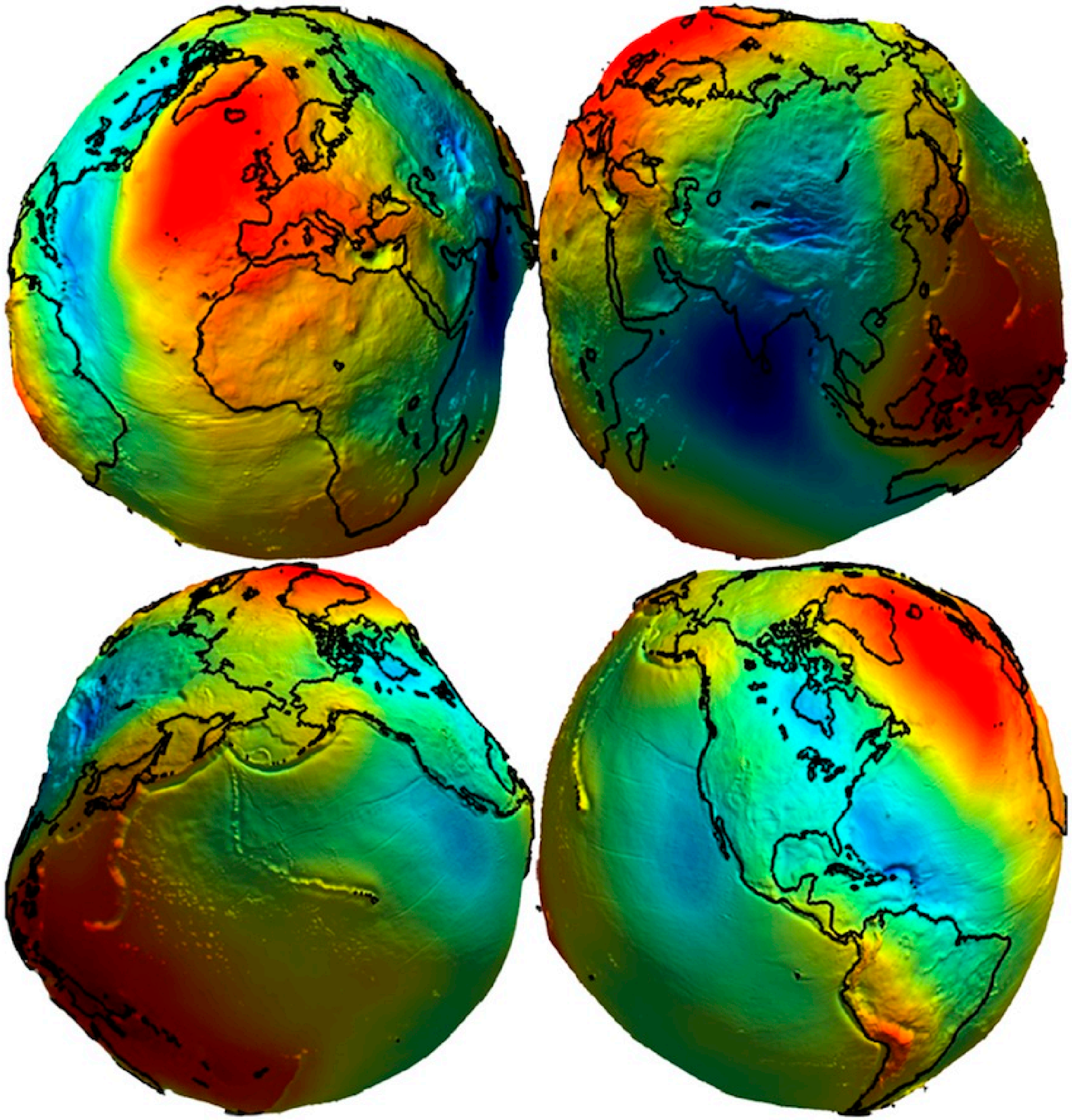
The gravitational field

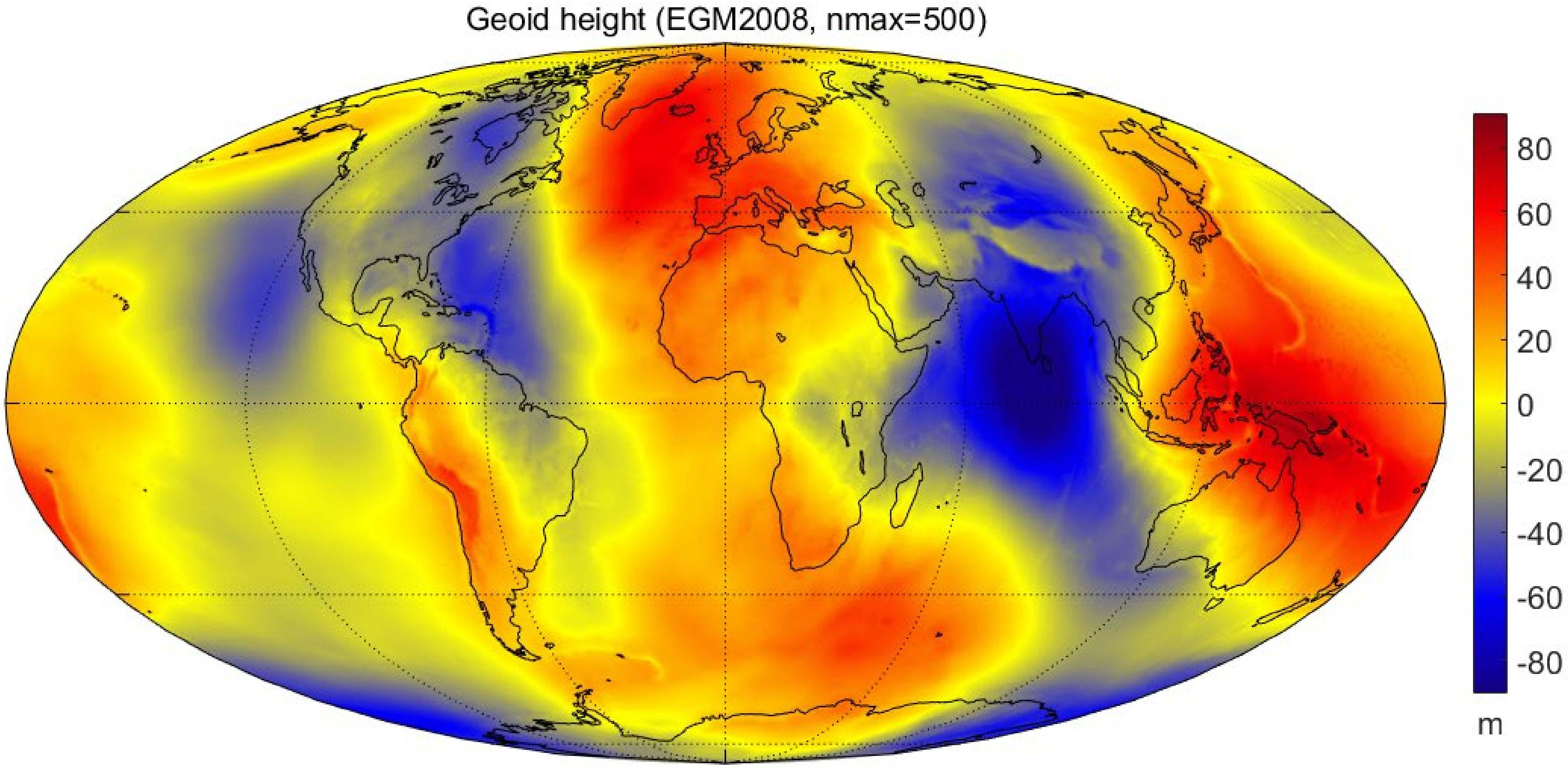
The gravitational field can be expressed as

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

where

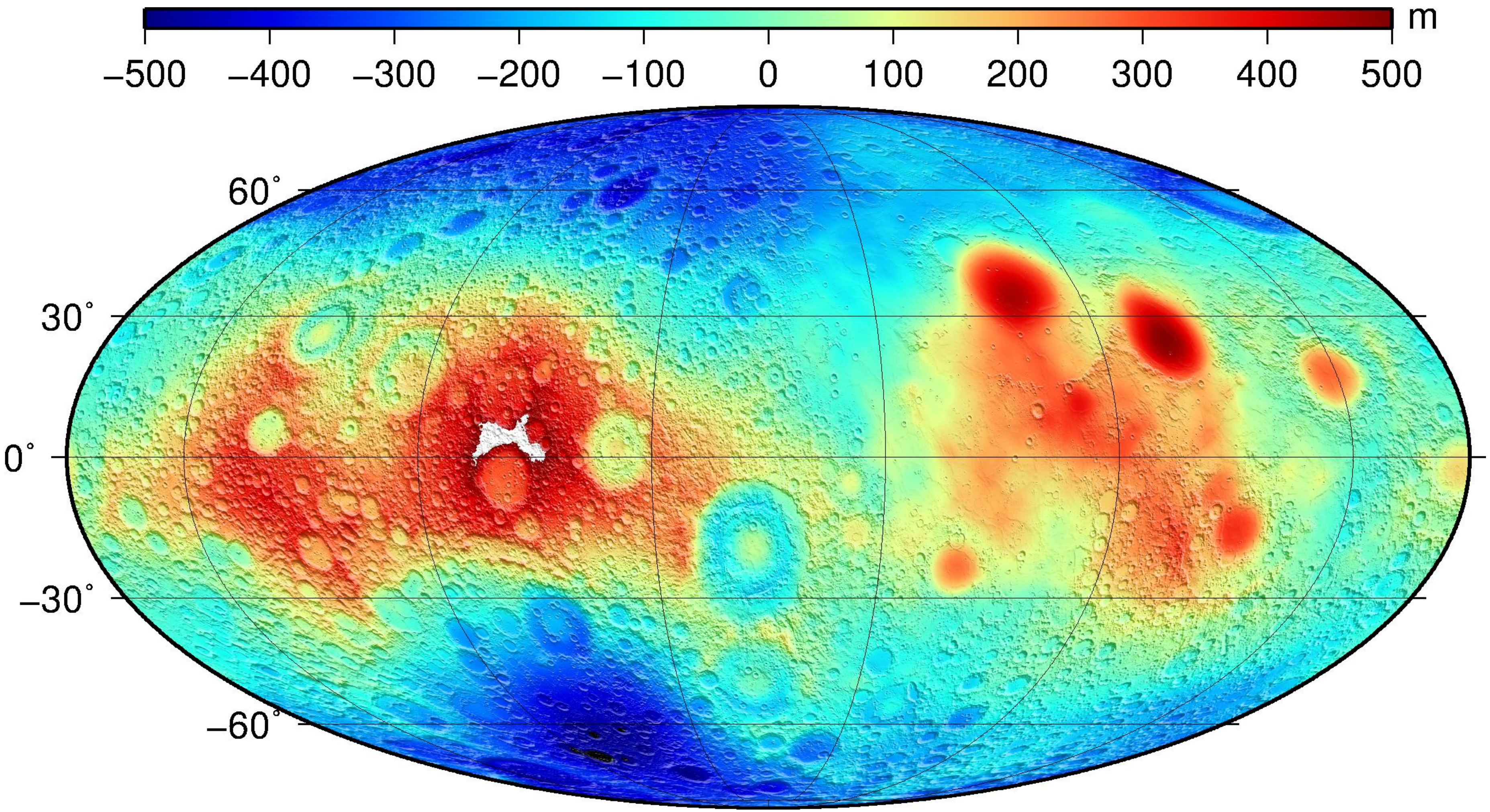
$$\mu = GM_\oplus = 3.986004418 \times 10^{14}\ \mathrm{m}^3\mathrm{s}^{-2}$$





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

Other celestial bodies have, obviously, different gravitational fields



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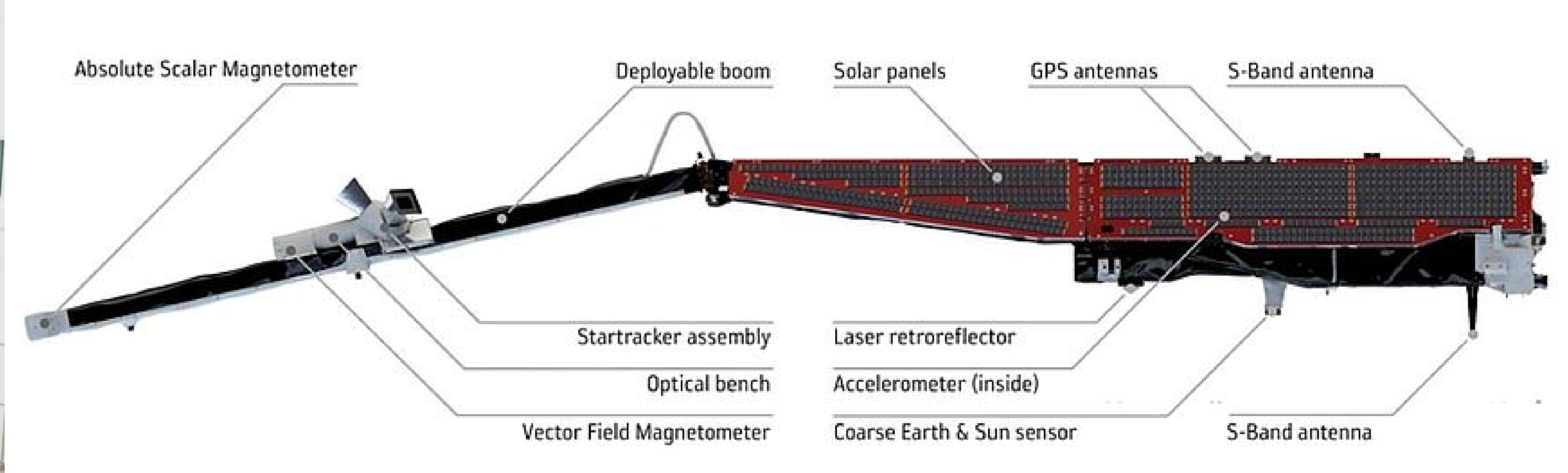
The magnetosphere and radiation belts

- 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)



Swarm is a constellation of three ESA's satellites devoted to the study of the terrestrial magnetosphere

IGRF12

The International Geomagnetic Reference Field, 12th generation, is one of the most widely used models to analyse the terrestrial magnetic field.

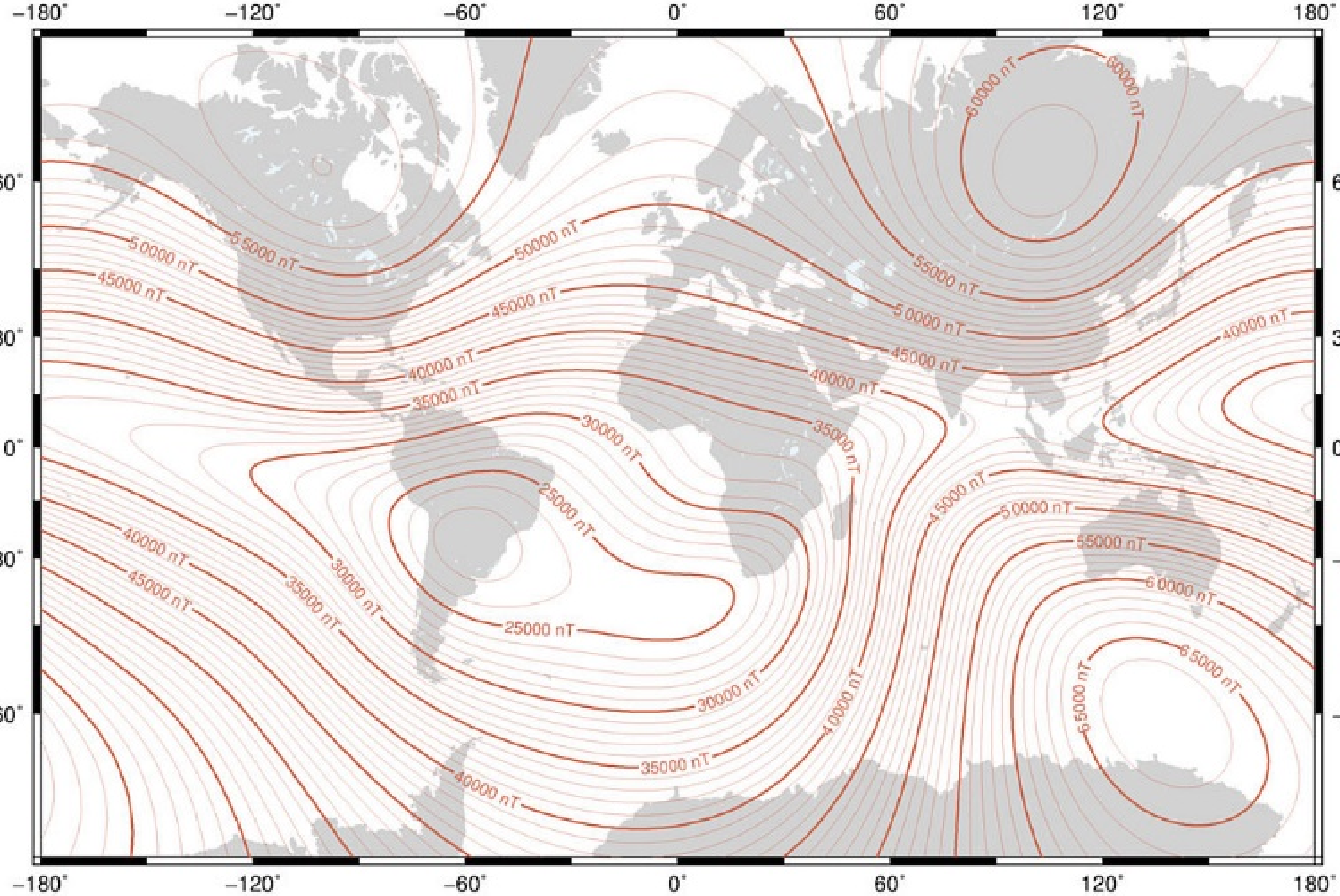
It has thousands of adjustable parameters.

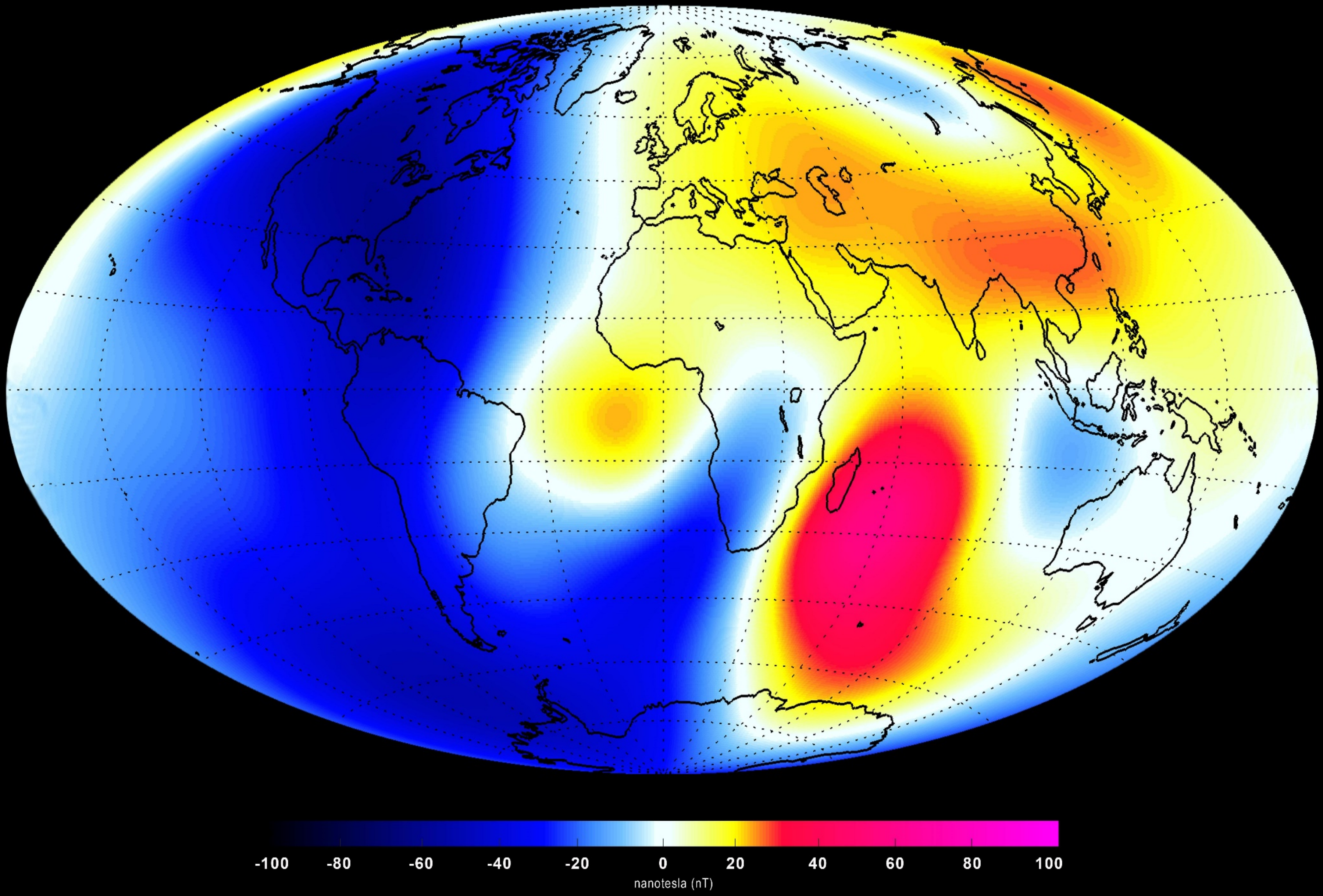
The scalar potential is of the form $\vec{B} = \vec{\nabla} V$

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

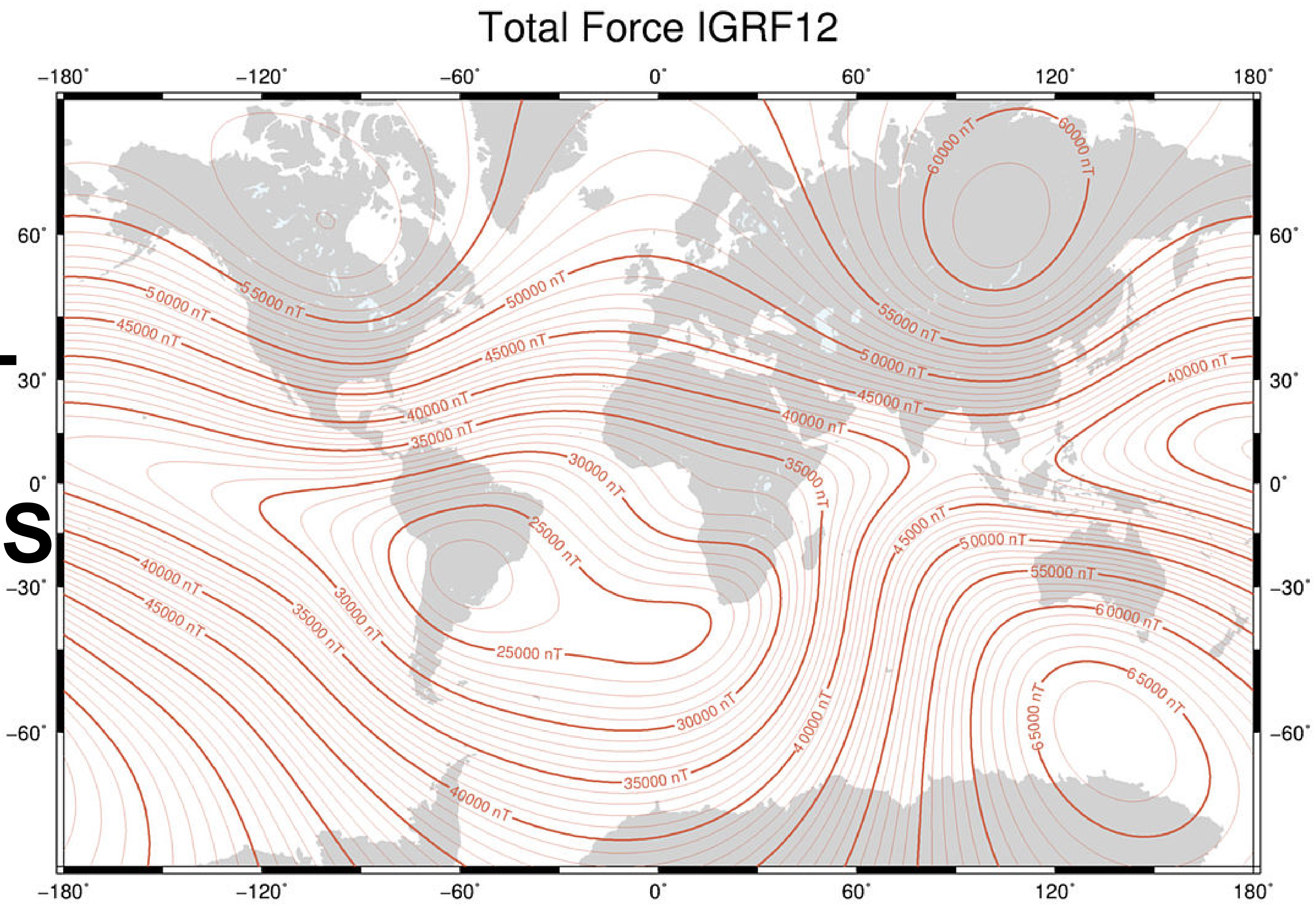
The coefficients g_m^n and h_m^n need to be recomputed every 5 years to ensure the accuracy of the model.

Total Force IGRF12




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

TERRESTRIAL MAGNETIC FIELD MODELS



Magnetic field models

Models for magnetic fields assume that there are no external sources (no electric currents; but see the lecture on plasma), and then

$$\vec{\nabla} \times \vec{B} = \vec{0}$$

which allows us to write

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

being V a scalar field (potential). It is this potential that is fit to observations.

V is represented using spherical harmonics based on associated Legendre functions.

Terrestrial magnetic field models

Two models are widely used: IGRF (International Geomagnetic Reference Field, new release 2020) and WMM (World Magnetic Model, new release 2020 valid until 2025).

Both are available at the NOAA web

IGRF: https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html

WMM: https://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml

These models forecast long-term changes of the magnetic field.

Terrestrial magnetic field models

The computed magnetic elements in IGRF and WMM are

D: Declination

I: Inclination

H: Horizontal field strength

X: North component

Y: East component

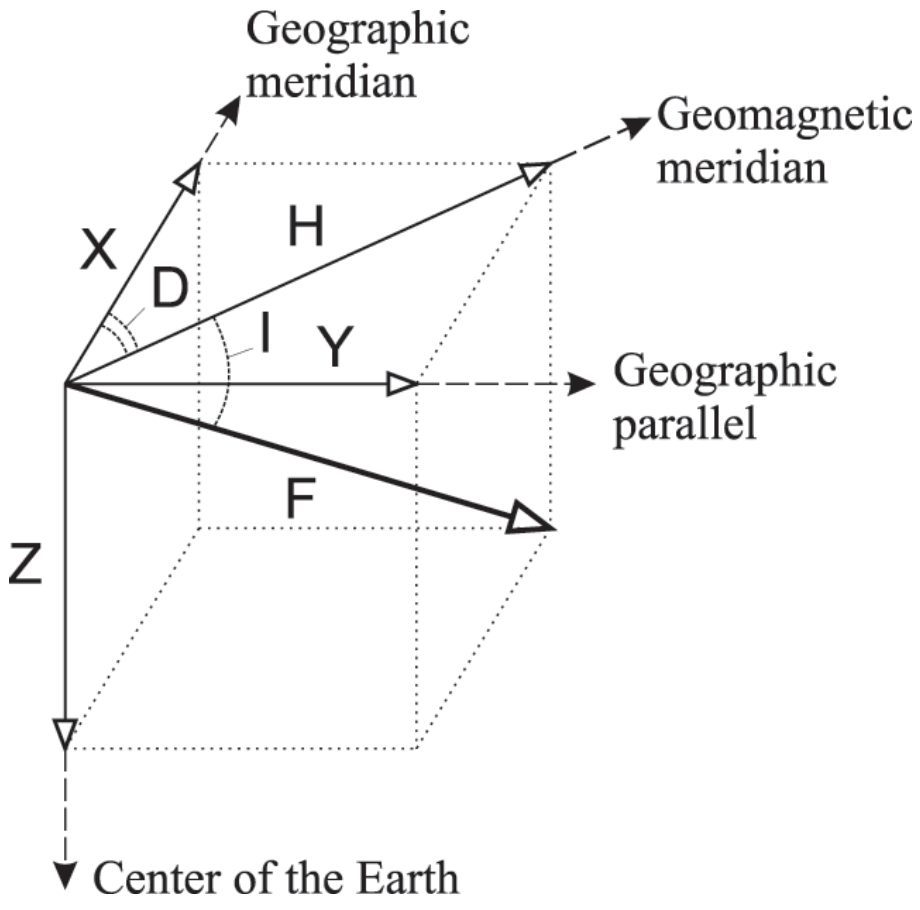
Z: Down component

F: Total field strength

dD, dI, dH, dX, dY, dZ, dF: secular change per year of the above quantities.

Terrestrial magnetic field models

The relations between these quantities are



© USGS

$$D = \tan^{-1}\left(\frac{Y}{X}\right)$$

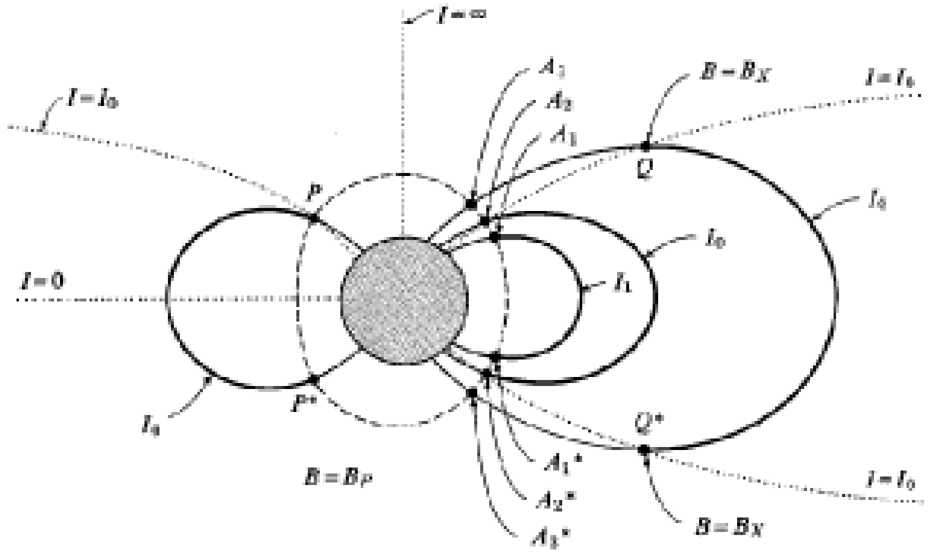
$$I = \tan^{-1}\left(\frac{H}{F}\right)$$

$$X = B \cos I \cos D$$
$$Y = B \cos I \sin D$$
$$Z = B \sin I$$
$$H = B \cos I$$

McIlwain (B,L) coordinates

This coordinate system gives the magnetic induction as

$$B = \frac{B_0}{(L \sin^2\theta)^3} (4 - 3 \sin^2\theta)^{1/2}$$



In a reference system centred in the dipole, L shells are given as a function of geomagnetic latitude λ as

$$r = L\, R_e \cos^2\lambda$$

L is the location of the intersection of a magnetic line with the magnetic equator

International geomagnetic reference field

The IGRF is in its 13th release, valid from 2019 to 2025

It gives the magnetic field as the negative gradient of a scalar potential:

$$\vec{B} = -\vec{\nabla} V(r, \theta, \varphi, t)$$

$$V(r, \theta, \varphi, t) = a \sum_{n=1}^{N} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+1} \left[g_{n,m}(t) \cos(m\varphi) + h_{n,m}(t) \sin(m\varphi)\right] P_{n,m}(\cos\theta)$$

Note that the coefficients are time-dependent, and so must be recomputed from time to time. The quantity a is the equatorial radius of the Earth (6371.2 km), φ is the longitude and θ the colatitude.

International geomagnetic reference field

IGRF models for specific years are designated IGRFyear (e.g. IGRF2021 for the current year), but in the future they are designated as DGRFyear (e.g., in 2022 we will have DGRF2021), where D means definitive.

These DGRF models do not use the forecasted values of the fitting coefficients, but the observed ones.

For our topic, spacecraft engineering, the value of these DGRF models is that they allow re-analysis of ADCS data in satellites.

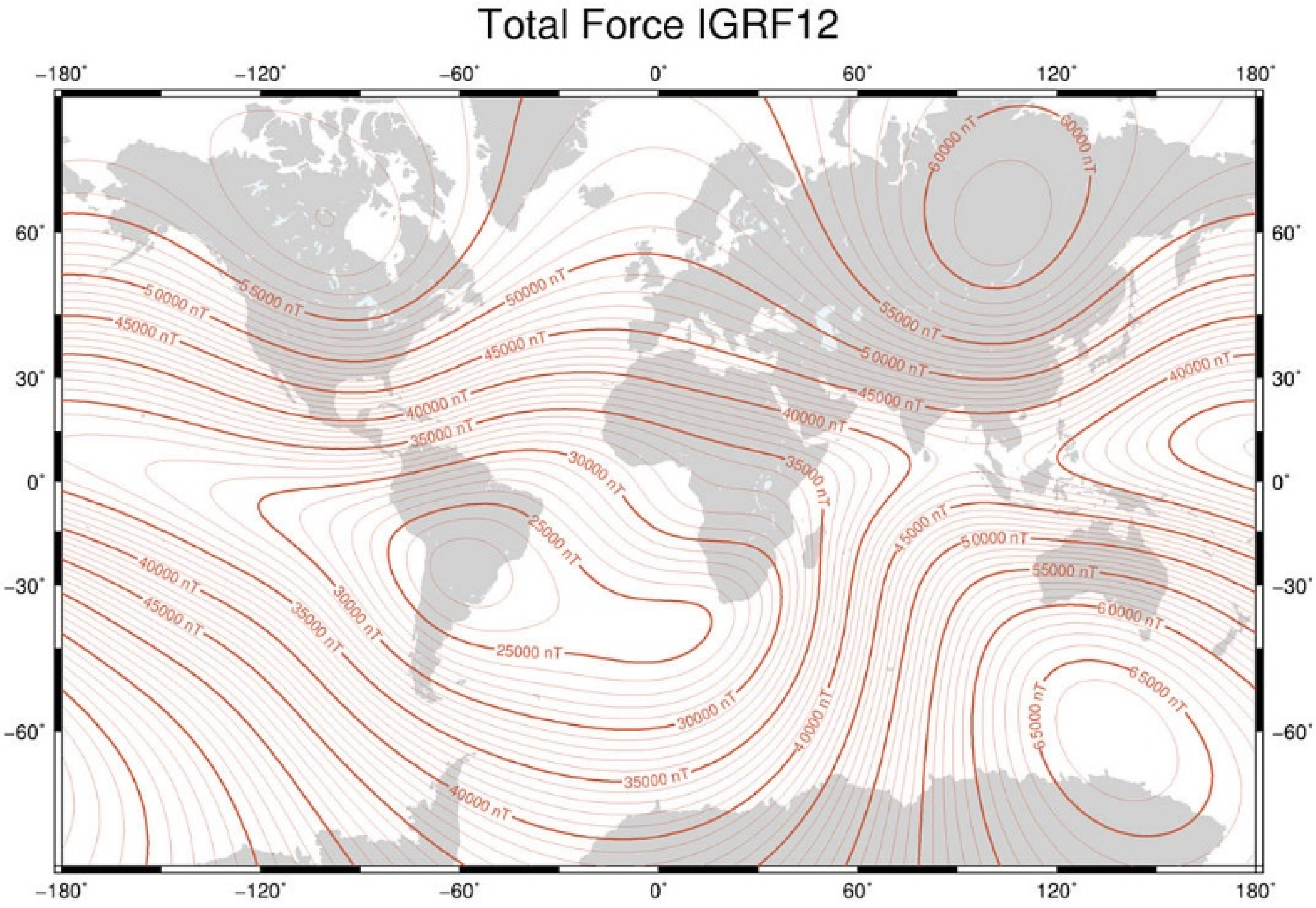
International geomagnetic reference field

There is a MatLab version of the model:

```
[magFieldVector,horIntensity,declination,inclination,totalIntensity,magFieldSecVariation,secVariationHorizontal,secVariationDeclination,secVariationInclination,secVariationTotal] =igrfmagm(height,latitude,longitude,decimalYear,generation)
```

Inputs: height (in m), latitude and longitude (in degrees), year (as a real number), generation (current is 13)

Outputs: xyz are the components of the magnetic field vector in nT, h the horizontal component, dec the magnetic declination, dip the magnetic inclination, and f the norm of the magnetic field vector.



IGRF13 calculator: https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml?useFullSite=true

Embedded problem

A satellite carries a magnet with a magnetic momentum of 2 A m^2. Determine the magnetic torque experienced by the satellite when it is 1000 km over Barcelona (41.390205N, 2.154007E) if

1. $\vec{\mu} = \mu \widehat{k}$
2. $\vec{\mu} \parallel \vec{B}$

Field:

	X component	Y	Z	Norm(B)
	16,295.3 nT	-105.9 nT	24,130.7 nT	29,117.7 nT

World Magnetic Model

It is a military project (US DoD, UK's Ministry of Defence, NATO), yet openly available for civilian use.

Very accurate, updated every 5 years.

$$V(r,\theta,\phi,t) = R_e \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{R_e}{r}\right)^{n+1} [g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi] P_n^m(\cos\theta) +$$

$$\cdots + R_e \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{r}{R_e}\right)^{n} \left[\bar{g}_n^m(t) \cos m\phi + \bar{h}_n^m(t) \sin m\phi\right] P_n^m(\cos\theta)$$

where the first term is for the internal field and the second is for the external one

World Magnetic Model

The coefficients $g_n^m(t)$, $h_n^m(t)$, $\bar{g}_n^m\,(t)$, and $\bar{h}_n^m(t)$ are the gaussian coefficients, and $P_n^m(\cos\theta)$ are the Schmidt quasi normalized associated Legendre functions, given by

$$P_n^m(x) = \left[\frac{2(n-m)!}{(n+m)!}(1-x^2)^m\right]^{1/2} \frac{d^m}{dx^m} P_n(x)$$

The units of the potential V are T·m.

The field is then found as

$$B_r = -\frac{\partial V}{\partial r} \quad B_\theta = -\frac{1}{r}\frac{\partial V}{\partial \theta} \quad B_\phi = -\frac{1}{r\sin\theta}\frac{\partial V}{\partial \phi}$$

World Magnetic Model

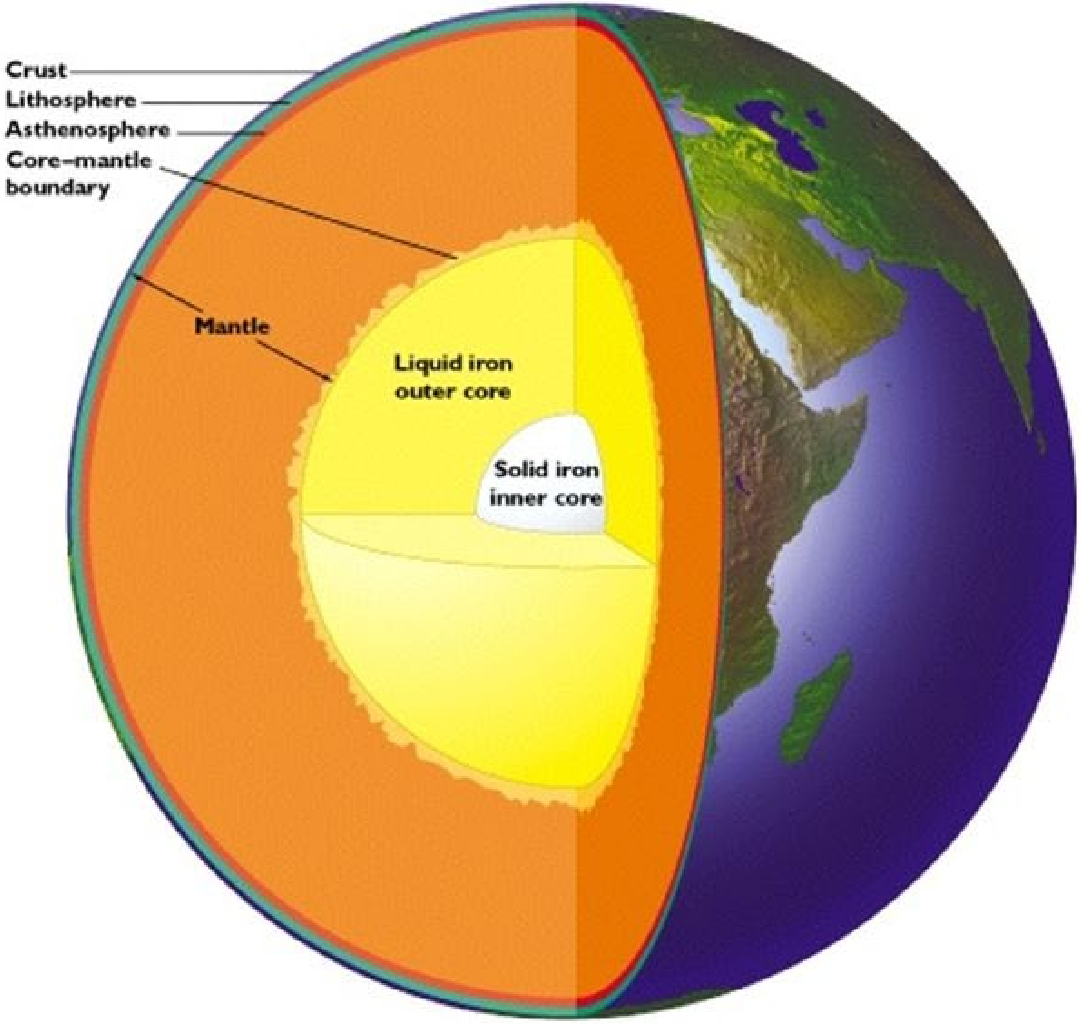
There is a MatLab version of the model:

[xyz, h, dec, dip, f] =wrldmagm(height,lat,lon,dyear)

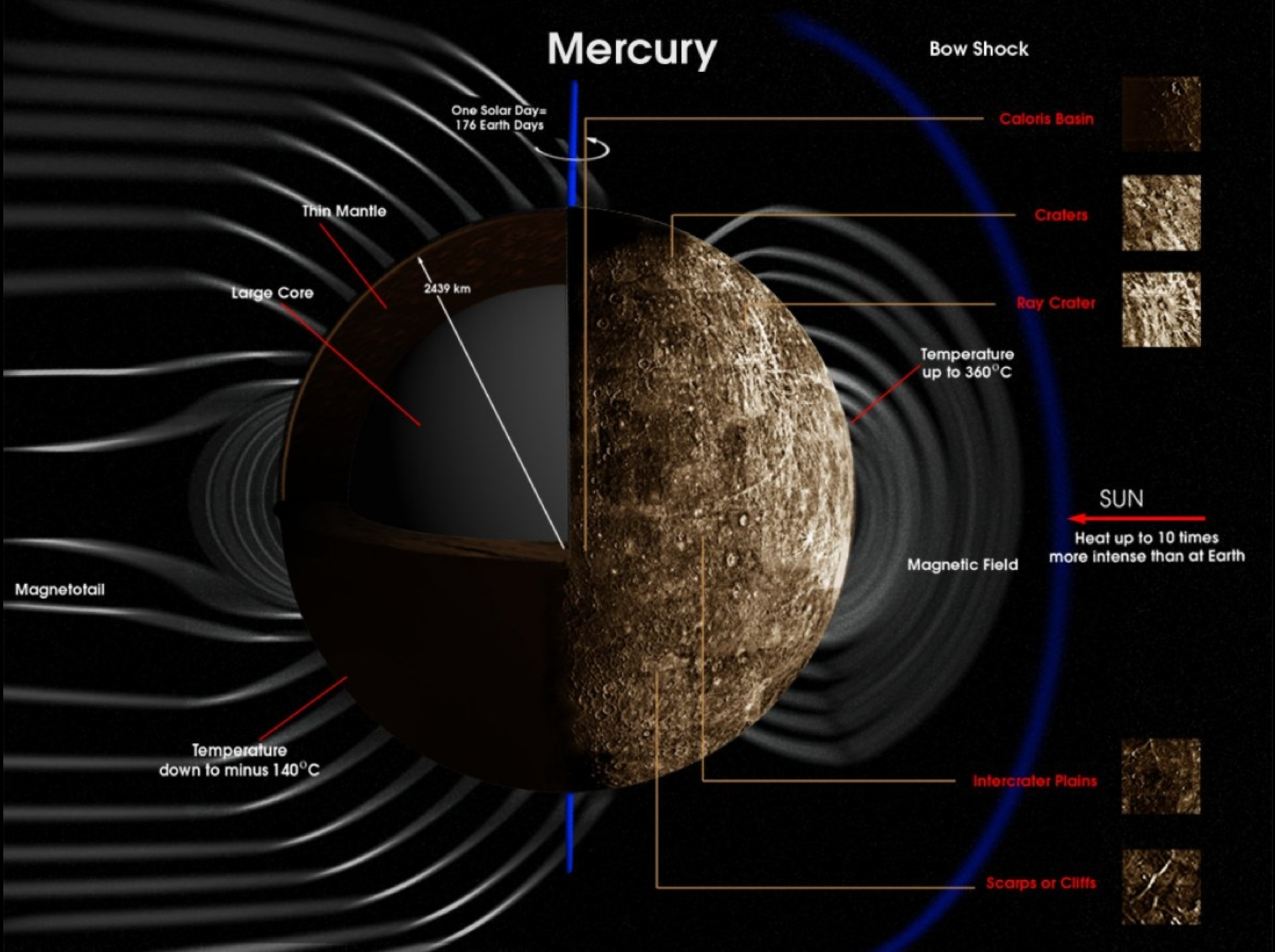
Inputs: height (in m), latitude and longitude (in degrees), year (as a real number)

Outputs: xyz are the components of the magnetic field vector in nT, h the horizontal component, dec the magnetic declination, dip the magnetic inclination, and f the norm of the magnetic field vector.

Earth's Internal Structure



- crust
- mantle
- core



Mercury
Bow Shock
One Solar Day=
176 Earth Days
Caloris Basin
Thin Mantle
Craters
Large Core
2439 km
Ray Crater
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

Embedded question

A satellite is moving at a height of 400 km and has a small magnet with a magnetic moment of 0.1 A·m^2. Determine the magnetic torque experienced by the satellite. Is it a useful torque for some purpose?

Recall that $\vec{\tau} = \vec{\mu} \times \vec{B}$ and use that $\vec{B}_{\oplus}\,(400\ \mathrm{km}) = (19451, -200, 33674)\ \mathrm{nT}$. Assume that the magnet is oriented along the third axis: $\vec{\mu} = (0, 0, 0.1)\ \mathrm{Am}^2$.

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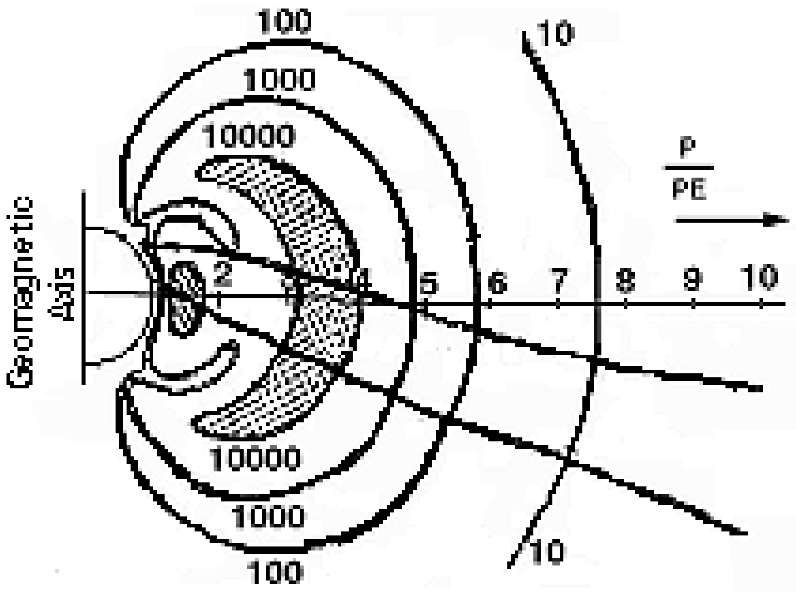
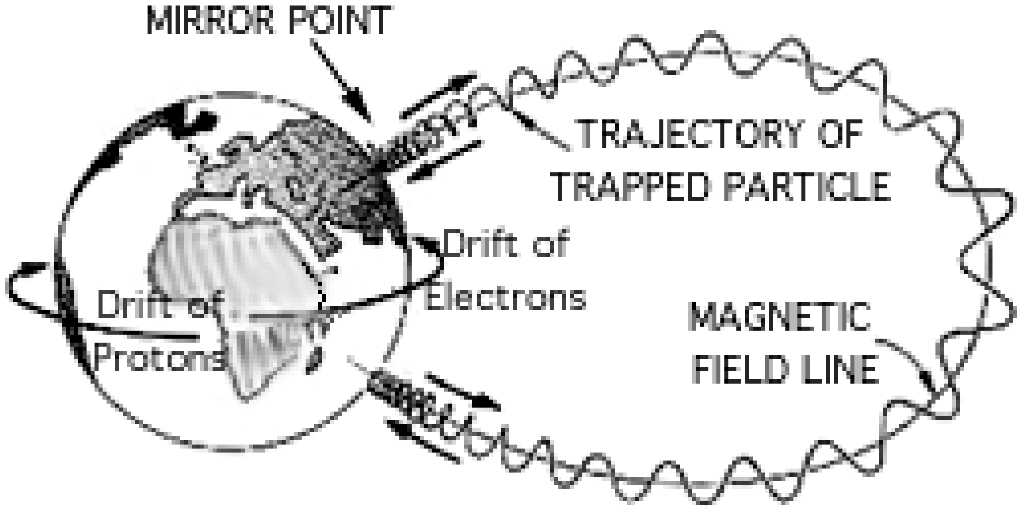
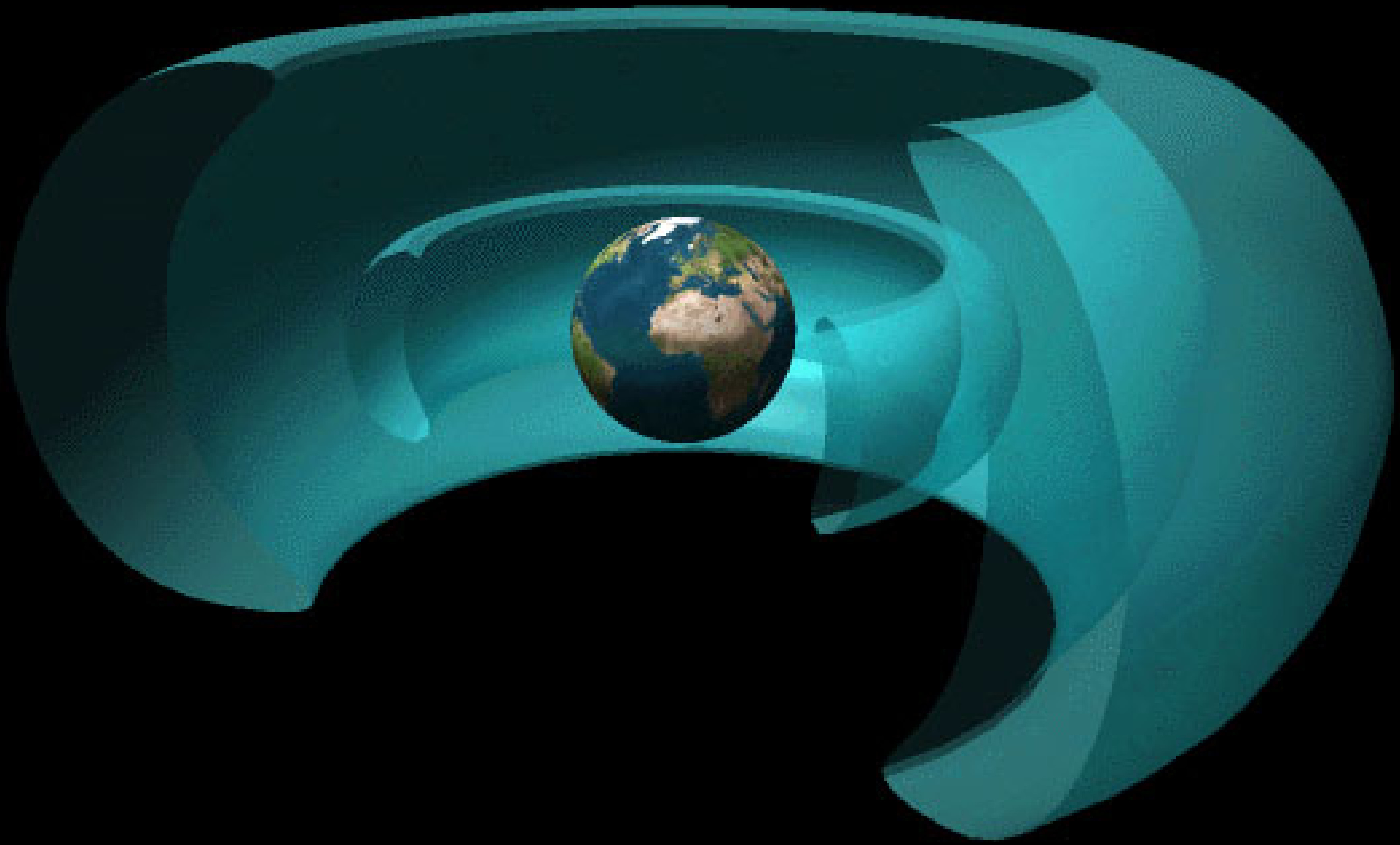
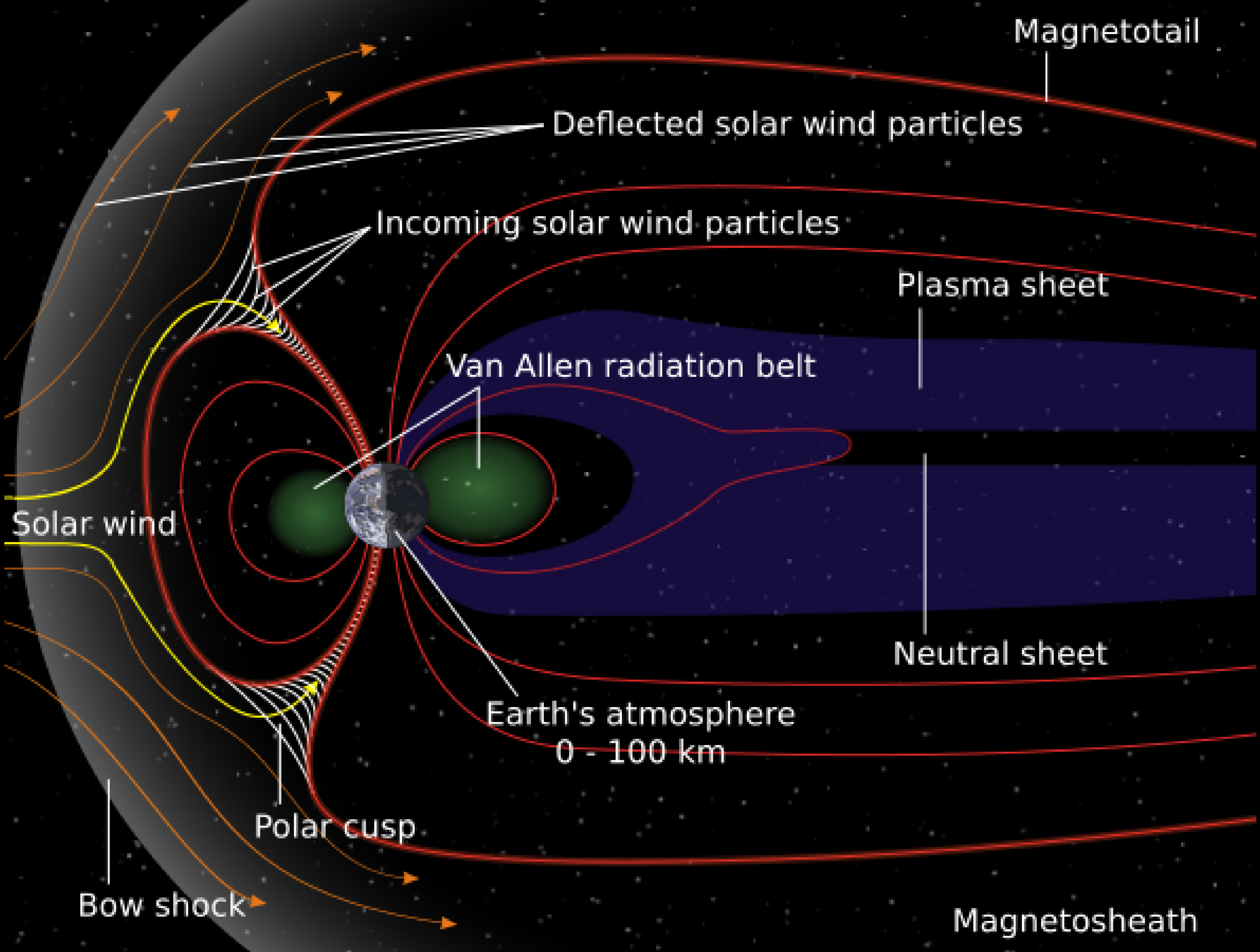




$$\vec{F} = q(\vec{v} \times \vec{B})$$

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

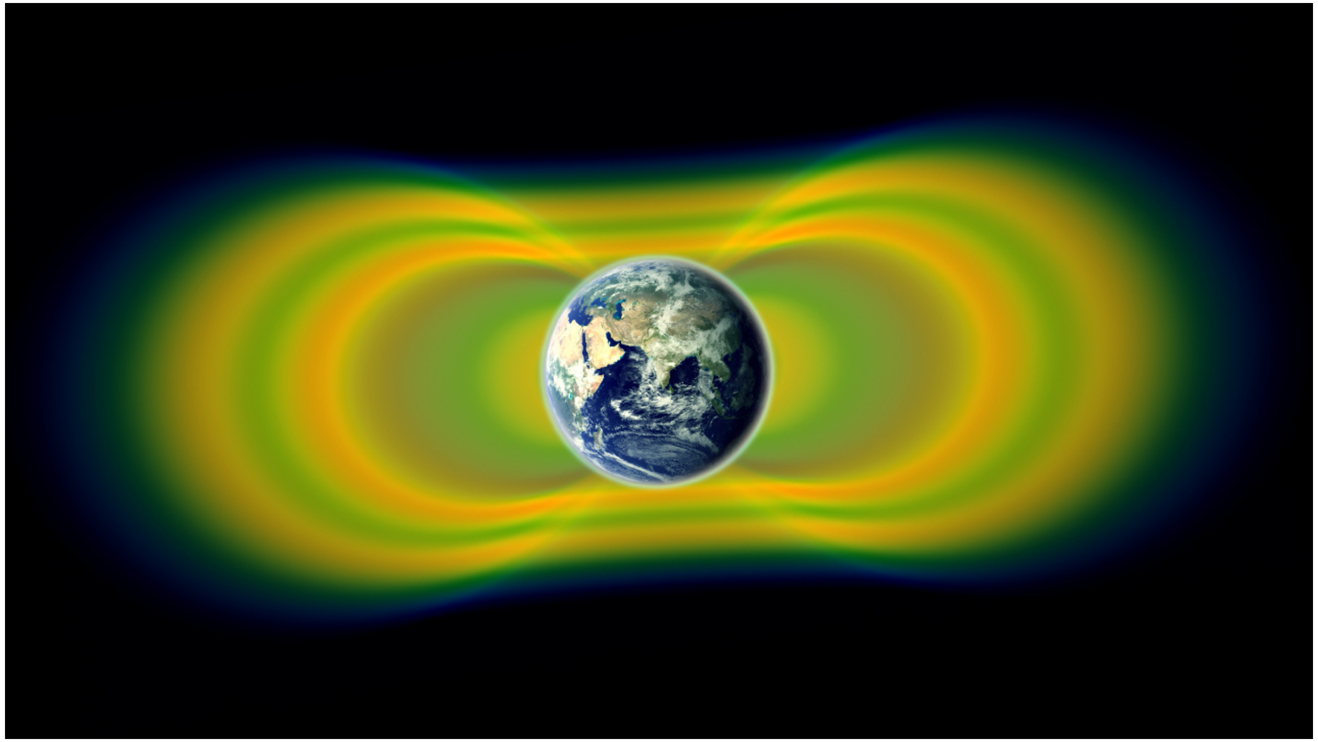
- Proton models:
  - Solar minimum: AP8MIN
  - Solar Maximum: AP8MAX
- Electron models
  - Solar minimum: AE8MIN
  - Solar maximum: AE8MAX

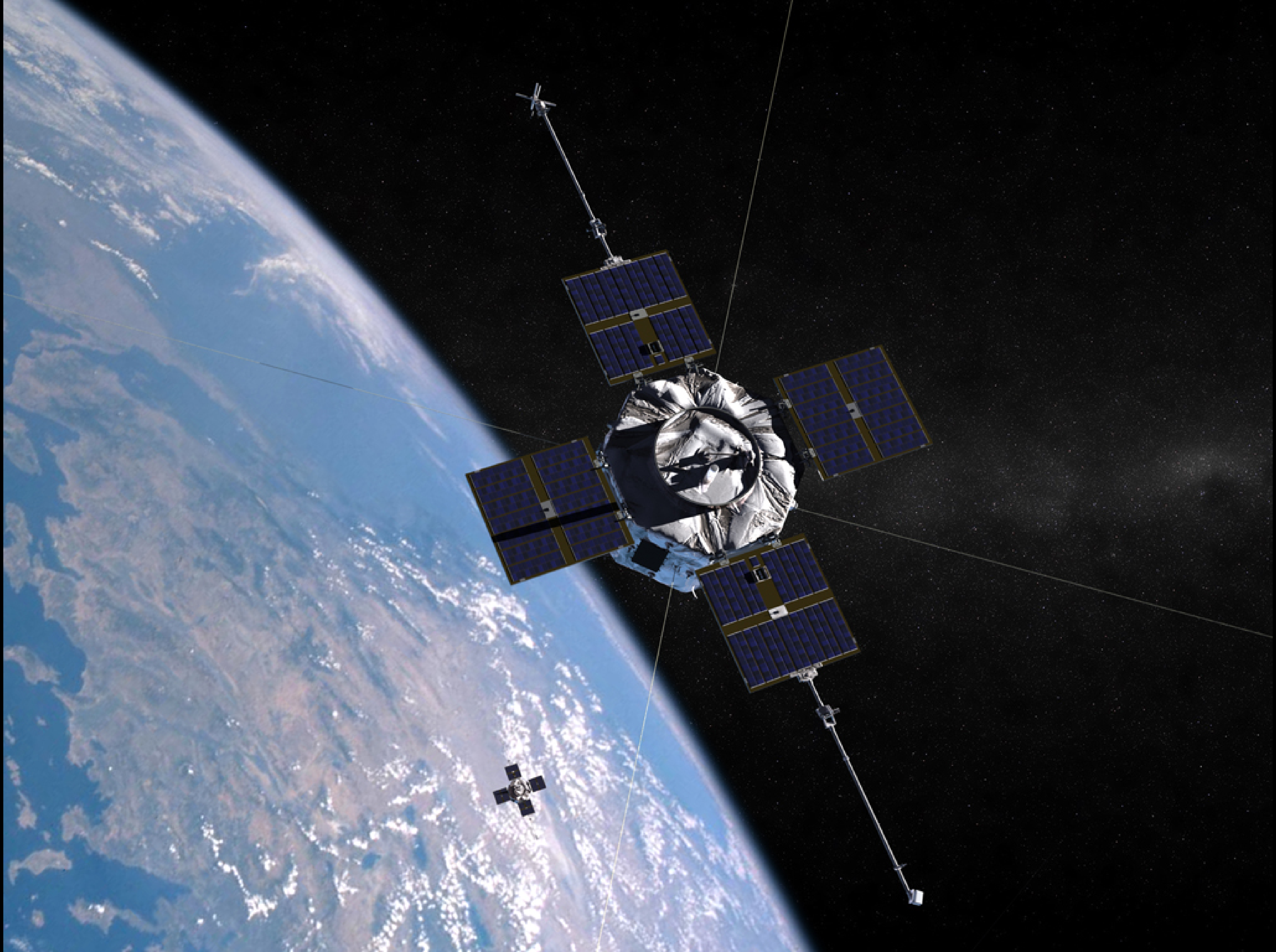
http://nssdcftp.gsfc.nasa.gov/models/radiation_belt/radbelt/

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

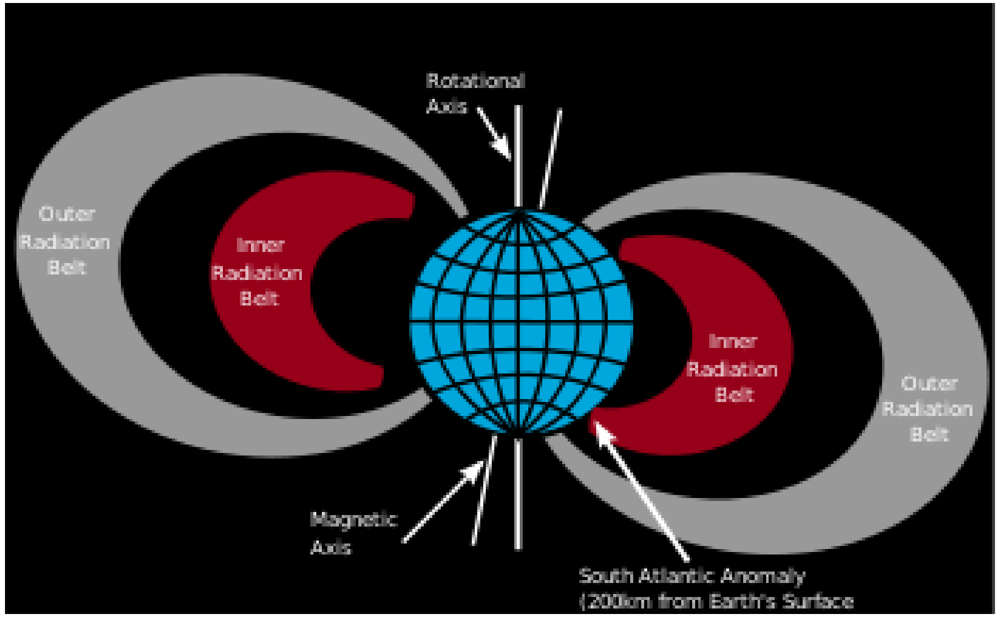




The South Atlantic Anomaly

The South Atlantic Anomaly is due to a lack of homogeneity in the proton belt

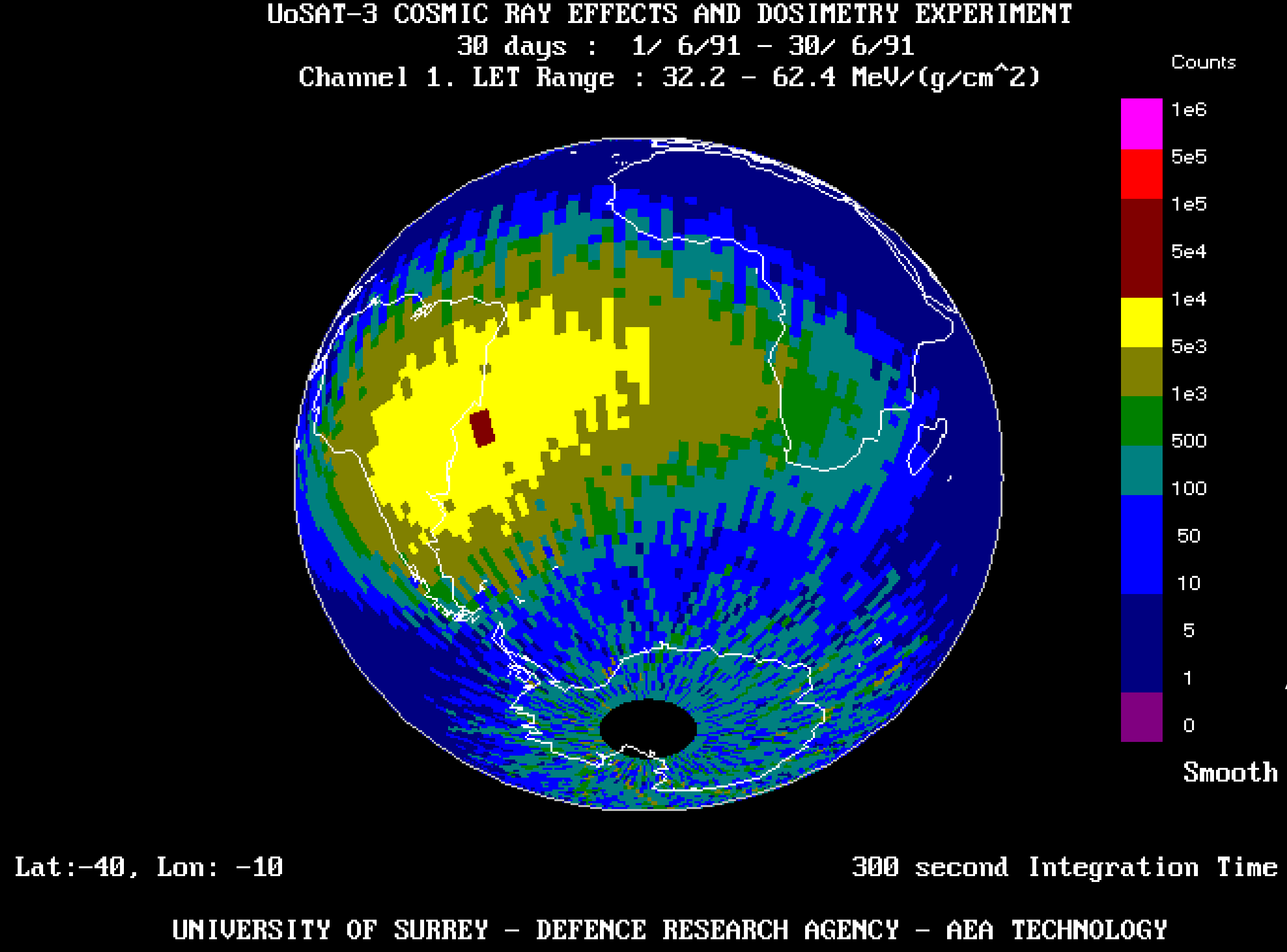
- The magnetic field of the Earth is off-center (by about 500 km)
- The magnetic axis is tilted 11 deg with respect to the rotation axis of the Earth



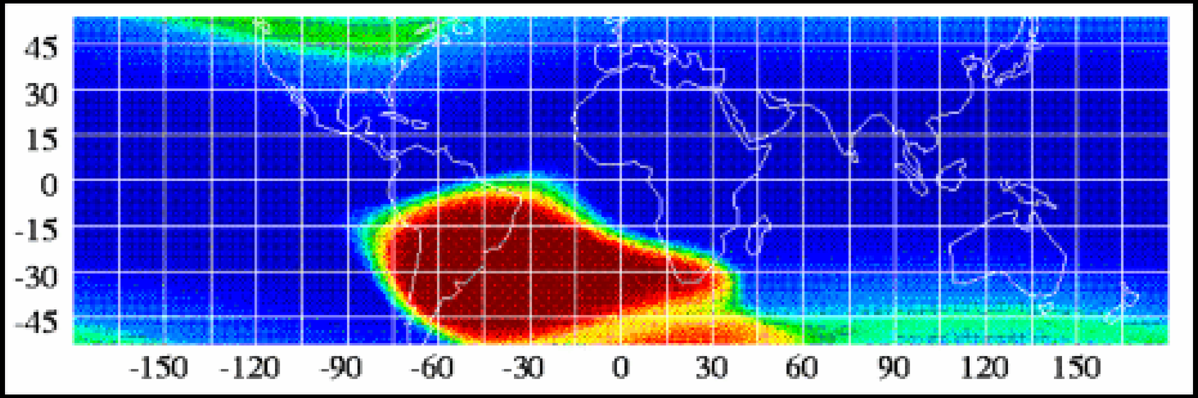
Radiation Effects

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

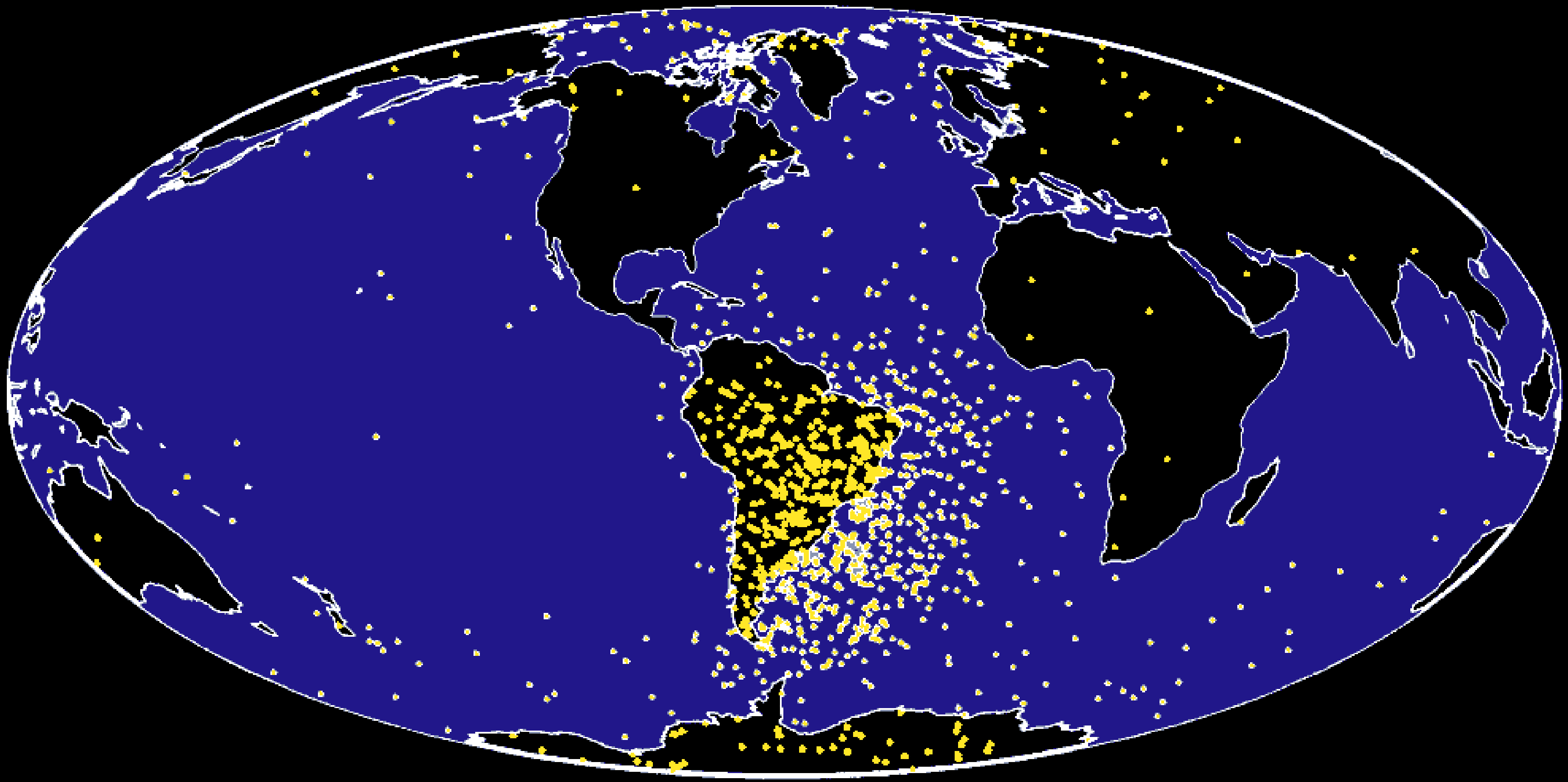
- The magnetic field of the Earth is off-center
- The magnetic axis is tilted with respect to the rotation axis of the Earth

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

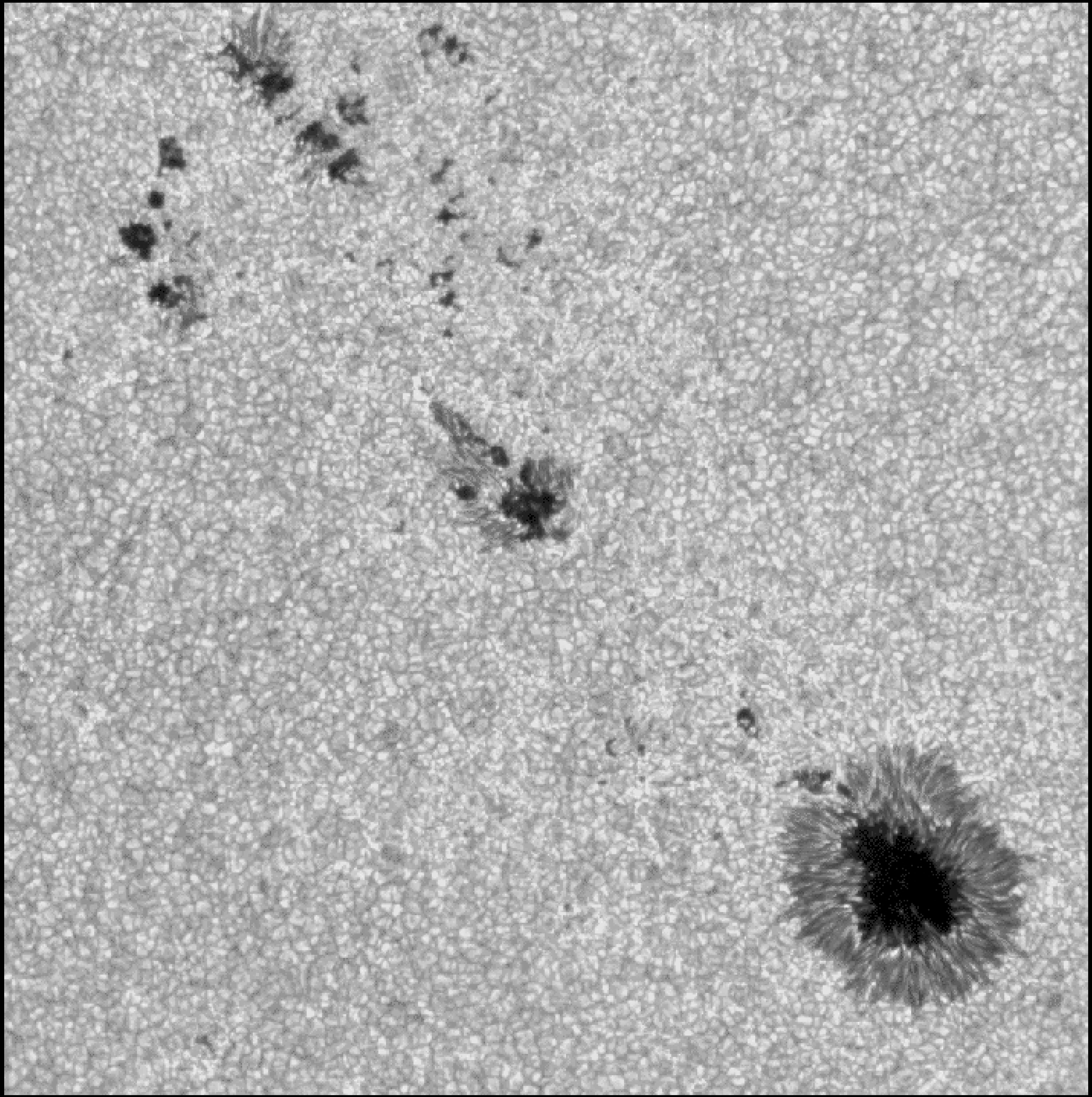
NOAA/NGDC Boulder

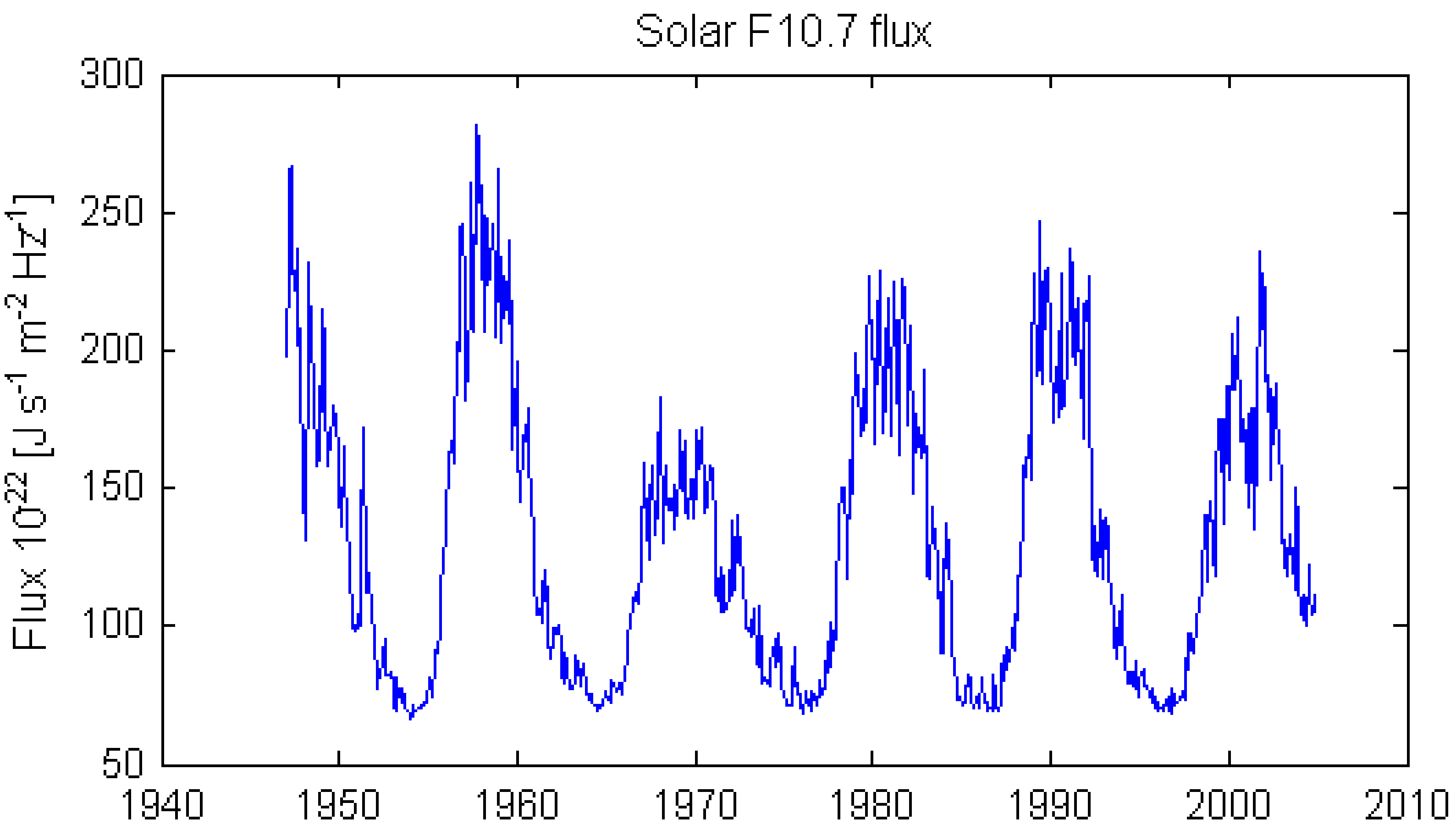
The Solar Cycle

The Sun experiences substantial changes in its activity with a period of ~11.2 years:

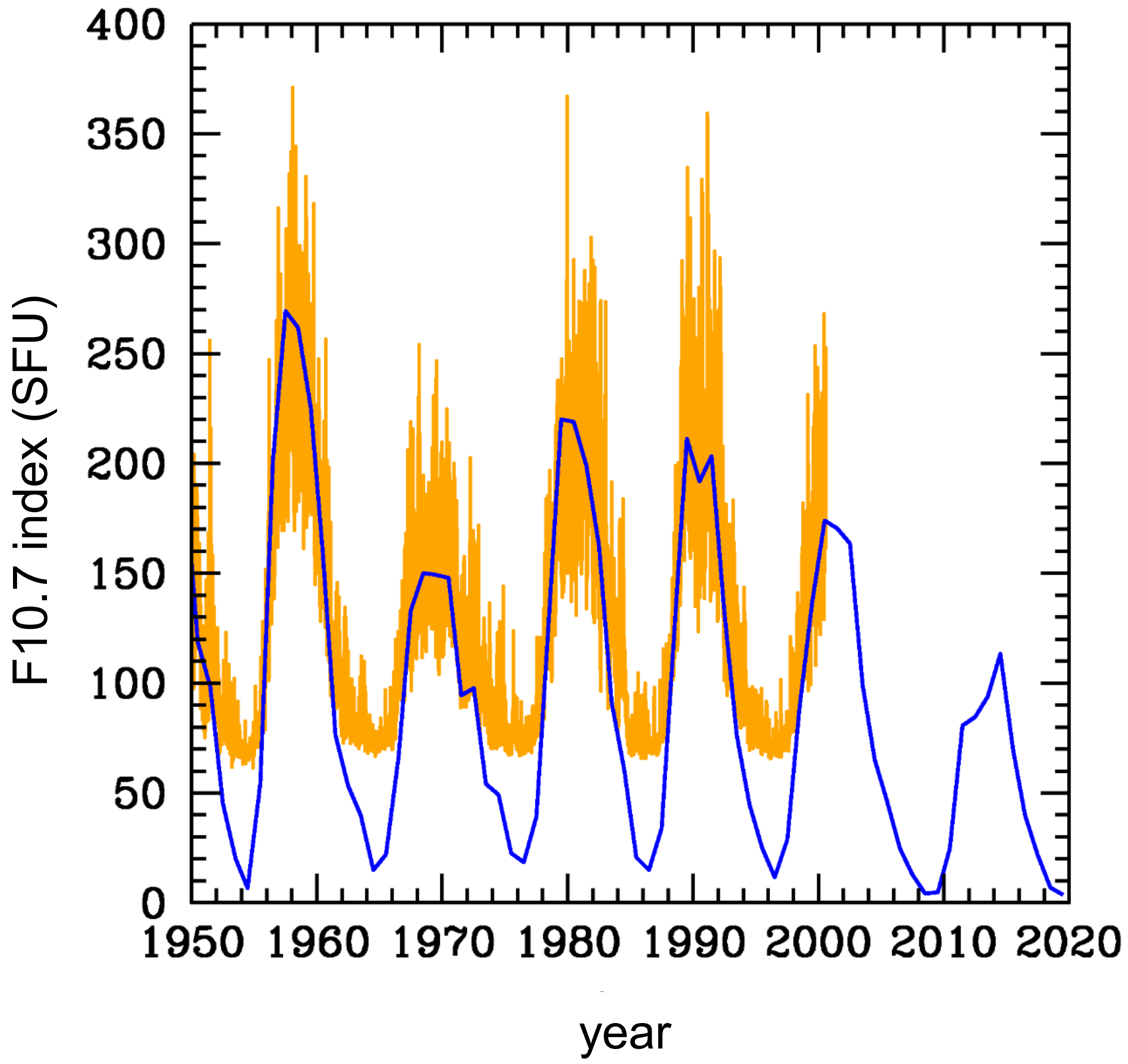
- Increased number of sunspots
- Increased number of energetic particle ejection
- Increase in the mean energy of particles

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

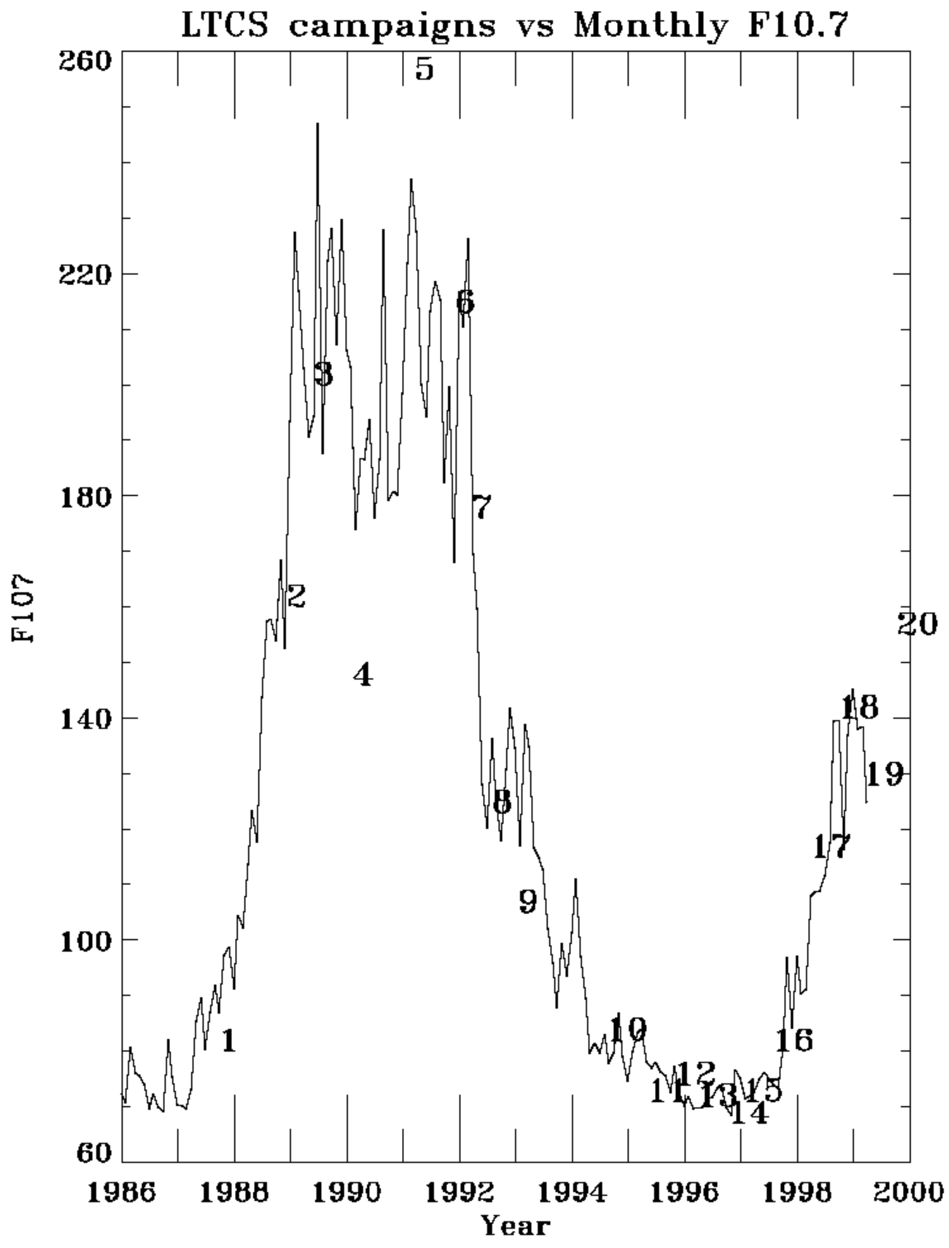




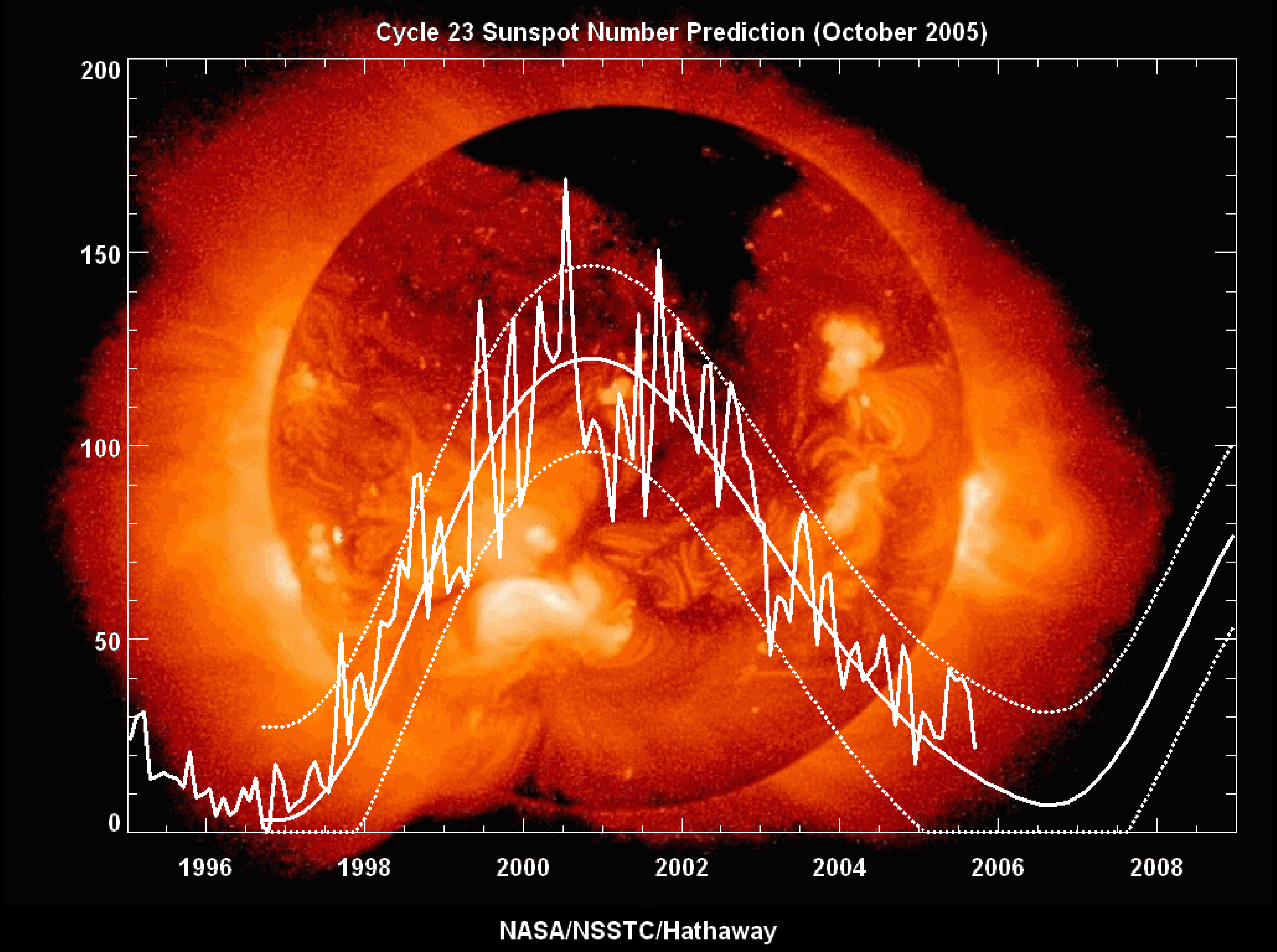
Variation of the F10.7 index throughout the last 60 years



Correlation between the F10.7 index and the sunspot index

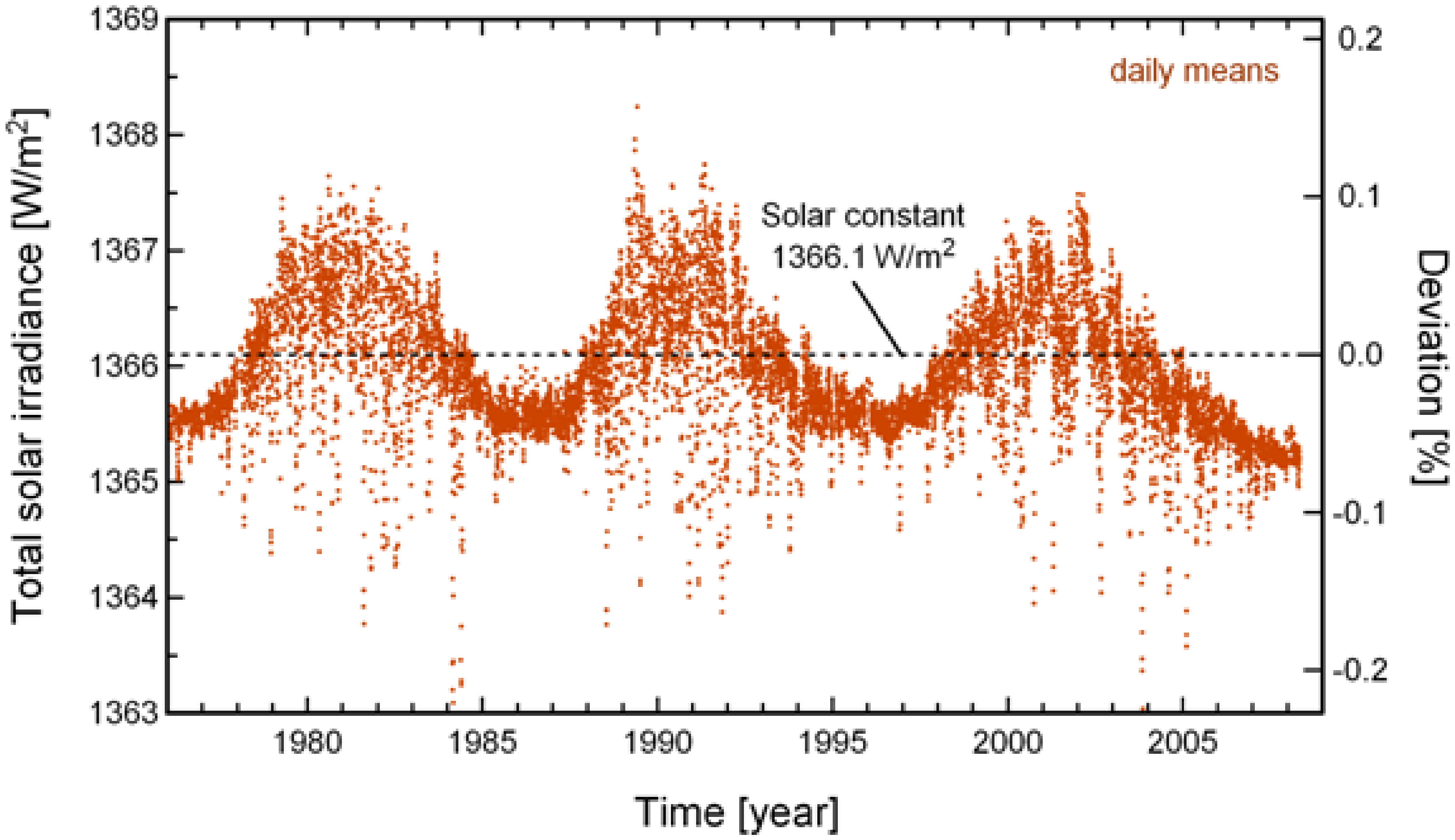


The structure of the F10.7 peaks is highly variable and difficult to predict



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

Despite the changes in solar activity, the extra-atmospheric irradiance is very stable



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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

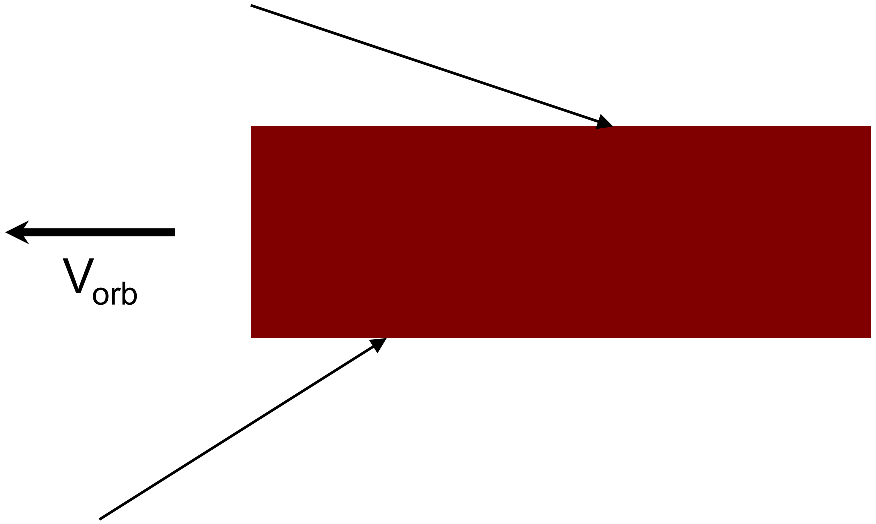
$$a = -0.5\left(\frac{C_D\,A}{m}\right)\rho\,v^2$$

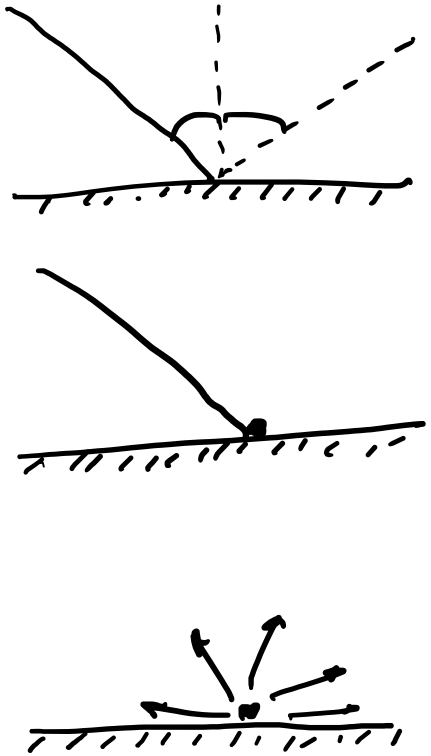
$$\overset{m \cdot a}{\overset{\parallel}{D}} = \frac{1}{2}\rho v^2 S C_D$$

- One of the most popular models is MSISE00 (https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php)

The Upper Atmosphere

- For most satellites $C_D \approx 1.90 - 2.60$ $\quad C_D \simeq 2.2 - 2.4$
- The presence of solar panels induce a lateral drag due to the thermal movement of the atmospheric constituents





specular reflexion

diffuse reflexion

?

Maxwell-Boltzmann Distribution

The particles of a gas at a macroscopic temperature T move at different speeds. In normal gases (or plasmas), the distribution of velocities follow the Maxwell-Boltzmann distribution

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

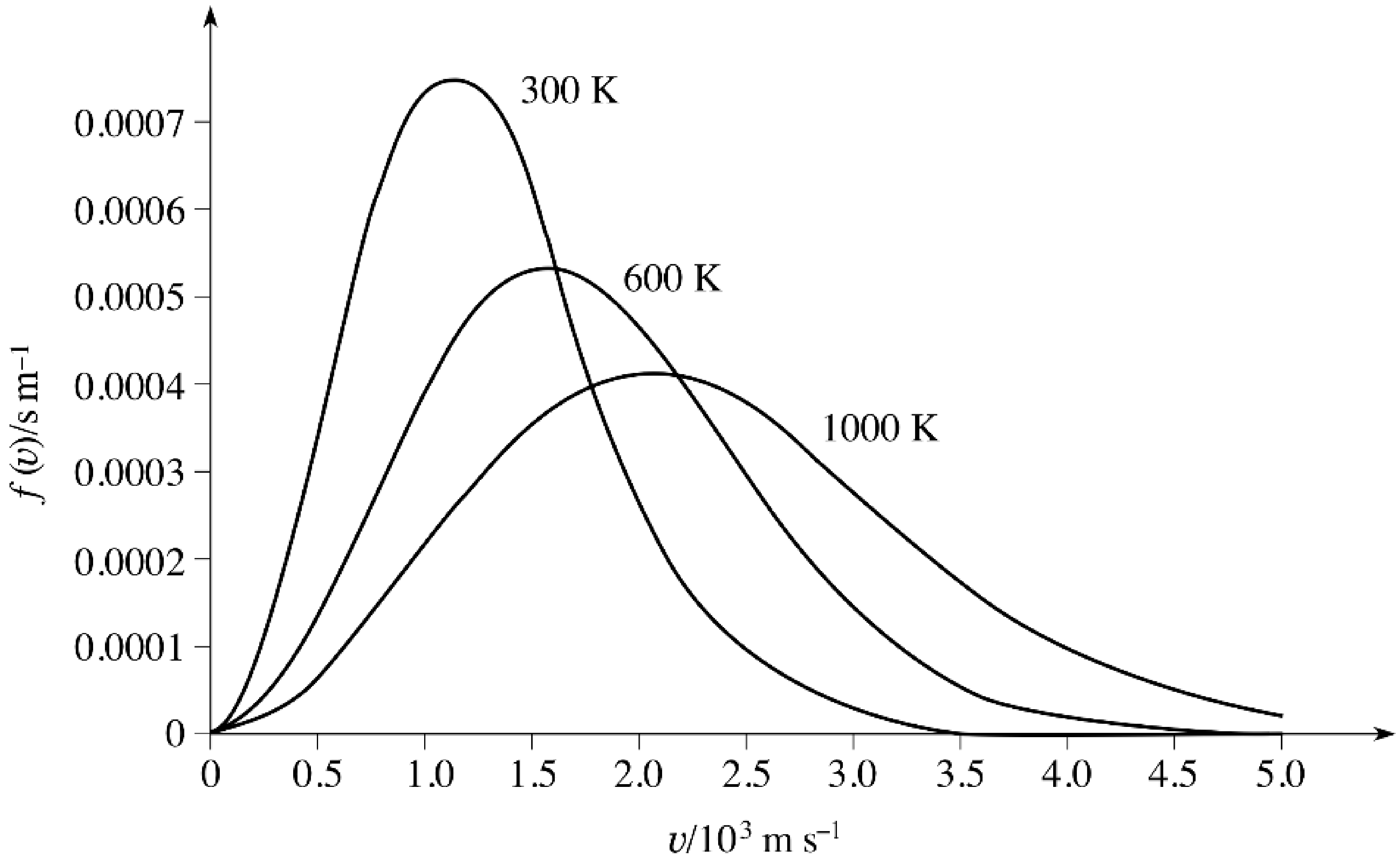
Maxwell-Boltzmann Distribution

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 ($Kn > 10$)

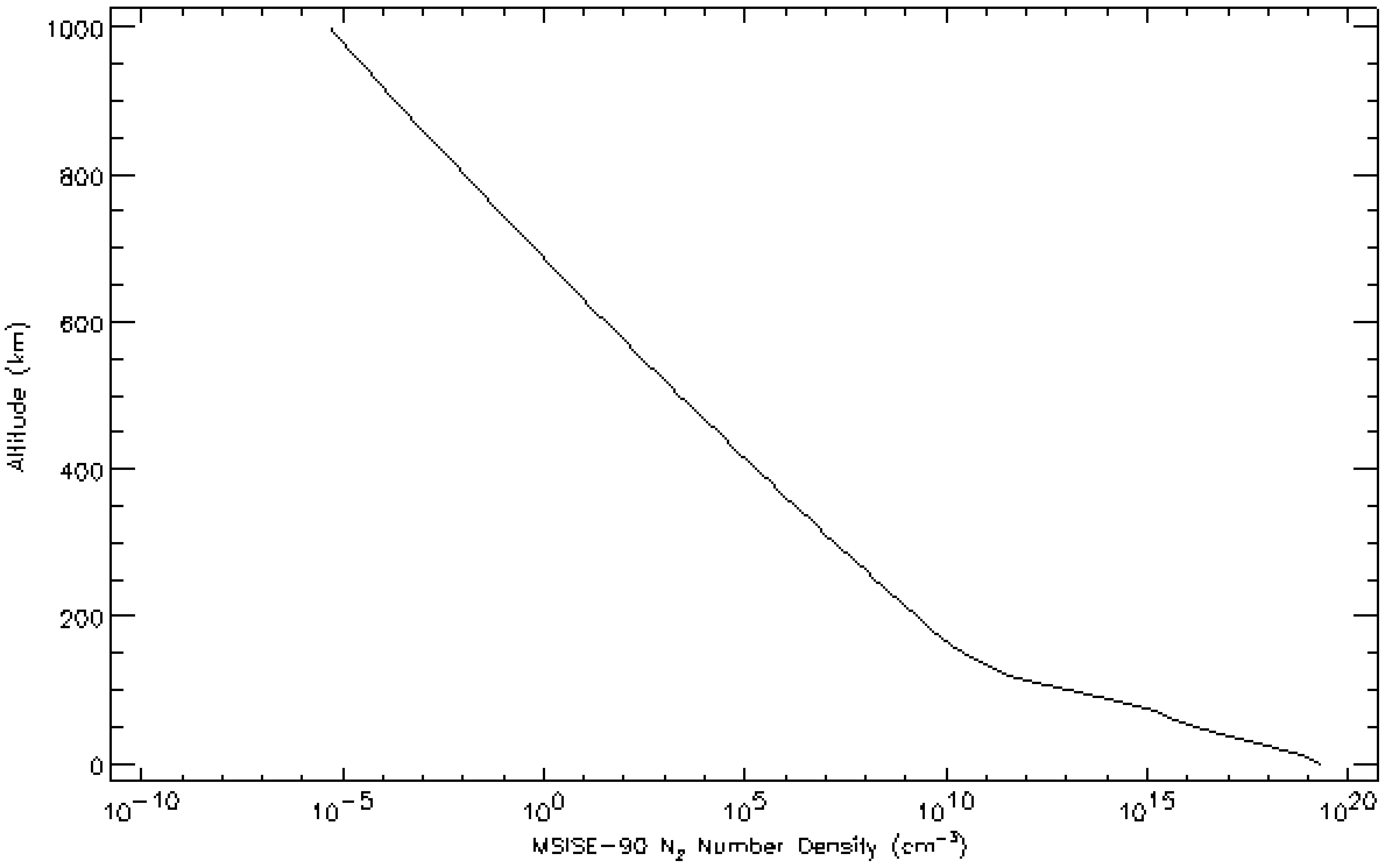
It is defined as

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

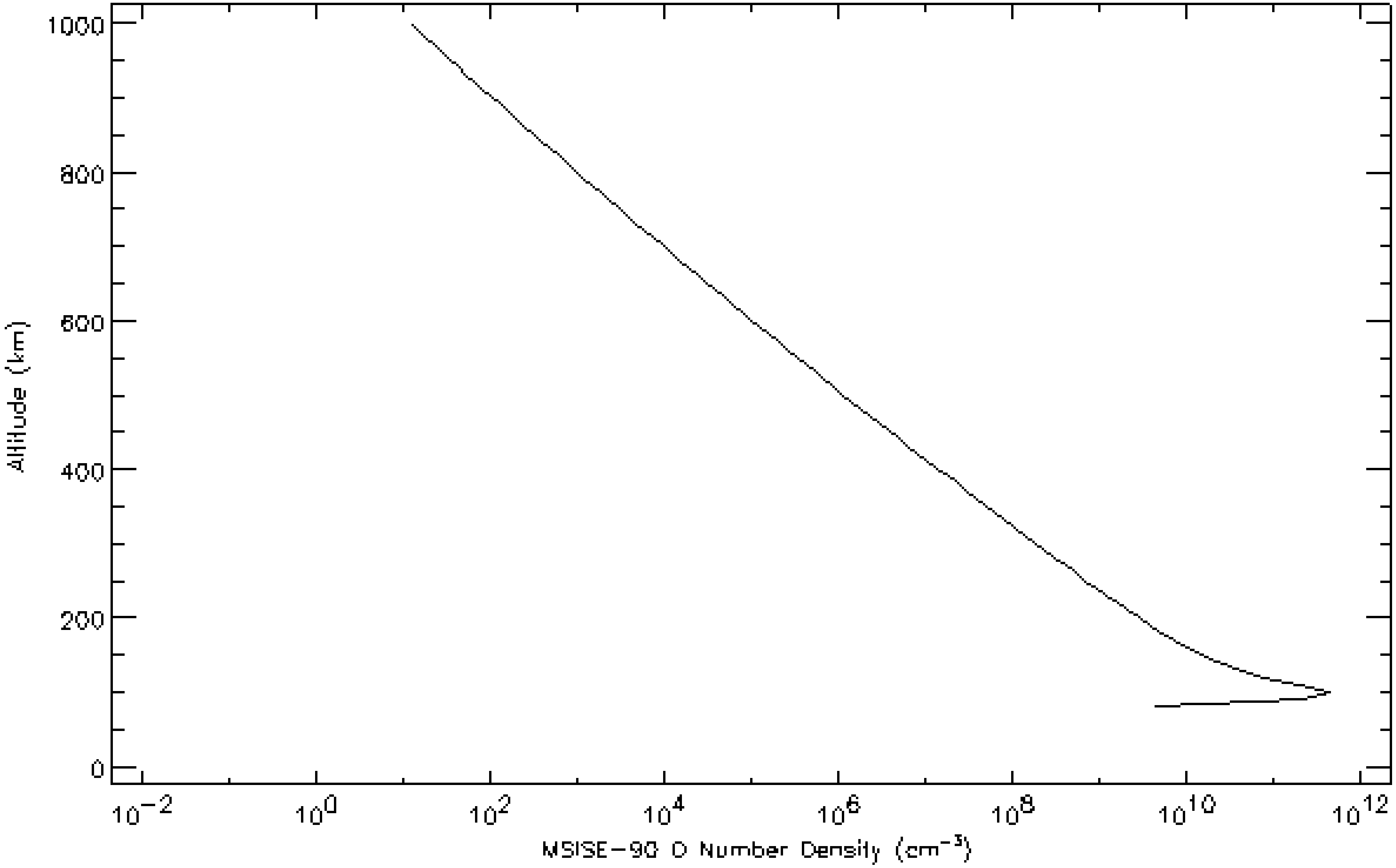
$$\lambda = \frac{k_B T}{\sqrt{2}\pi \sigma^2 P}$$

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

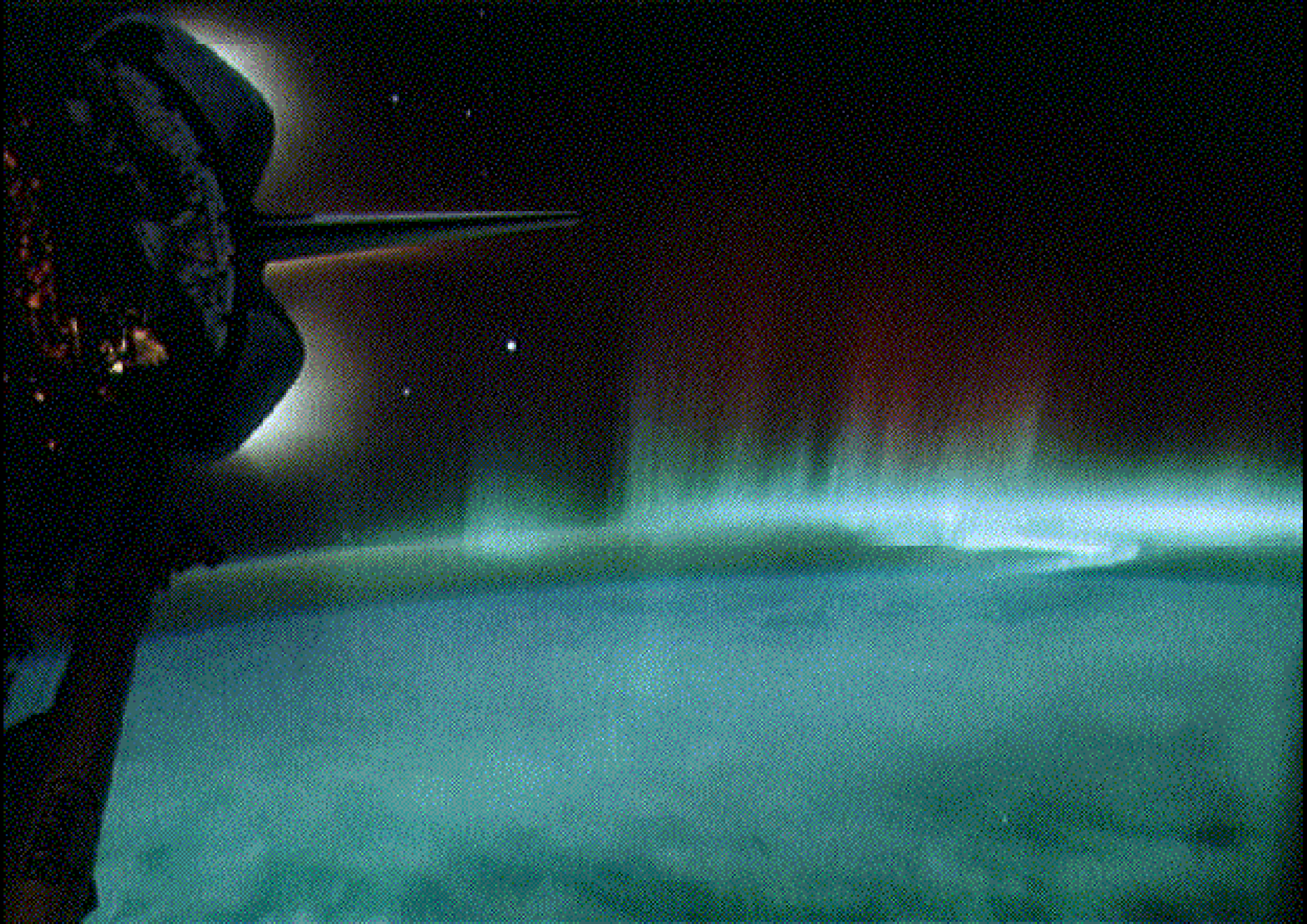
In LEO $Kn \gg 1$ always

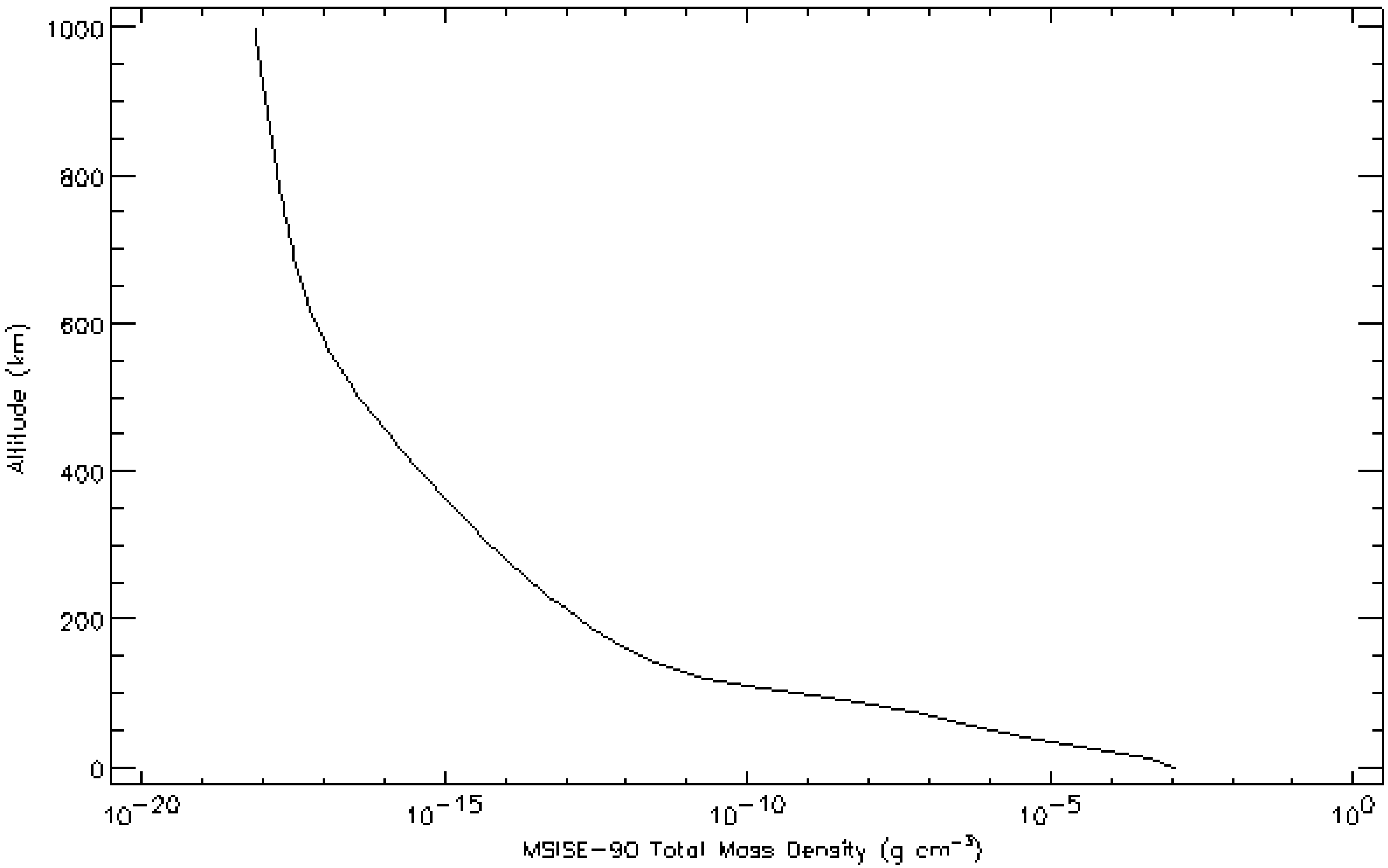


1000
800
600
400
200
0
Altitude (km)
10^-10
10^-5
10^0
10^5
10^10
10^15
10^20
MSISE-90 N2 Number Density (cm^-3)



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

There are also changes caused by climatic change (CO_2 diffuses to the upper atmosphere)

The region between 120 km and 600 km belongs to the thermosphere (with T in the range 600 K to 1200 K)

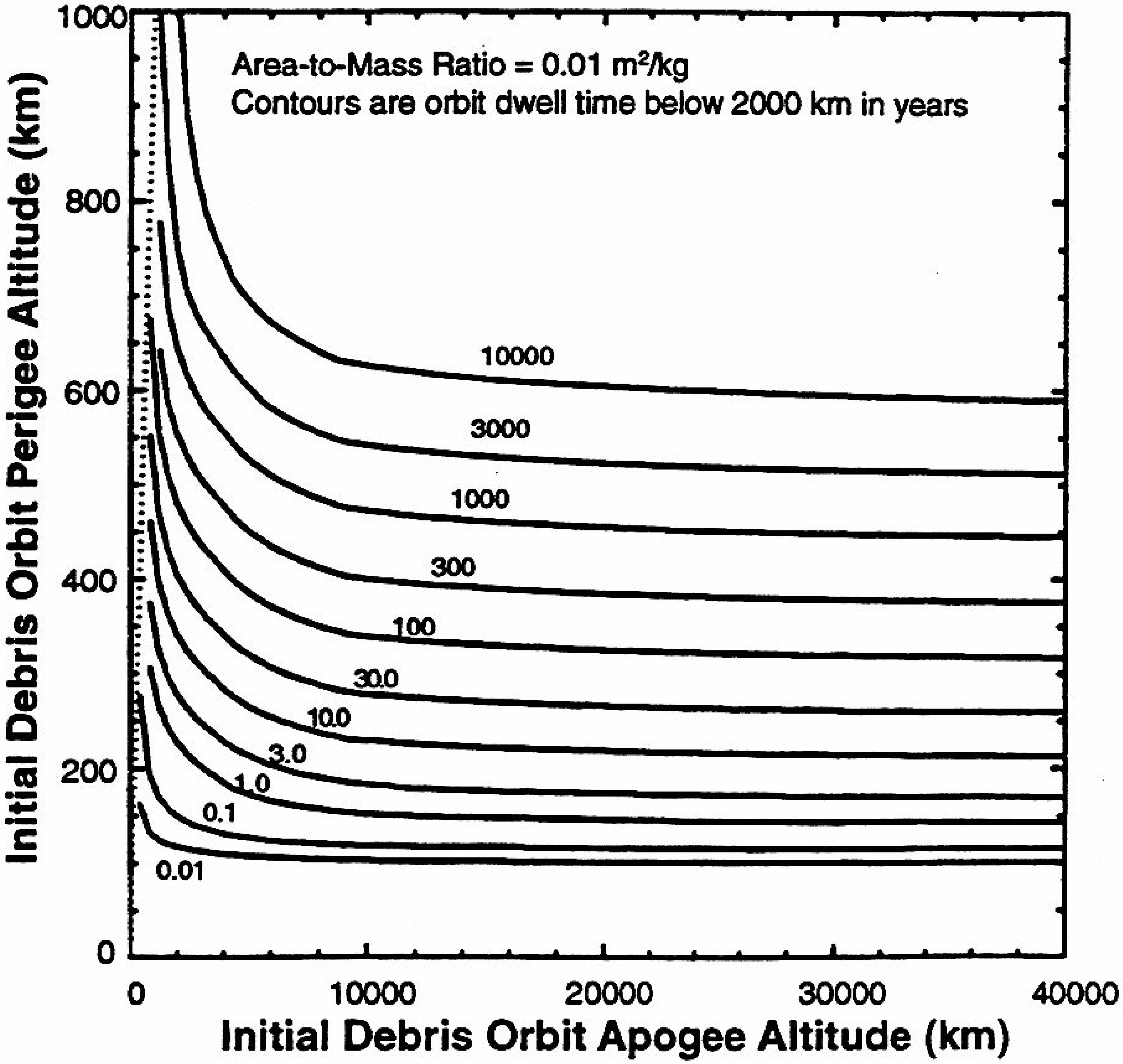
- Heated by XUV

Effects of the Upper Atmosphere

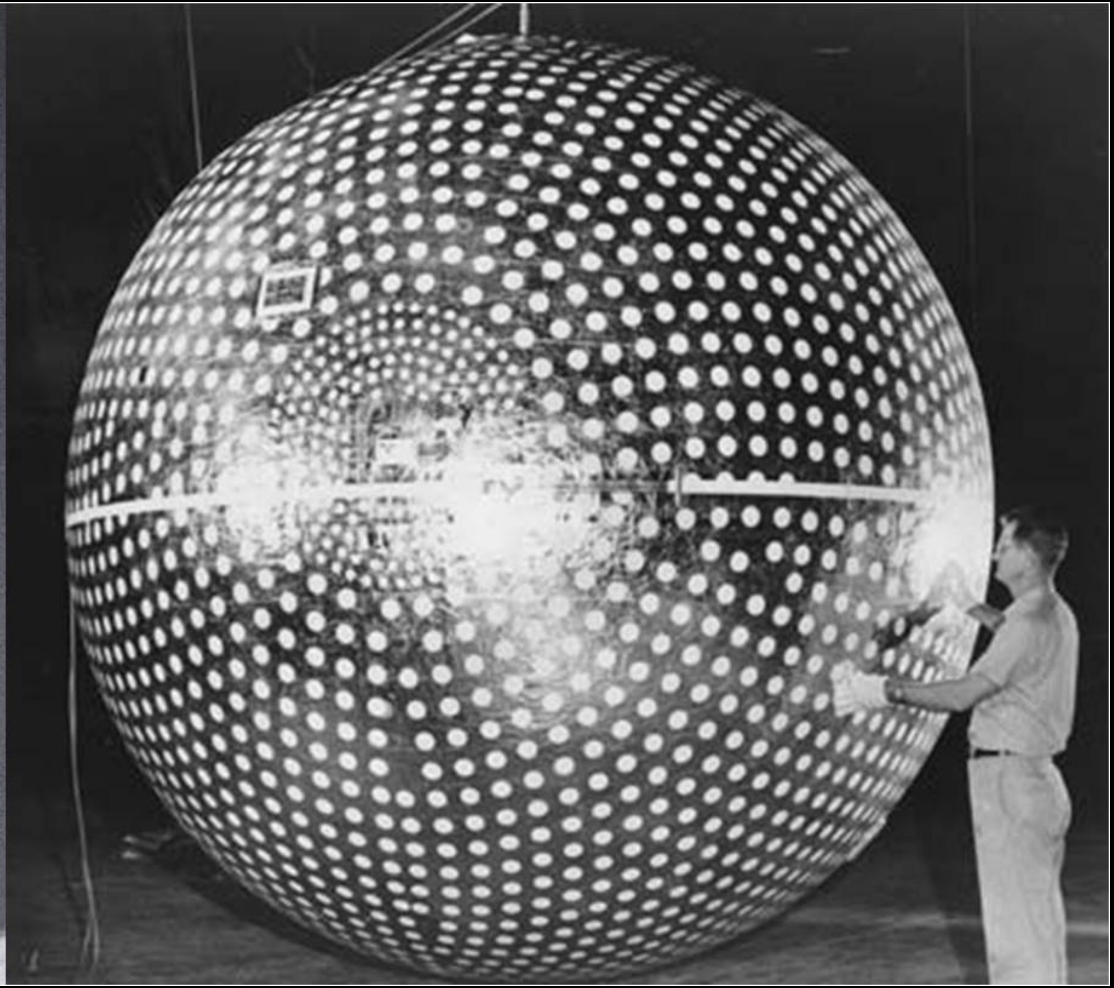
- Aerodynamic drag which can lead to orbit decay
  - Depends of ballistic coefficient

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

- 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)
0
200
400
600
800
1000
Initial Debris Orbit Apogee Altitude (km)
0
10000
20000
30000
40000



Mass = 7 kg
Diameter = 3.7 m
BC = 0.326 kg/m^2 (C_D=2.0)

Apogee = 2581 km
Perigee = 635 km
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

Embedded question

A spherical satellite is in VLEO at 355 km of height. Determine its specific mechanical energy, and make a rough guess of the energy lost during a single orbit due to drag. Assume $C_D = 2.4$, $A = 0.15\ \mathrm{m}^2$, and $M = 5.7\ \mathrm{kg}$. Use that $\rho = 2.376 \times 10^{-15}\ \mathrm{g\,cm^{-3}}$.

$\mathcal{E} = \frac{v^2}{2} - \frac{\mu}{r} \quad \frac{J}{kg}$ $\quad v = \left(\frac{\mu}{r}\right)^{1/2}$

$\Delta \mathcal{E} = D \cdot d$ ← Rough!

$d = 2\pi r$

Drama (ESA)

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)

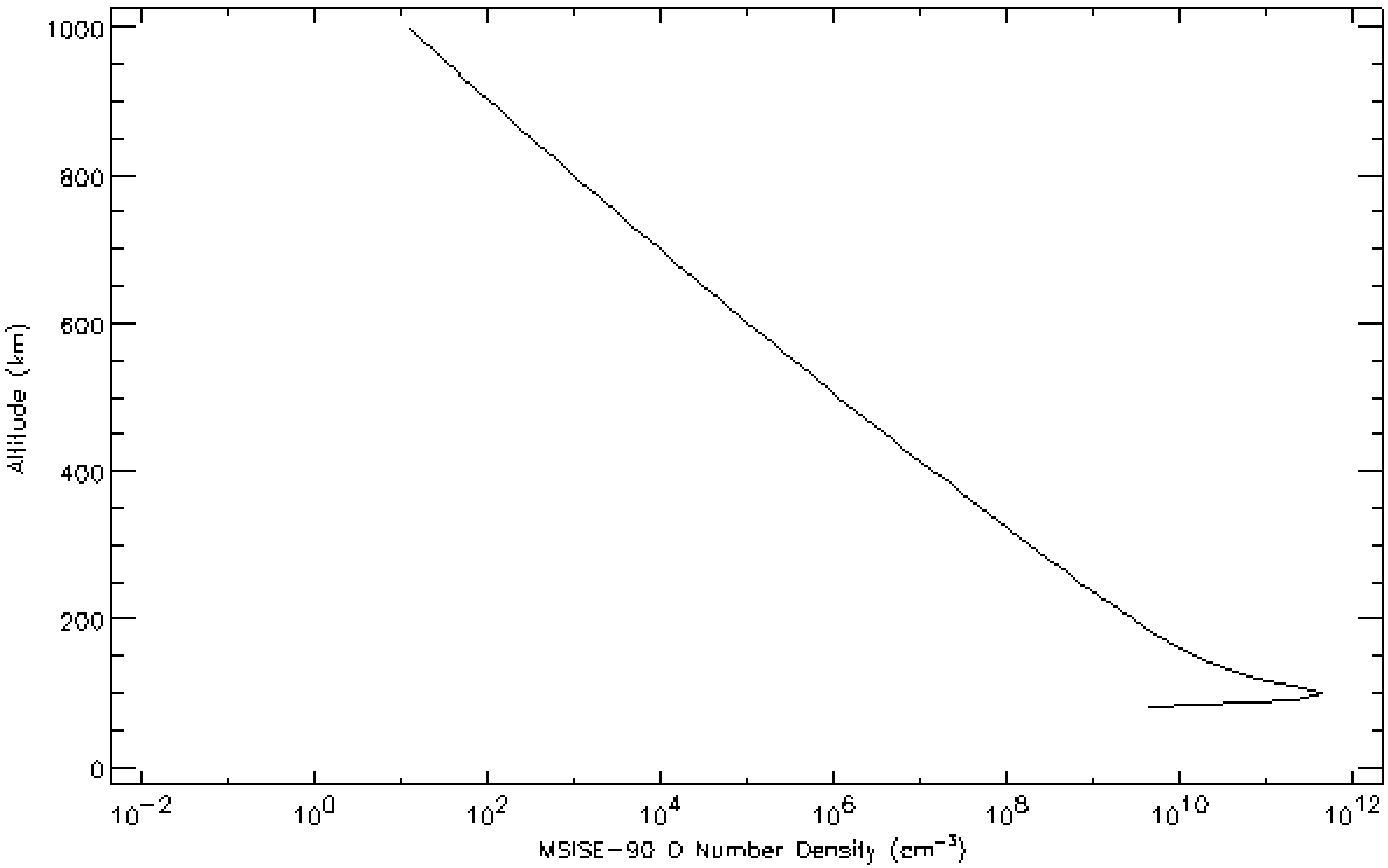
The mass lost by AO impacts is

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

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).

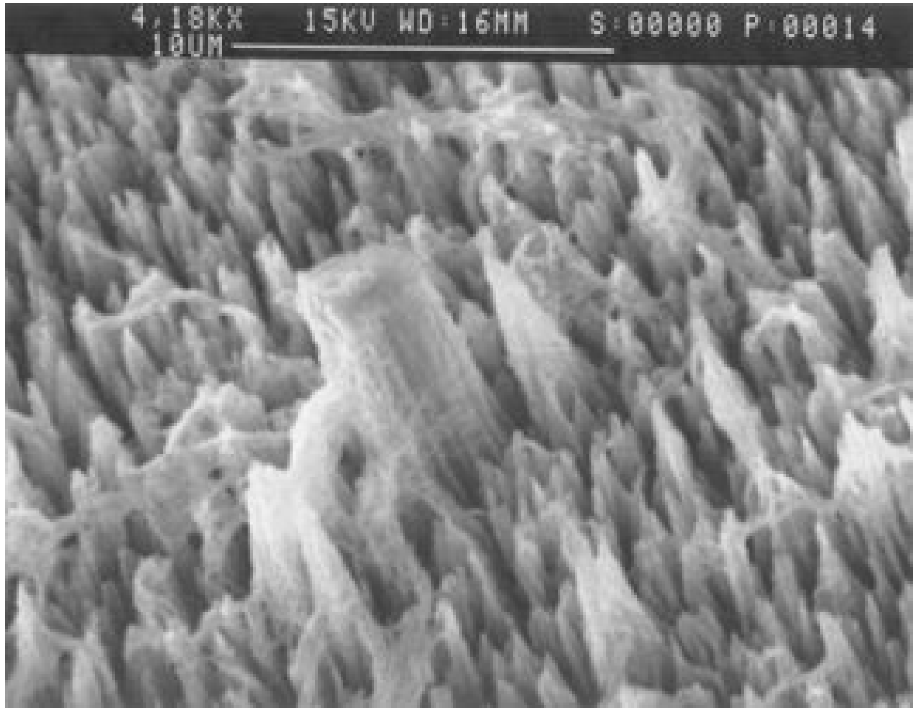
Al_2O_3

AgO



Altitude (km)
1000
800
600
400
200
0
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

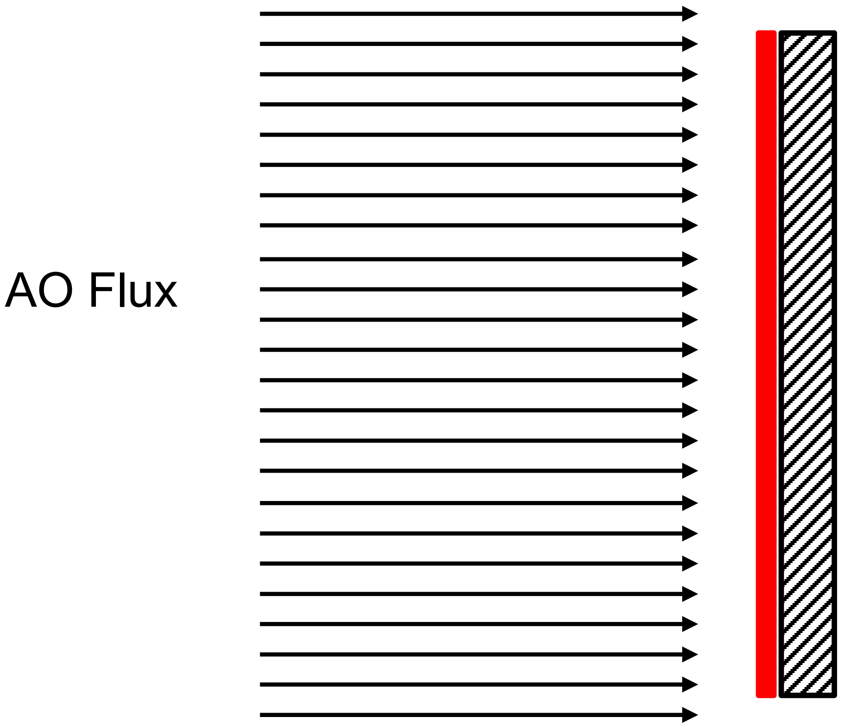
Atomic oxygen erosion (3)

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

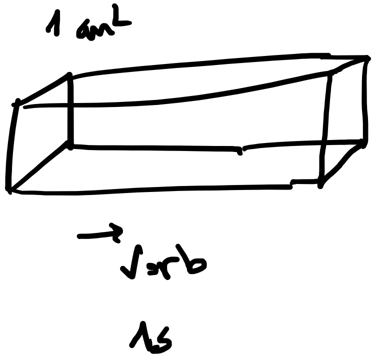
Target material	**RE** (10^{-24} cm^3/AO particle)
C	0.9 – 1.7
Teflon	0.03 – 0.50
Mylar	1.5 – 3.9
S13GLD (paint)	0.0
Kapton	1.4 – 2.5

Embedded question

A surface of a satellite is covered with a 0.1 mm layer of kapton and is always exposed to the ram at 90 degrees. If the satellite is at a height of 400 km, determine the survival time of the kapton layer if the density of AO is 2.9×10^{7} cm^{-3}.



RE = 2×10^{-24} cm^3/AO particle



$$V_{AO} = A \cdot v_{orb} \cdot \Delta t$$

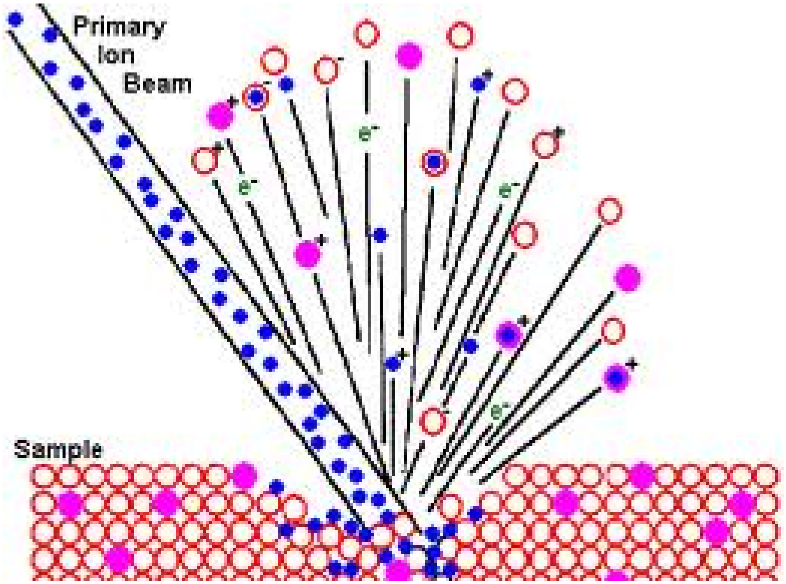
Sputtering (1)

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

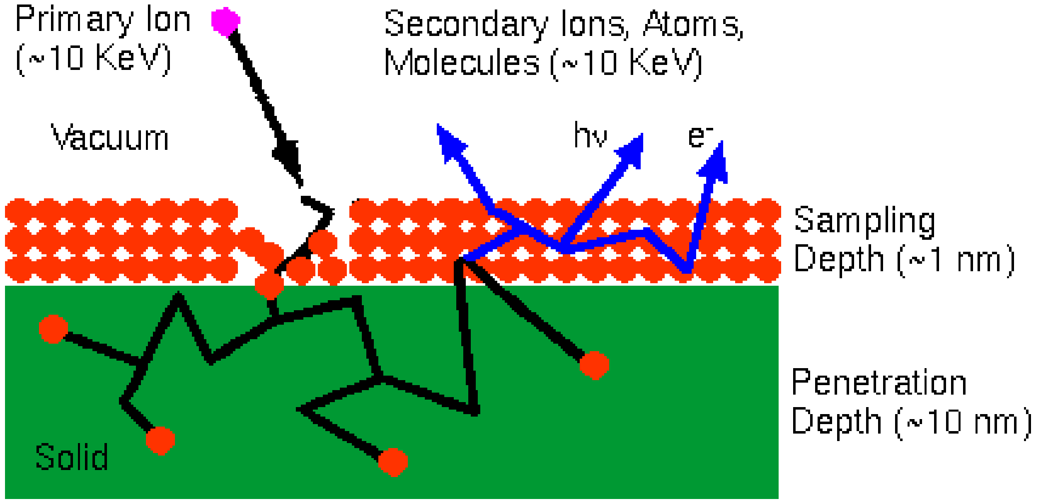
$1\,eV = 1e \cdot 1V = 1.6\,10^{-19}\,C \cdot 1V = 1.6\,10^{-19}\,J$

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

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

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

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

Syllabus

- Introduction
- Gravitational field
- Magnetic field
- Van Allen Belts
- The upper atmosphere
- **High vacuum effects**
- Cosmic Rays
- Space Debris and Micrometeoroids

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 $\sim$0.1 Pa, and at 350 km is $\sim 10^{-4}$ 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 ($Kn \gg 1$).

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 $\phi(t,T)$ 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

Syllabus

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- Gravitational field
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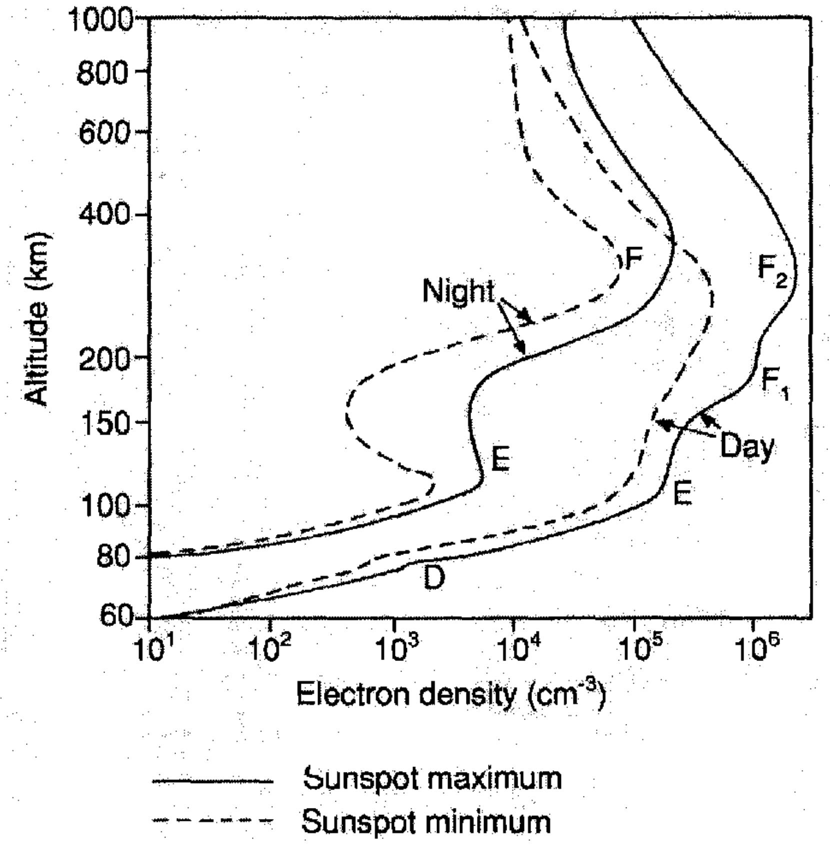
- High vacuum effects
- **The plasma environment**
- Cosmic Rays
- Space Debris and Micrometeoroids

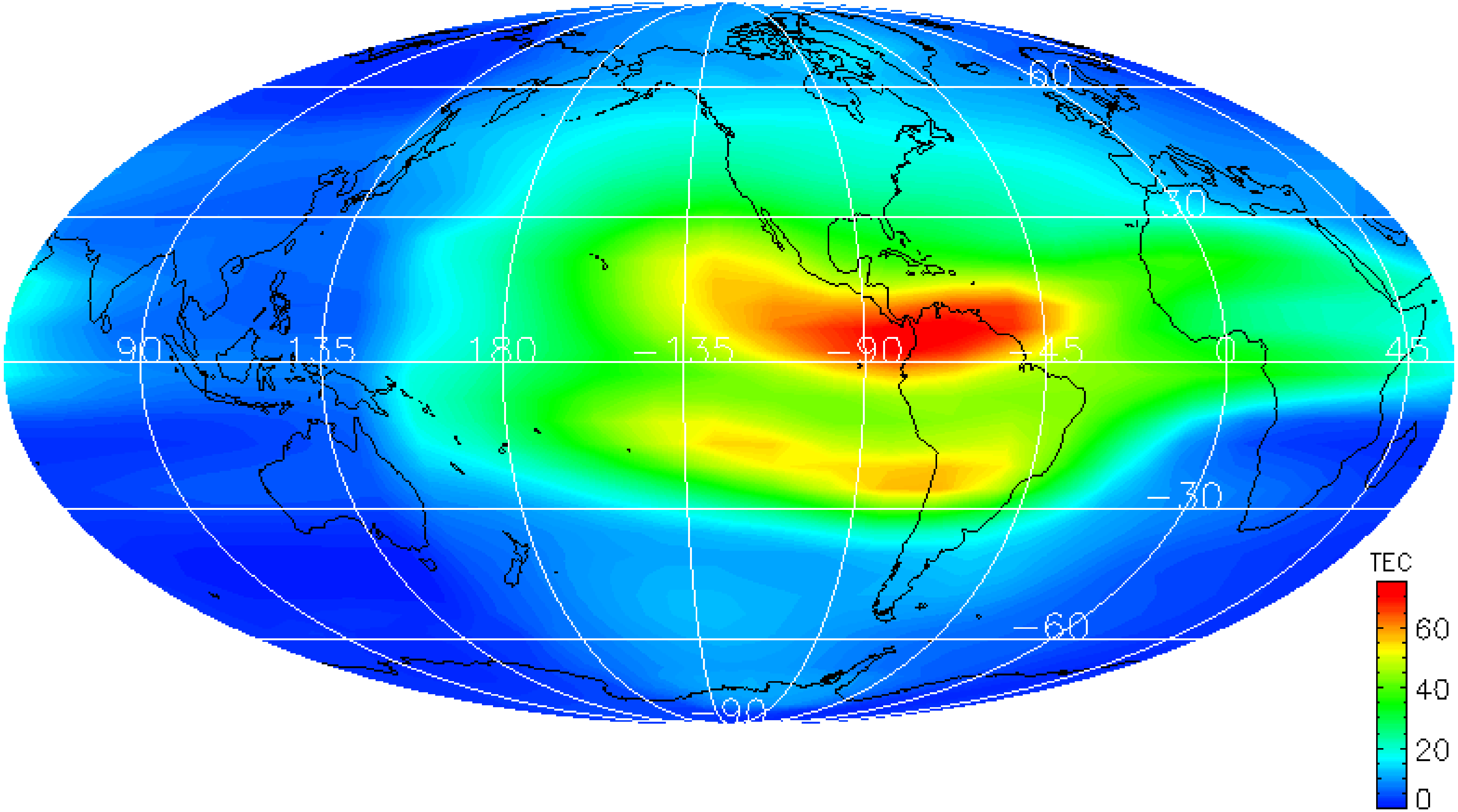
The plasma environment

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

11



The plasma environment



The plasma environment

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

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

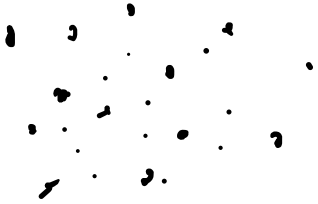
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t}$$

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

The plasma environment

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

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



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

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

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

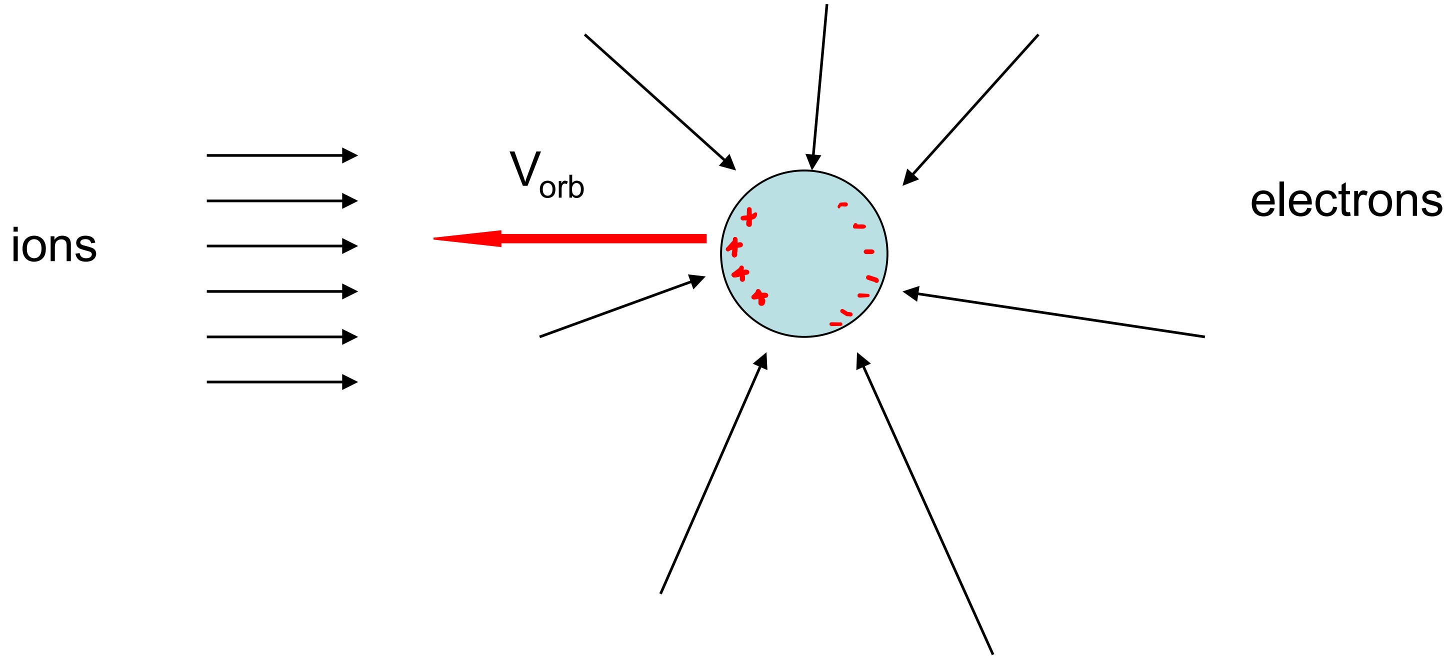
$$\nu_{p,e} = \frac{1}{2\pi}\left(\frac{n_0 e^2}{\varepsilon_0 m_e}\right)^{1/2} \approx 9\, n_0^{1/2}\left(m^{-3}\right)$$

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):

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

Embedded question

Determine the floating potential for a satellite in LEO

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

Assume that $\frac{1}{4} A_e = A_i$, a temperature $T_e = 1050$ K, and an orbital velocity of 7.8 km/s.

Physical constants:

Spark ~ 2-3 $\frac{MV}{m}$

Electron charge $e = 1.601 \times 10^{-19}$ C

Boltzmann's constant: $k_B = 1.38064852 \times 10^{-23}$ J/K

$m_e = 9.11\ 10^{-31}$ kg

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

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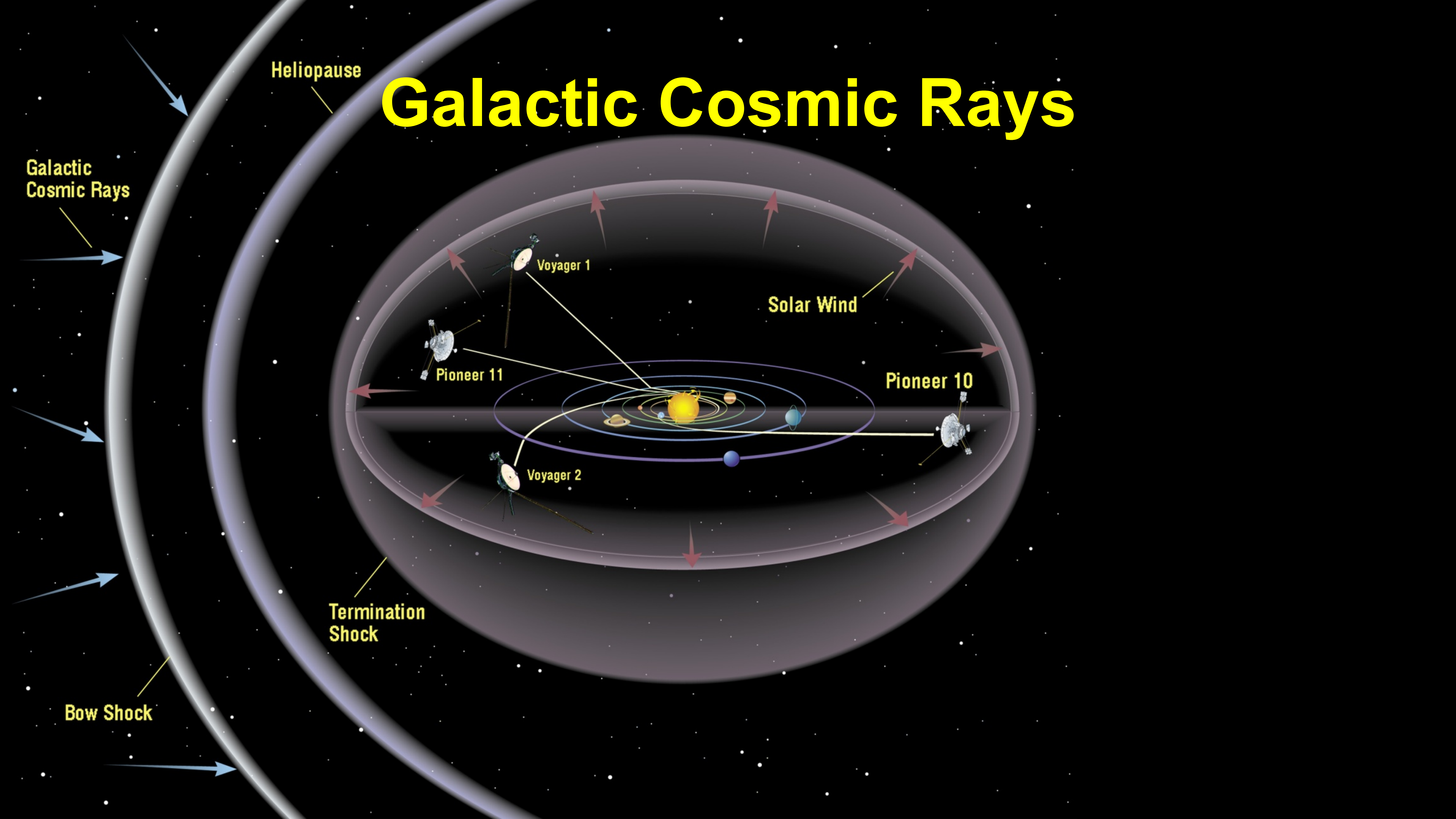
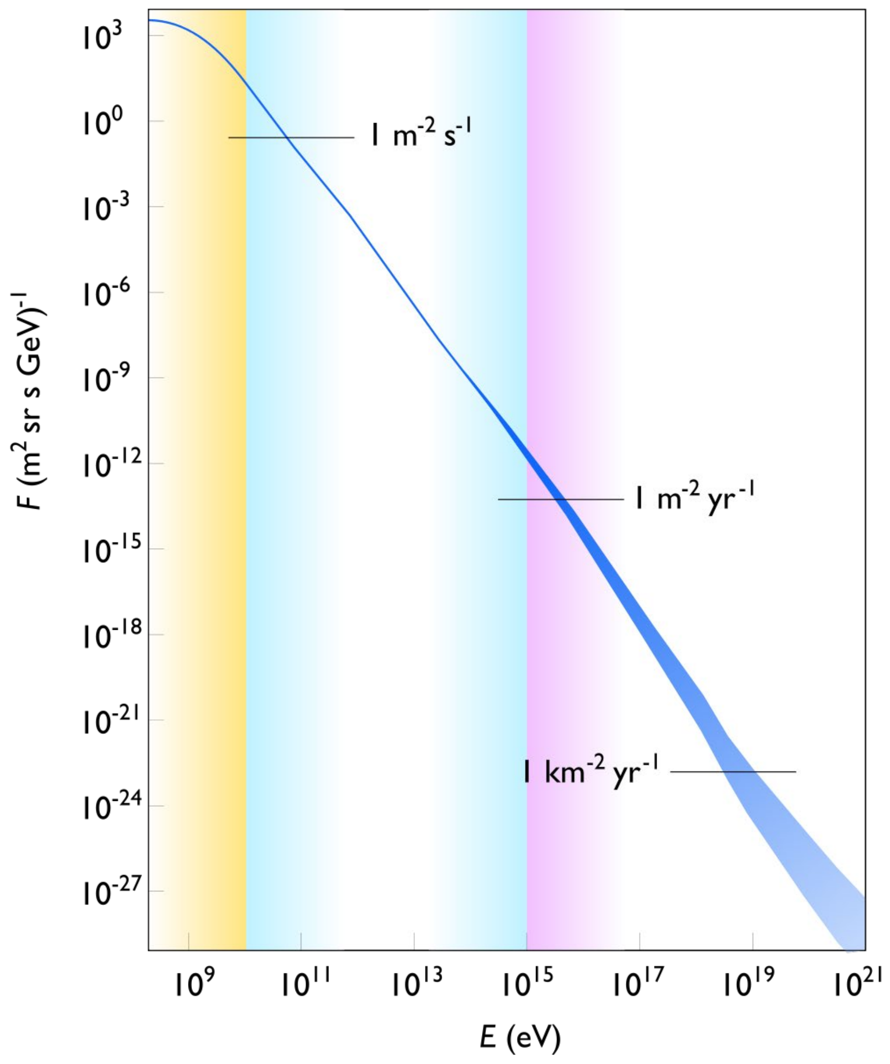
Galactic Cosmic Rays

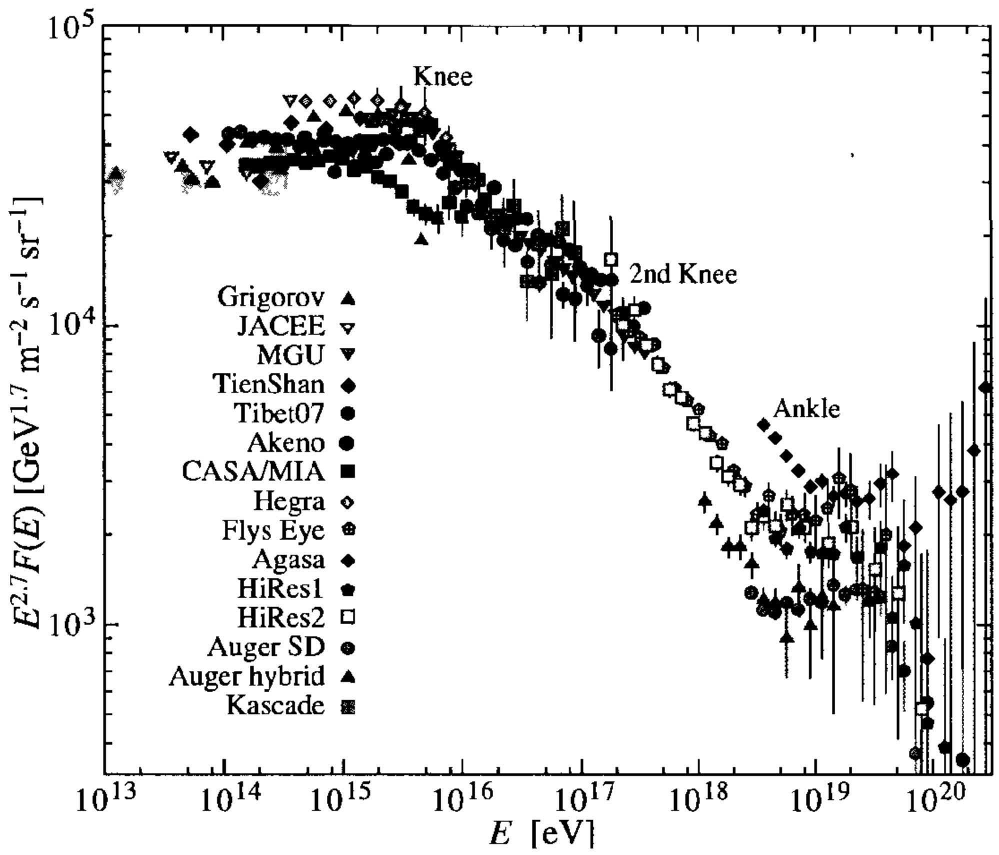
- High energy particles coming from outside the Solar System
- Composition: 85% p, 14% α, 1% heavy ions
- Hard spectrum
- Fluxes and spectra are modulated by solar activity (GCR have maximum fluxes at minimum solar activity, and vice versa)

Galactic Cosmic Rays



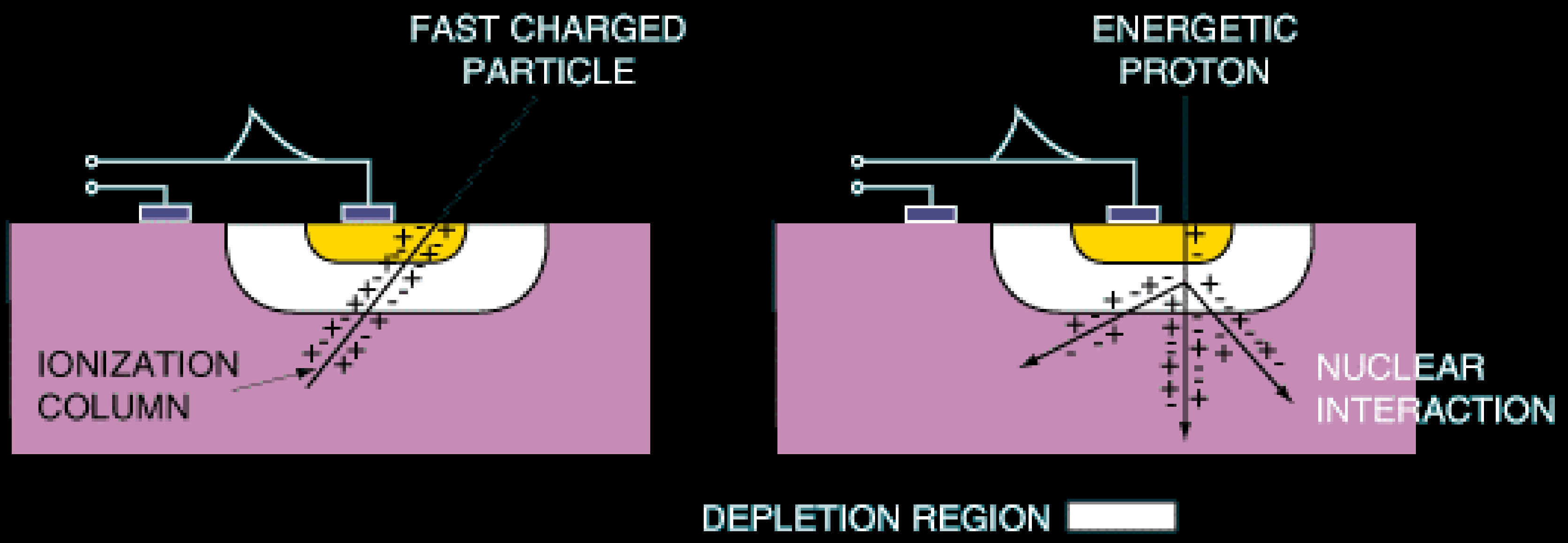
Galactic Cosmic Rays





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

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.

EDAC

EDAC (Error Detection and Correction) checks for bit flips (from 0 to 1 or vice versa) caused by single events.

Parity bits are a simple and fast mechanism to detect errors.

Hamming codes can correct single errors and detected double errors (to flipped bits in the analyzed string).

Scrubbing consists in reading the memory contents in a continuous way. Then, single errors can be corrected and the right information is rewritten. This strategy reduces the likelihood of double errors. Double bit errors in COTS devices occur at a low rate of 10^{-3}/word/day.

Parity Check

Parity check bits add a 0 or a 1 to a bit string to inform whether the number of 1s is even (then a 0 parity bit is added) or odd (a 1 bit is added):

Right string:	10010011 0
Wrong string:	10011011 0
Wrong string:	10010011 1

The flipped bit can also be the parity bit.

This mechanism is not robust as double errors are not detected and detected errors do not indicate which bit is wrong.

Hamming code

Hamming code consists in assigning parity bits to different strings in the message.

Algorithm:

1. Number all bits
2. Insert parity checks in all positions which are a power of 2 (1,2,4,8,16…)
3. The rest of bits of the message are data
4. Each bit belongs to at least 2 parity checks. Parity checks are calculated as follows:

Hamming code

4. Each bit belongs to at least 2 parity checks. Parity checks are calculated as follows:
   – For the n-th parity bit, we skip the first $2^{n-1} - 1$
   – Then, we pick the first string of 2^n bits, discard the next string of 2^n bits and so on until the end of the message
   – Determine the parity of the selected strings and determine the parity bit

Error detection: the flipped bit is in the string position obtained adding all the parity check bits that are wrong. If only one parity check is wrong, the parity check itself is flipped.

Hamming code

Example:

Original data: 111101001011100 15 bit

Add parity bits: _ _ 1_111_0100101_1100 20 bit (15 data + 5 parity)

First bit: parity of bits in positions 1, 3, 5, 7, 9 to 15, plus the parity check in the first bit of the stream:

_ _ 1_111_0100101_110

6 bits are 1, three are zero, then the parity is 0 and then the first bit is 0

Hamming code

Example (cont.):

0 _ 1_111_0100101_110

Second parity bit: check the parity of bit in the positions 2-3 (10, 11 in binary), 6-7 (110,111), 10-11 (1010,1011), 13-14 (1101,1110)

0_1_111_0100101_110

6 ones, which makes for a 0 parity bit

Then, the message is now: 001_111_0100101_110

Hamming code

Example (cont.):

For the third parity bit (located in position 4), we skip the first three bits and select strings of 4 bits: one in, one out until the end of message:

001_111_0100101_110

There are five 1, then the parity check must be 1

0011111_0100101_110

Hamming code

Embedded calculation:

Determine the last two parity bits:

0011111_0100101_110

Solution:

Hamming code

It is easy to notice that Hamming code results in some communications overhead as it adds more bits:

Total bit	Data bits	Parity bits	Hamming code	Data ratio
3	1	2	(3,1)	1/3 = 0.3333…
15	11	4	(15,11)	11/15 = 0.7333…
31	26	5	(31,26)	26/31 = 0.8387
63	57	6	(63,57)	57/63 = 0.9048
255	247	8	(255,247)	247/255 = 0.9686
$2^m - 1$	$2^m - m - 1$	m	$(2^m-1, 2^m - m - 1)$	$(2^m - m - 1)/(2^m-1)$

Syllabus

- Introduction
- Gravitational field
- Magnetic field
- Van Allen Belts
- The upper atmosphere
- High vacuum effects
- The plasma environment
- Cosmic Rays
- **Space Debris and Micrometeoroids**

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

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

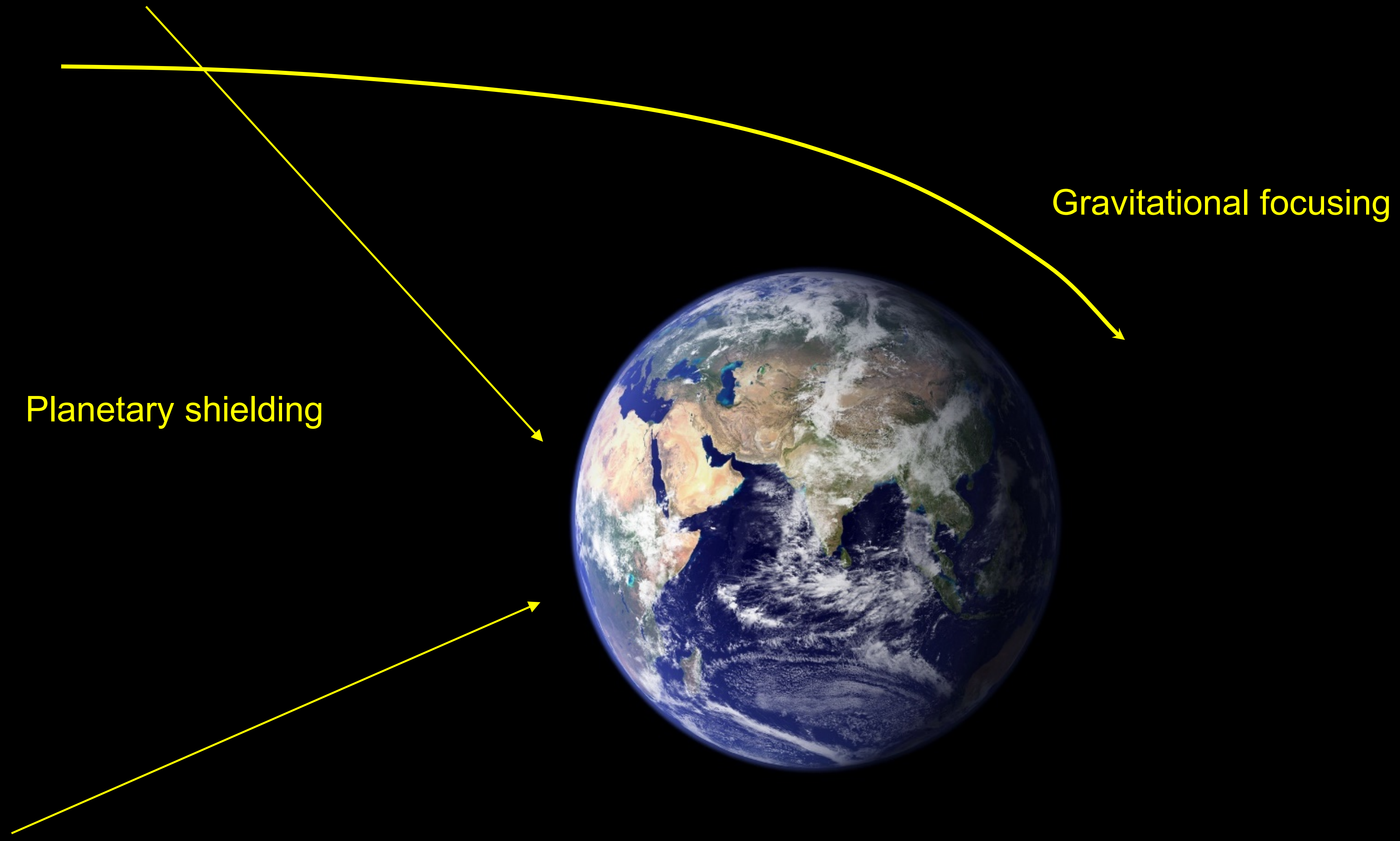
Micrometeoroids (3)

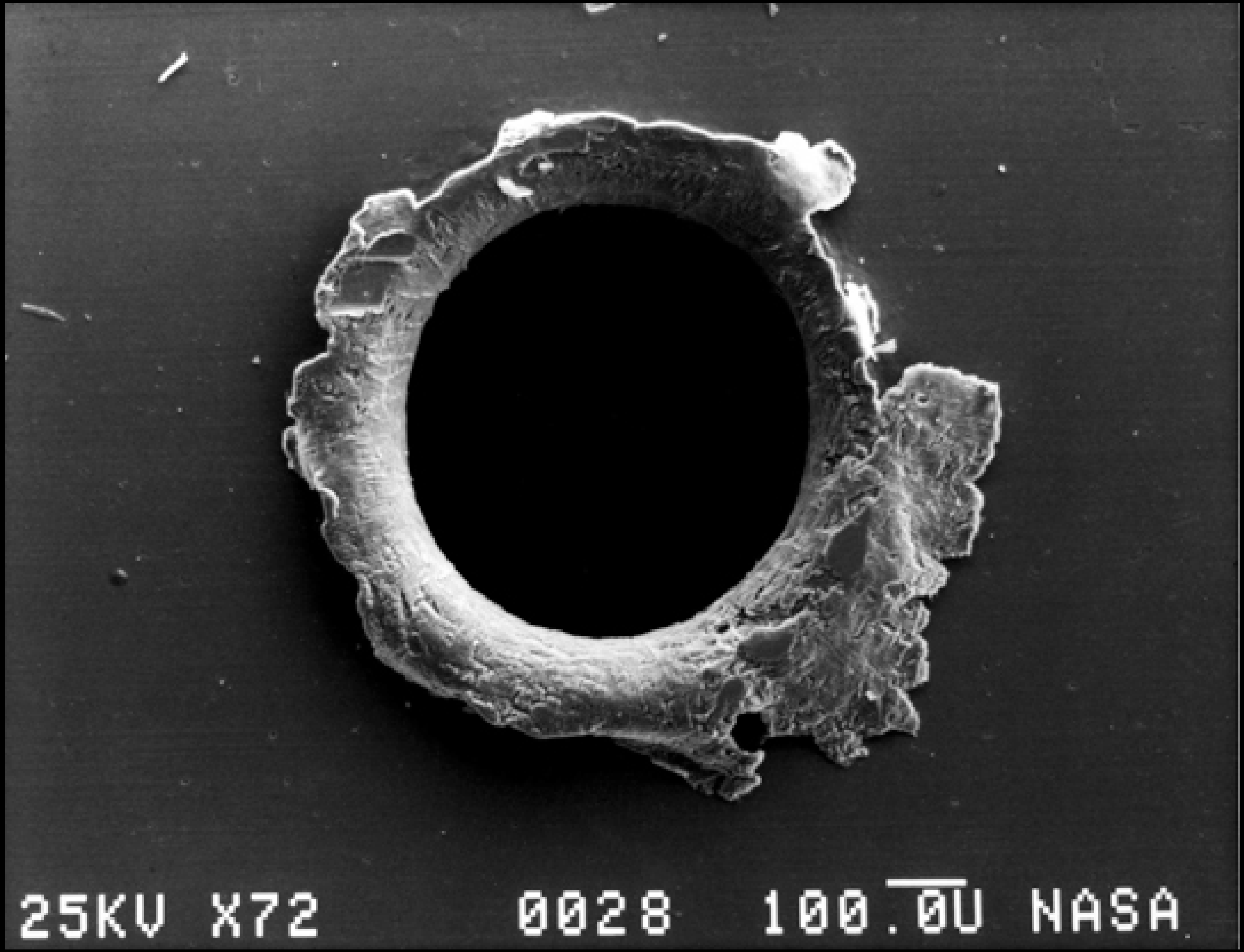
- And also acts as a shield

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

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

- Most impacts are produced on the space-facing surfaces

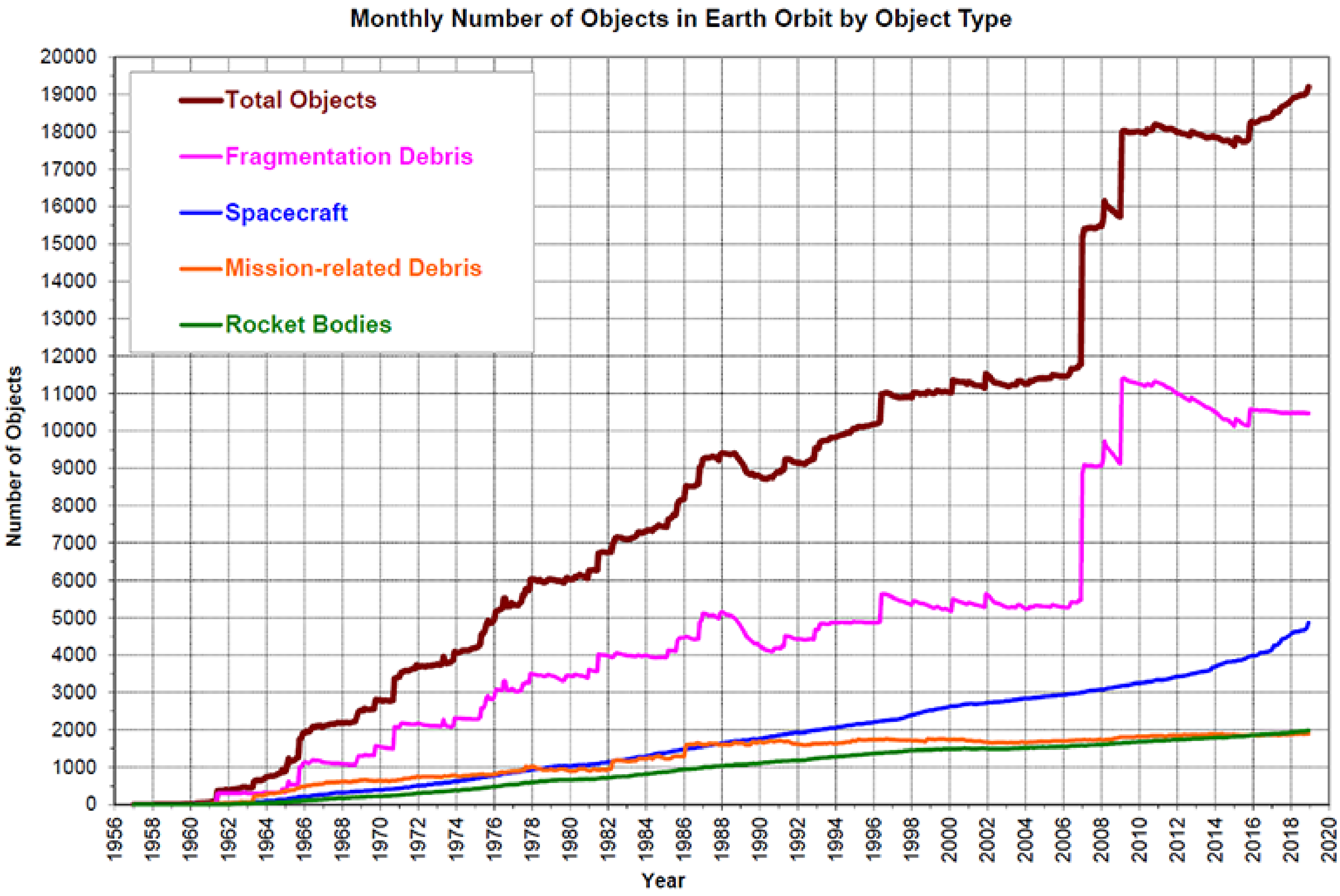

Gravitational focusing
Planetary shielding


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

Optical Telescopes. © Deimos Space


Monthly Number of Objects in Earth Orbit by Object Type
Total Objects
Fragmentation Debris
Spacecraft
Mission-related Debris
Rocket Bodies
Number of Objects
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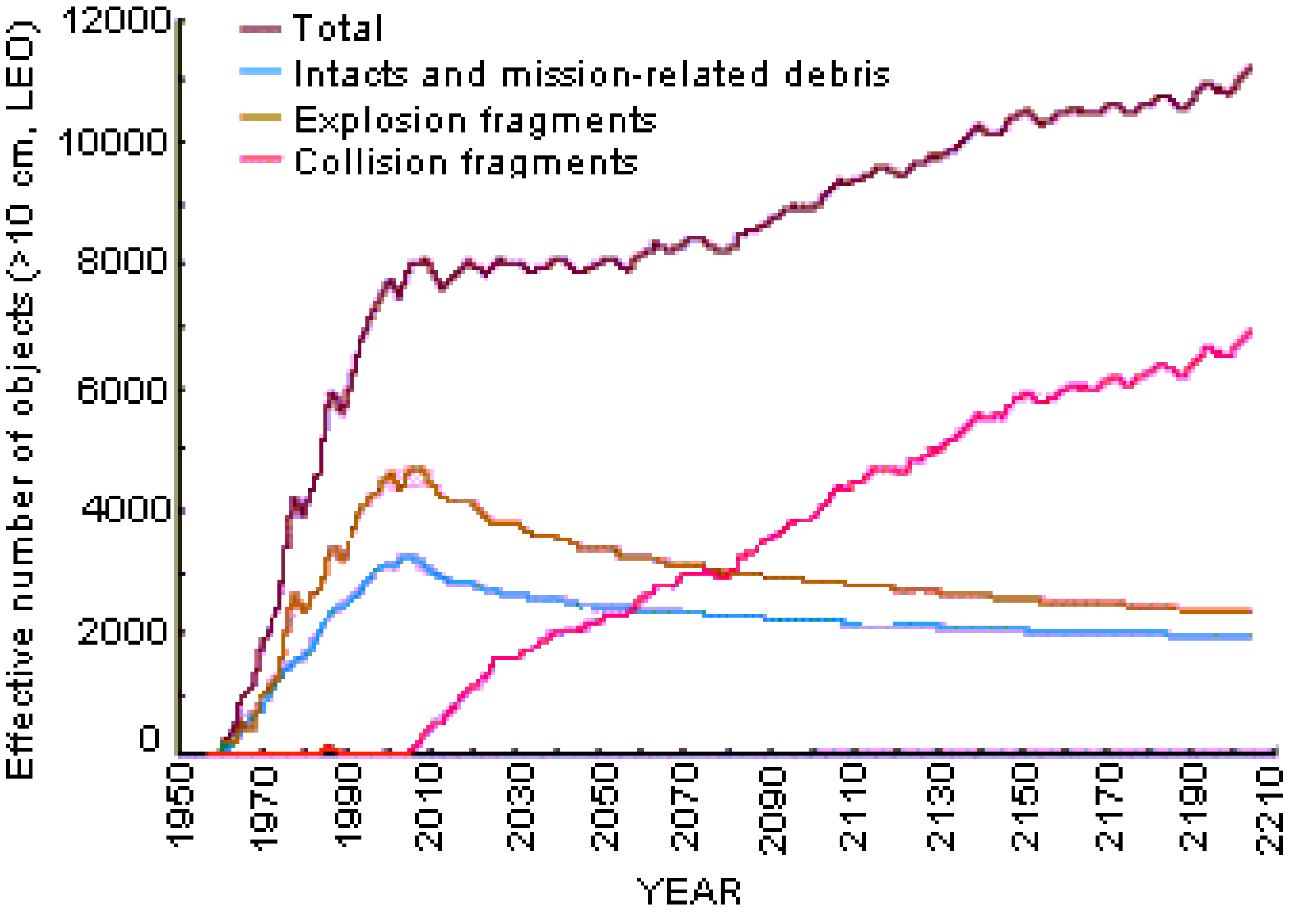
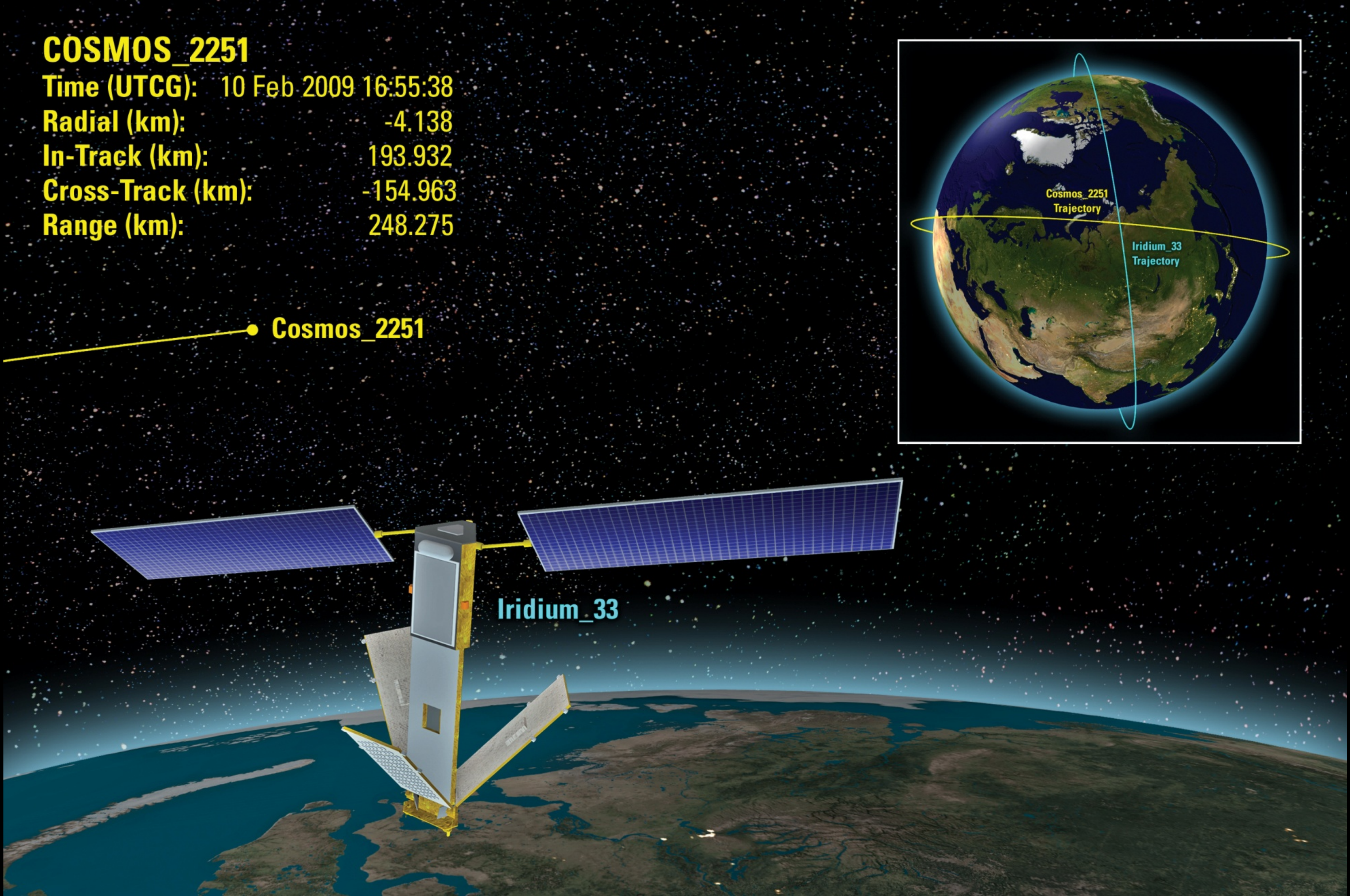
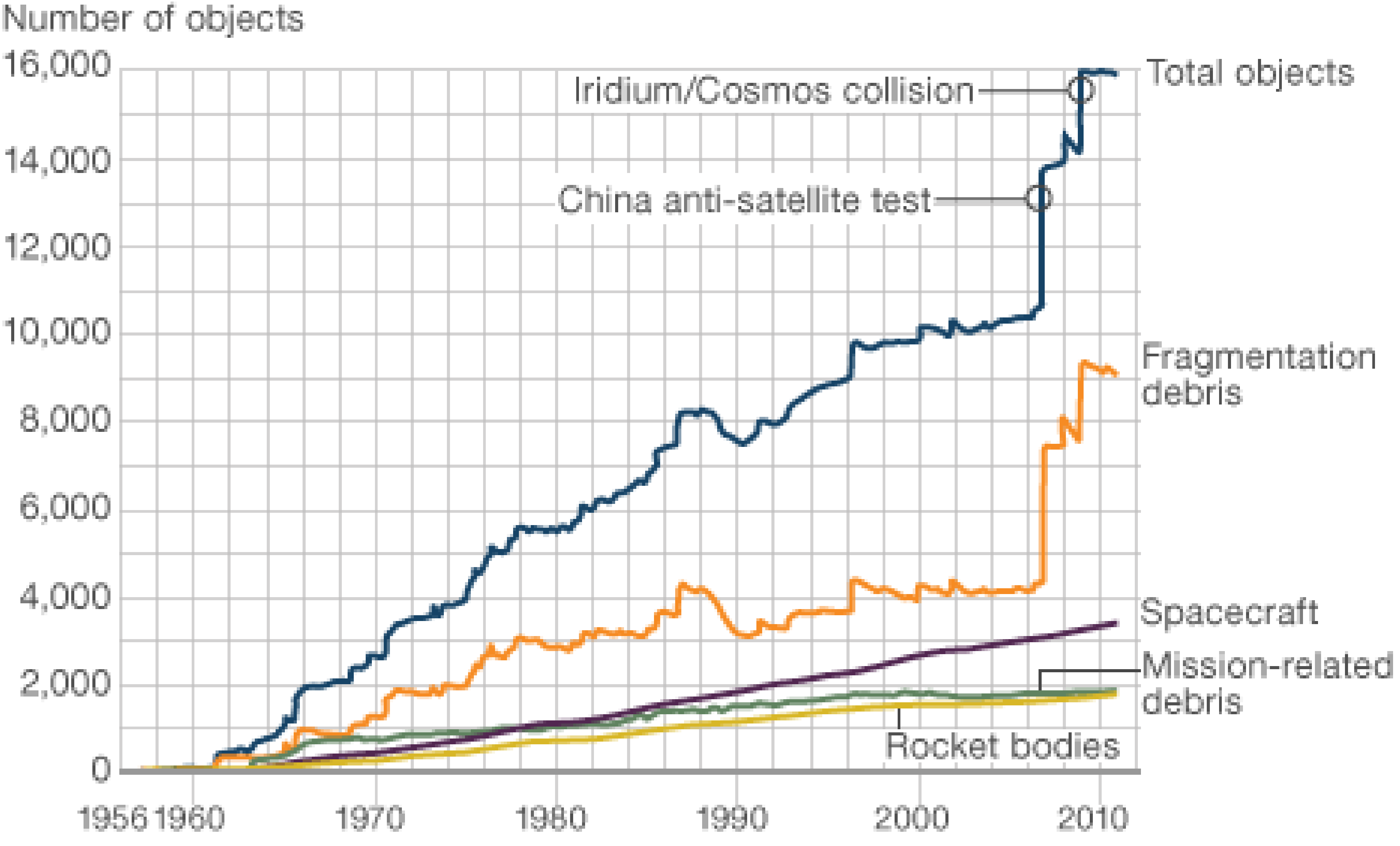


Growth of future populations. Effective number of LEO objects, 10cm and larger, from the LEGEND simulation. The effective number is defined as the fractional time, per orbital period, an object spends between 200 and 2000 km altitudes. Intacts are rocket bodies and spacecraft that have not experienced 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
Iridium_33
Cosmos_2251 Trajectory
Iridium_33 Trajectory

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

Software tools for space debris

- There are some software packages to analyze the problem of space debris:
  - Drama (ESA, https://sdup.esoc.esa.int)
  - ORDEM (NASA, https://software.nasa.gov/software/MSC-25457-1)
  - Stela, Debrisk (CNES, https://logiciel.cnes.fr/en/content/estela)

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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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

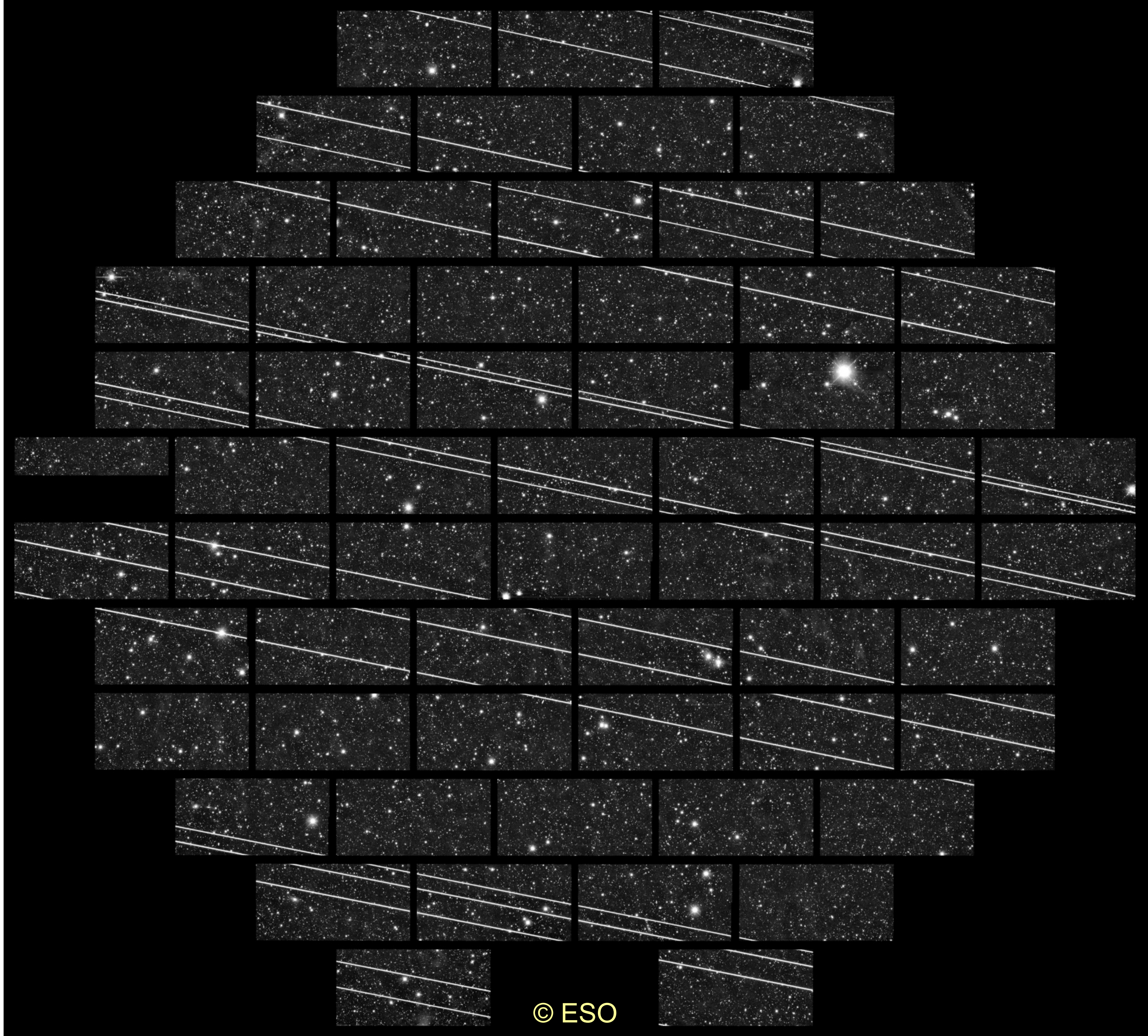
Megaconstellations

While not strictly speaking Space Debris, some plans for huge constellations (involving thousands, or even thousands of satellites) can potentially cause a serious situation for other users of LEO

Starlink (SpaceX project for providing world-wide Internet coverage) envisions a constellation formed by 42000 satellites in orbits between 500 and 1200 km of altitude

The SSA of this scenario is rather complex, even if *Starlinks* have manoeuvring capabilities

Stream of *Starlink* satellites imaged by a CCD mosaic on the European Southern Observatory



Stuff in space

http://stuffin.space/?intldes=2015-049G

Projected megaconstellations

- Starlink: 12000–42000 satellites
- OneWeb: about 2000 satellites
- Kuiper: 3236 satellites
- Lightspeed: 298 satellites

Space situational awareness

Space situational awareness (SAA) is the space equivalent of air traffic management, with the difference that most of the objects tracked cannot modify their trajectories

It will be mandatory to obtain high-quality orbits (thus, with a very good knowledge of atmospheric drag, gravitational field irregularities, third body effects, and solar radiation pressure)

Ground and space-based observations will be essential to gather the required information and achieve high-accuracy

Megaconstellations forecast difficult times in LEO unless some international regulations enter into force

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Shall we be forced to
destroy you all?