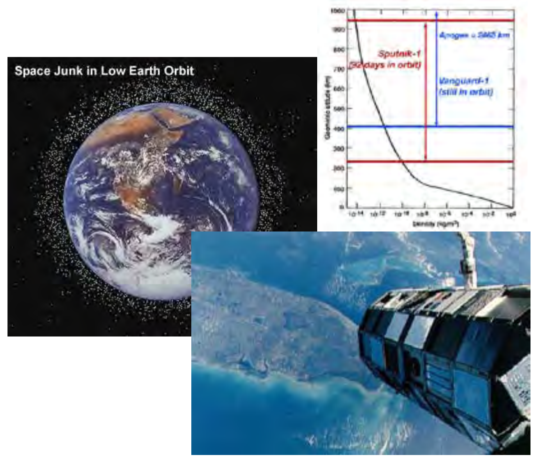
Spacecraft Environment

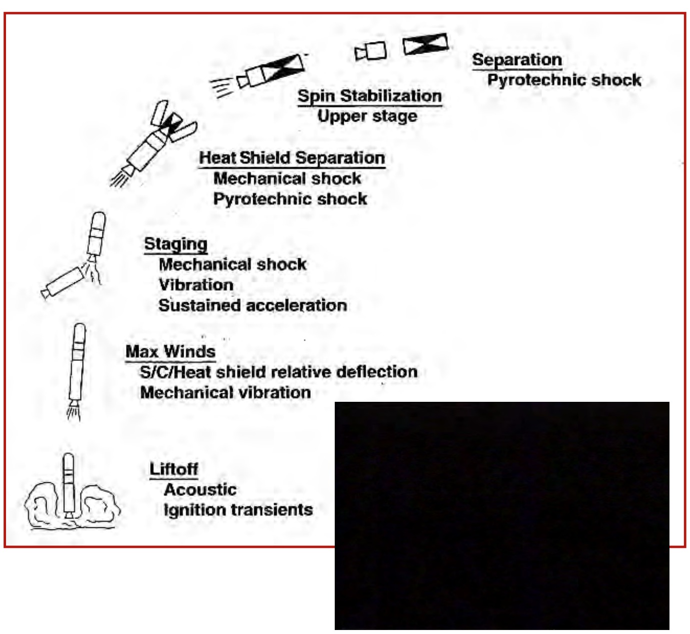
Space System Design, MAE 342, Princeton University
Robert Stengel

- Atmospheric characteristics
- Loads on spacecraft
- Near-earth and space environment
- Spacecraft charging
- Orbits and orbital decay



http://www.princeton.edu/~stengel/MAE342.html

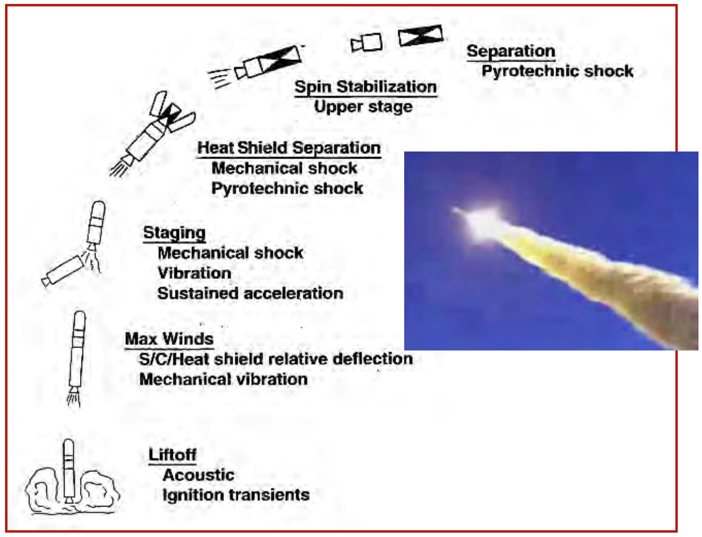
Launch Phases and Loading Issues-1



- Liftoff
  - Reverberation from the ground
  - Random vibrations
  - Thrust transients
- Winds and Transonic Aerodynamics
  - High-altitude jet stream
  - Buffeting
- Staging
  - High sustained acceleration
  - Thrust transients

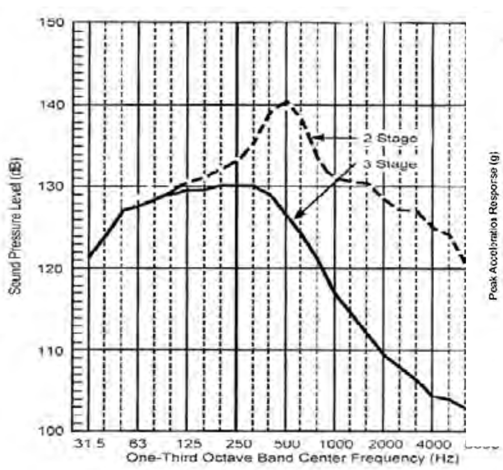
Launch Phases and Loading Issues-2

- Heat shield separation
  - Mechanical and pyrotechnic transients
- Spin stabilization
  - Tangential and centripetal acceleration
  - Steady-state rotation
- Separation
  - Pyrotechnic transients

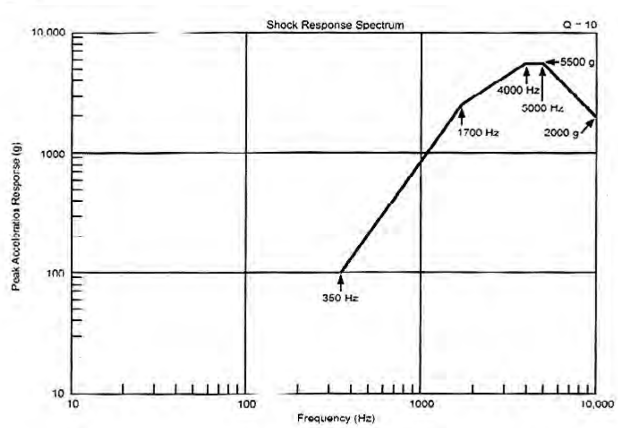


Typical Acoustic and Shock Environment (Delta II)

Sound Pressure (dB)



Peak Acceleration (g)



Decibel (dB)

$$10\log_{10}\left(\frac{\textit{Measured Power}}{\textit{Reference Power}}\right) \quad or \quad 20\log_{10}\left(\frac{\textit{Measured Amplitude}}{\textit{Reference Amplitude}}\right)$$

http://dangerousdecibels.org/education/information-center/decibel-exposure-time-guidelines/

Transient Loads at Thrusting Cutoff

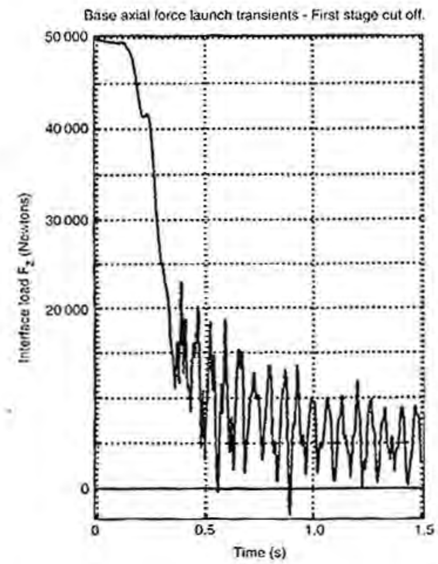


Figure 8.8 Base axial force launch transient for Ariane 4 first stage cut off (Reproduced by permission of Arianespace)

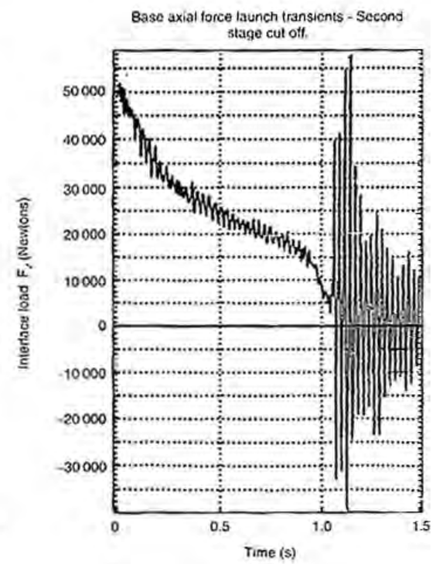


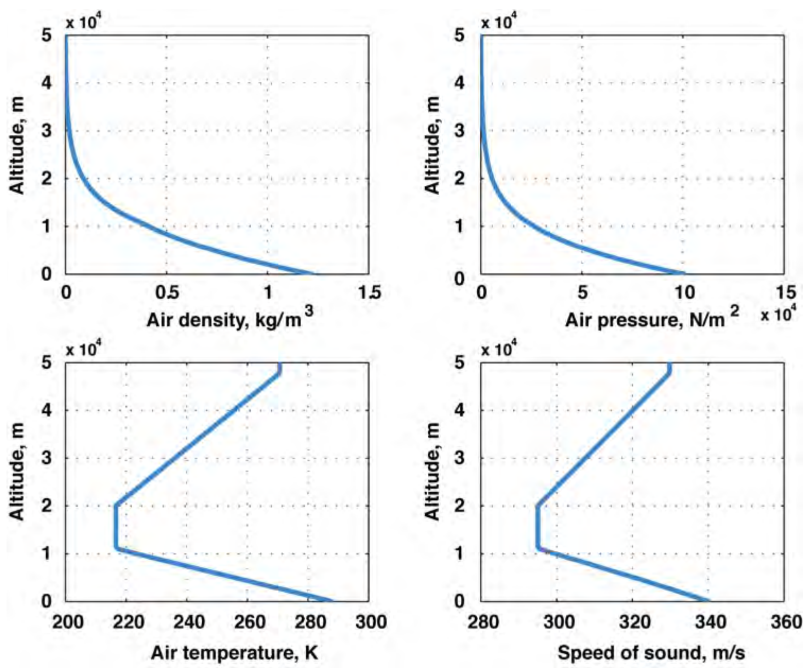
Figure 8.9 Base axial force launch transient for Ariane 4 second stage cut off (Reproduced by permission of Arianespace)

Fortescue, et al, 2003

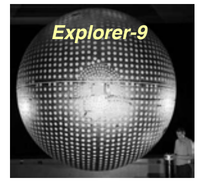
Properties of the Lower Atmosphere

- **Air density and pressure decay exponentially with altitude**
- **Air temperature and speed of sound are linear functions of altitude**

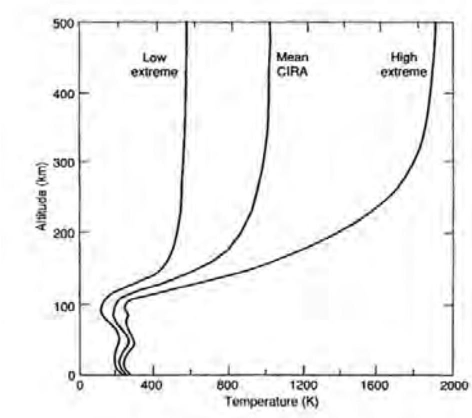
US Standard Atmosphere, 1976



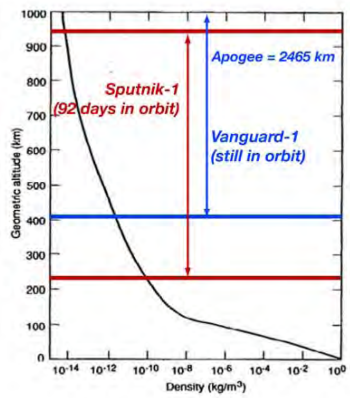
Earth's High-Altitude Atmosphere



Temperature of the Atmosphere



Density of the Atmosphere

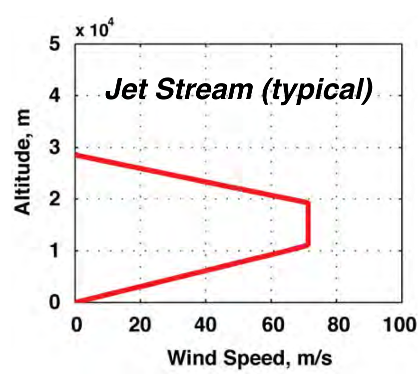


Atmosphere not well-represented as a continuum at high altitude

Altitude	Molecules/cc	Mean Free Path
Sea Level	2 x 10^19	7 x 10^-6 cm
600 km	2 x 10^7	10 km

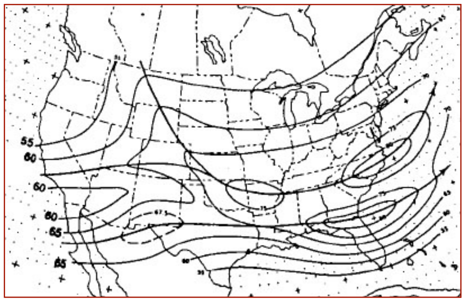
Lower Atmosphere Rotates With The Earth

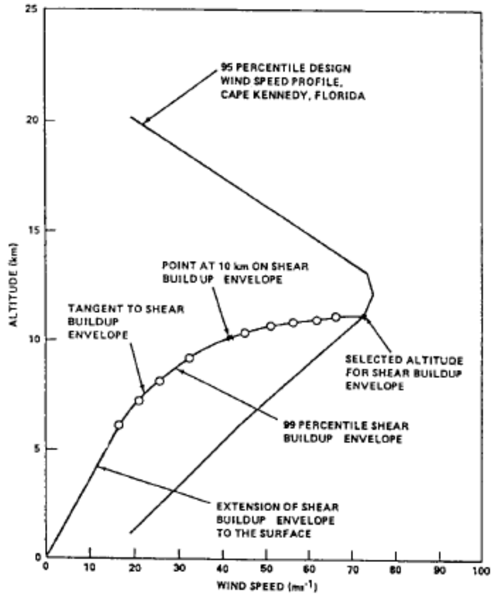
- Zero wind at Earth's surface = Inertially rotating air mass
- Wind measured with respect to Earth's rotating surface
- Jet stream magnitude typically peaks at 10-15-km altitude



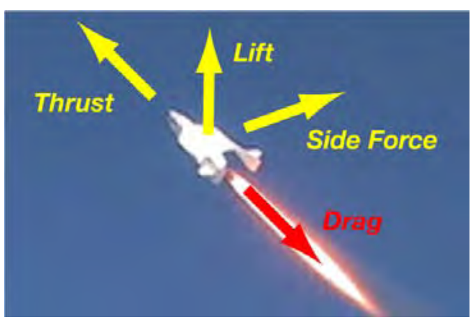
Jet Stream Produces High Loads on Launch Vehicle

- **Launch vehicle must able to fly through strong wind profiles**
- **Design profiles assume 95th-99th-percentile worst winds and wind shear**





Aerodynamic Forces



$$\begin{bmatrix} \text{Drag} \\ \text{Side Force} \\ \text{Lift} \end{bmatrix} = \begin{bmatrix} C_D \\ C_Y \\ C_L \end{bmatrix} \frac{1}{2}\rho V^2 S$$

- **V = air-relative velocity = velocity w.r.t. air mass**
- **Drag measured opposite to the air-relative velocity vector**
- **Lift and side force are perpendicular to the velocity vector**

Aerodynamic Force Parameters

$$\rho = \textbf{air density}, \text{ function of height}, h$$
$$= \rho_{sealevel} e^{-\beta h}$$
$$\rho_{sealevel} = 1.225\, kg/m^3; \quad \beta = 1/9{,}042\, m$$
$$V = \left[v_x^{\,2} + v_y^{\,2} + v_z^{\,2}\right]^{1/2} = \left[\mathbf{v}^T \mathbf{v}\right]^{1/2}, m/s$$
$$\textbf{Dynamic pressure} = \bar{q} = \frac{1}{2}\rho V^2, N/m^2$$
$$S = \textbf{reference area}, \ m^2$$
$$\begin{bmatrix} C_D \\ C_Y \\ C_L \end{bmatrix} = \textbf{non-dimensional aerodynamic coefficients}$$

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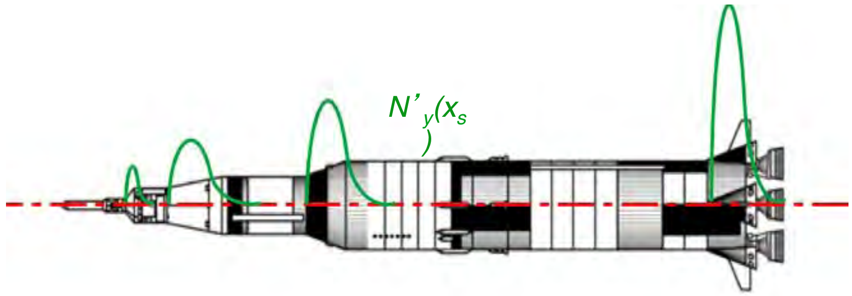
Aerodynamic Drag

$$\boxed{Drag = C_D \frac{1}{2}\rho V^2 S}$$

- **Drag components sum to produce total drag**
  - **Skin friction**
  - **Base pressure differential**
  - **Forebody pressure differential (M > 1)**

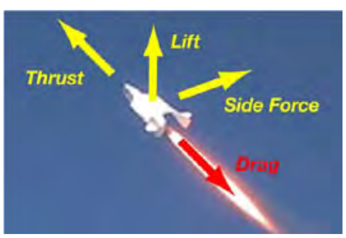
Aerodynamic Moment



Lengthwise lift variation causes bending moment

$N'(x) = \text{normal force variation with length} \approx \text{lift variation}$

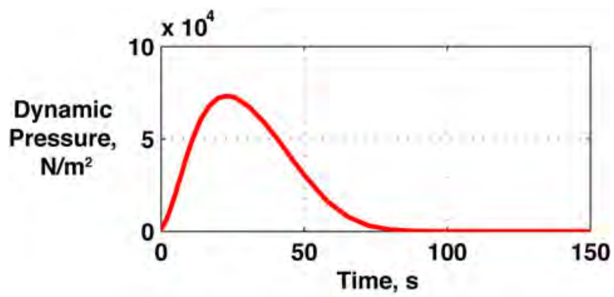
$$M_y(x) = \int_{x_{\min}}^{x_{\max}} N_y(x)\left(x - x_{cm}\right)dx$$
$$= \int_{x_{\min}}^{x_{\max}} \int_{x_{\min}}^{x_{\max}} N'_y(x)\,dx\left(x - x_{cm}\right)dx$$



Typical Velocity Loss due to Drag During Launch

- Aerodynamic effects on launch vehicle are most important below ~50-km altitude
- Maintain angle of attack and sideslip angle near zero to minimize side force and lift
- Typical velocity loss due to drag for vertical launch
  - Constant thrust-to-weight ratio
  - $C_D S/m$ = 0.0002 m^2/kg
  - Final altitude above 80 km

Thrust-to-Weight Ratio	Velocity Loss, m/s
2	336
3	474
4	581

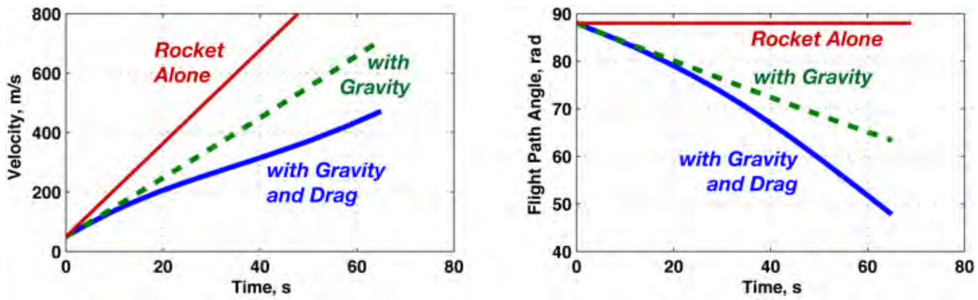


Effects of Gravity and Drag on the Velocity Vector

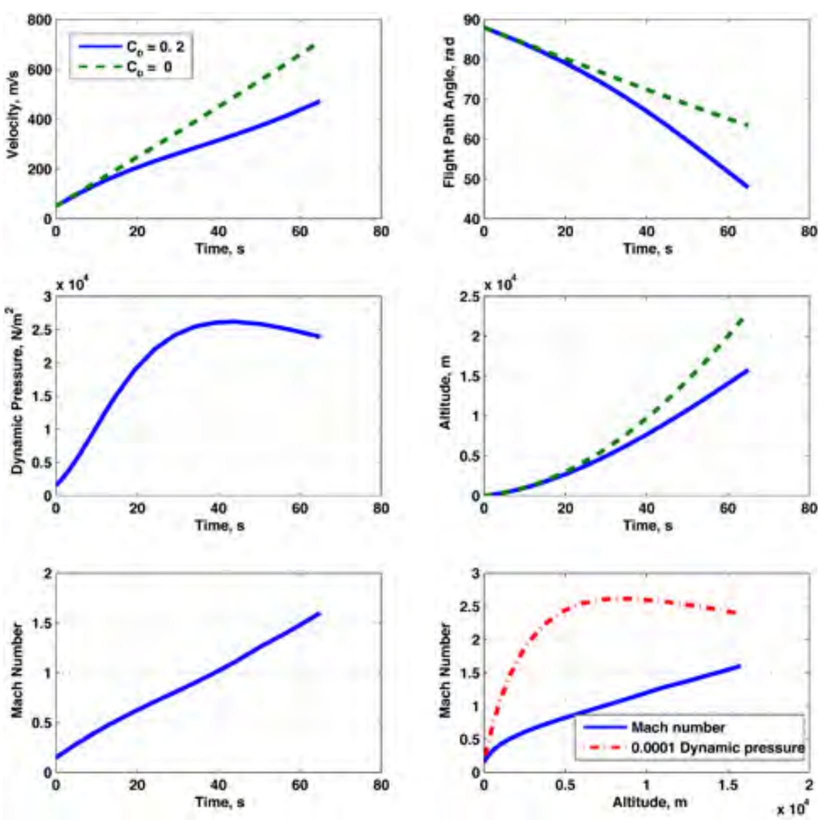
Thrust/Weight = T/W = 2
Thrust = 1960
C_D = 0.2
S = 0.1
Mass = 100

$$\dot{V}(t) = \frac{Thrust - \left[C_D S \frac{1}{2}\rho(h)V^2(t) + mg\sin\gamma(t) \right]}{m}$$

$$\dot{\gamma}(t) = -g\cos\gamma(t)/V(t)$$



Significant reduction in velocity magnitude
Strong curvature of the flight path



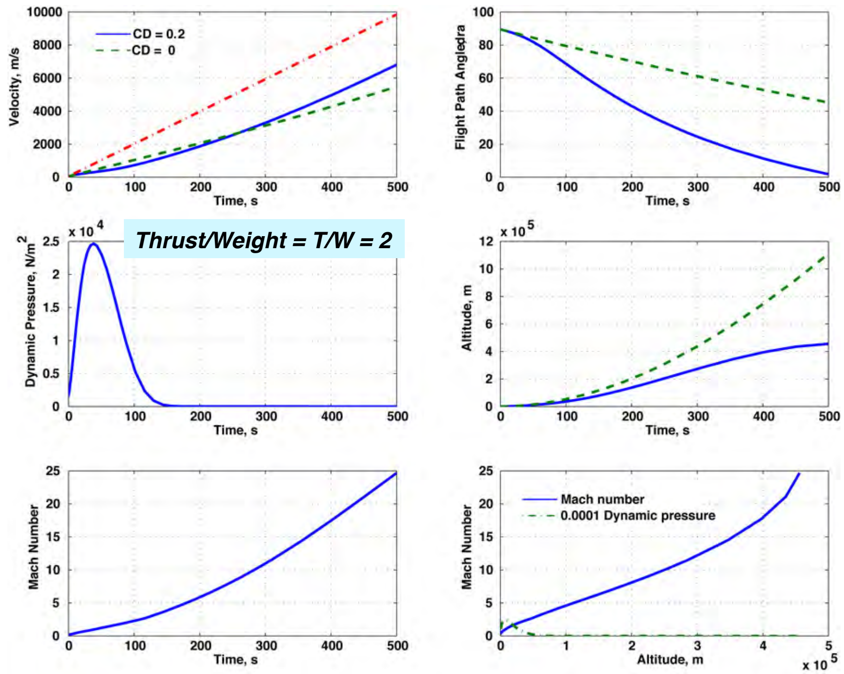
Typical Properties of Launch Trajectories

Thrust/Weight = 2

- **Maximum dynamic pressure**
- **Mach = 1**
- **maximum drag**
- **maximum jet stream magnitude**

tend to occur at similar altitudes

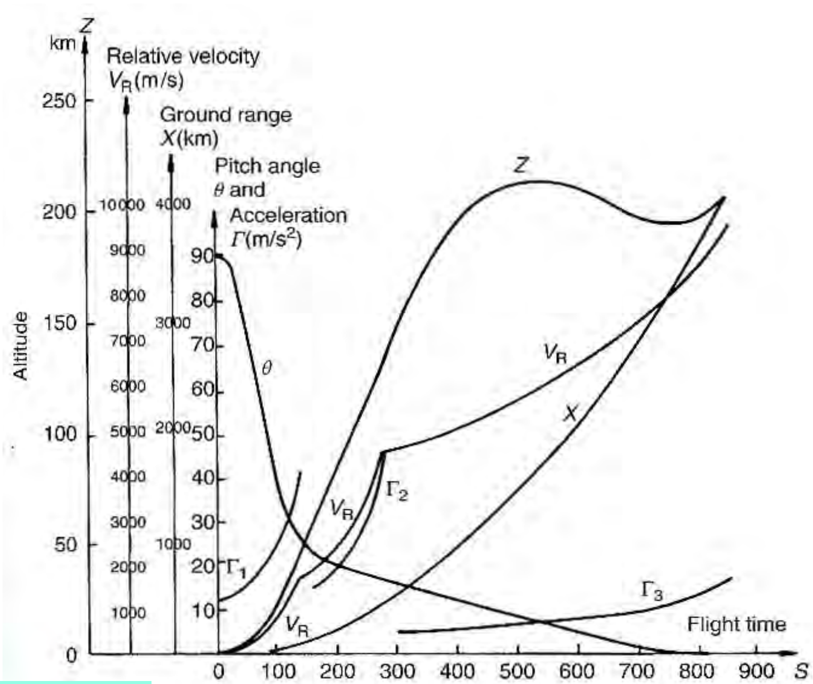
Gravity and Drag Effects during Single-Stage Orbital Launch



- Launch trajectory using flat-earth model
- Red line signifies velocity due to rocket alone
- Several km/s lost to gravity and drag

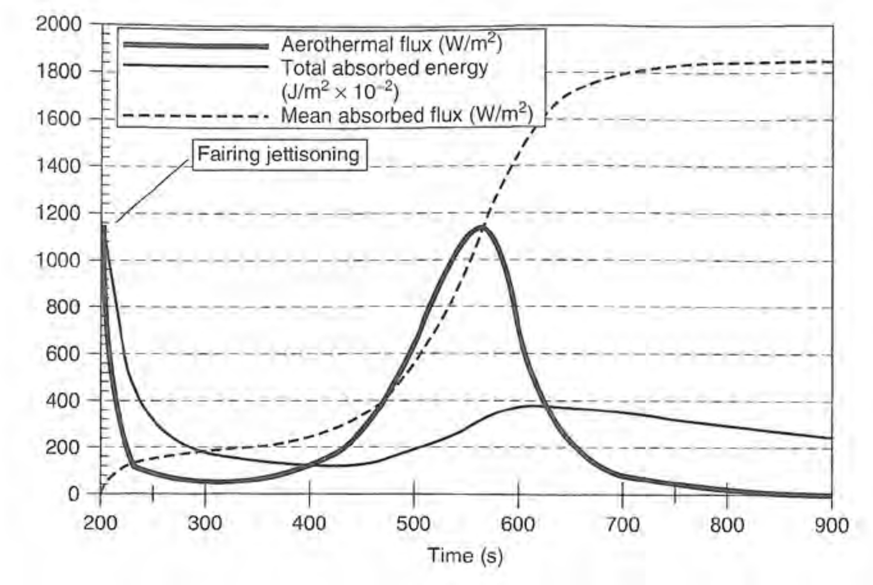
- With higher T/W
  - Shorter time to orbit
  - Increased loss due to drag
  - Decreased loss due to gravity

Typical Ariane 4 Launch Profile



Fortescue, et al, 2003

Ariane 5 Aerothermal Flux



Fortescue, et al, 2011

Orbital Lifetime of a Satellite

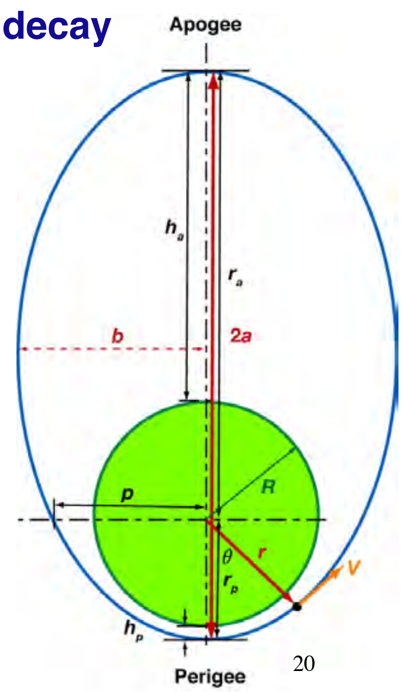
- **Aerodynamic drag causes orbit to decay**

$$\frac{dV}{dt} = -\frac{C_D \rho V^2 S/2}{m} \equiv -B^* \rho V^2 S/2$$
$$B^* = C_D S/m$$

- **Air density decreases exponentially with altitude**

$$\rho = \rho_{SL} e^{-h/h_{scale}}$$
$$\rho_{SL} = \text{air density at sea level}$$
$$h_{scale} = \text{atmospheric scale height}$$

- **Drag is highest at perigee**
  - Air drag "circularizes" the orbit
    - Large change in apogee
    - Small change in perigee
    - Until orbit is ~circular
    - Final trajectory is a spiral



Orbital Lifetime of a Satellite

- Aerodynamic drag causes energy loss, reducing semi-major axis, *a*

$$\frac{da}{dt} = -\sqrt{\mu a} B^* \rho_{SL} e^{-(a-R)/h_{scale}}$$

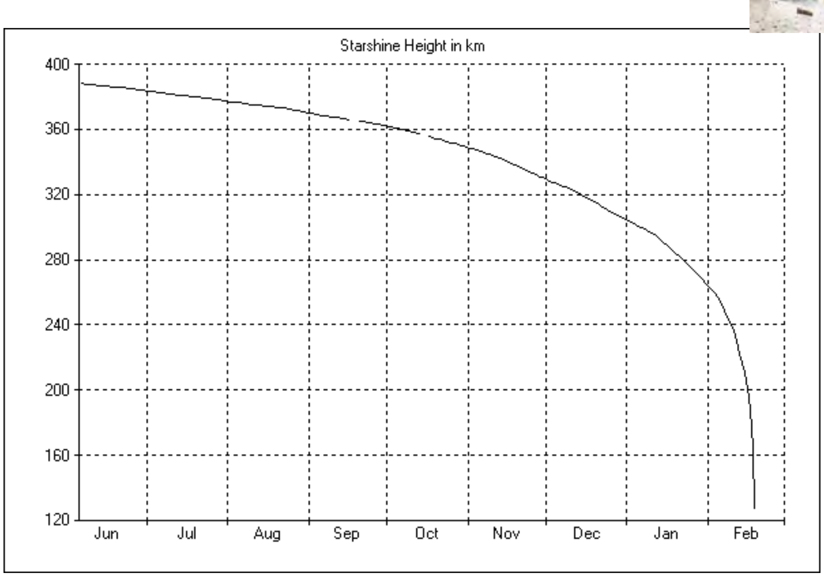
- Variation of *a* over time

$$\int_{a_0}^{a} \frac{e^{-(a-R)/h_s}}{\sqrt{a}} da = -\sqrt{\mu} B^* \rho_{SL} \int_0^t dt$$

- Time, t_{decay}, to reach earth's surface ($a = R$) from starting altitude, h_0

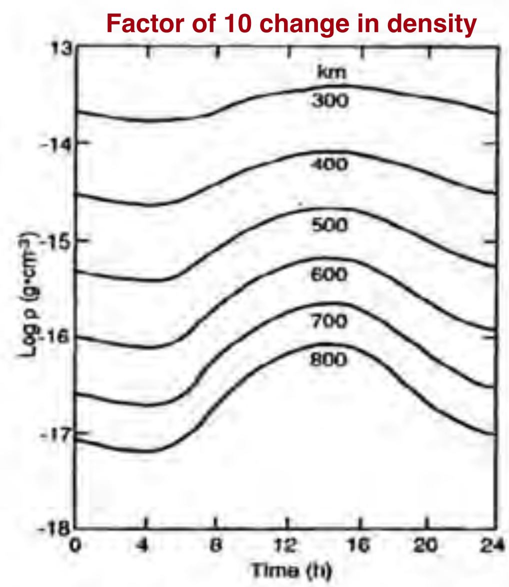
$$t_{decay} = \frac{h_{scale}}{\sqrt{\mu R} B^* \rho_{SL}} \left(e^{h_0/h_{scale}} - 1 \right)$$

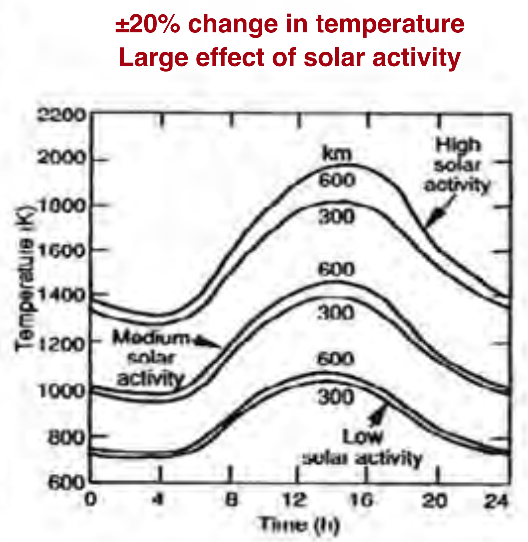
NRL Starshine 1 Orbital Decay (2003)



http://www.azinet.com/starshine/descript.htm

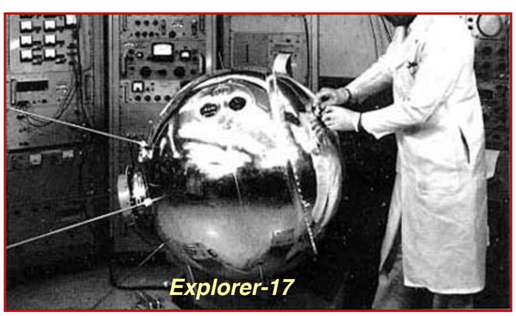
Diurnal Variations in Earth's Upper Atmosphere



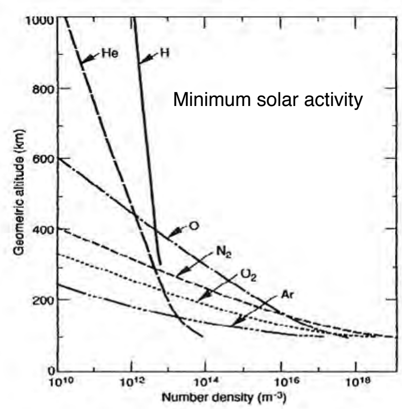


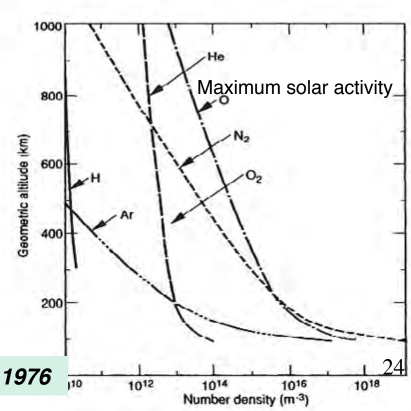
Pisacane, 2005

Atmospheric Constituents



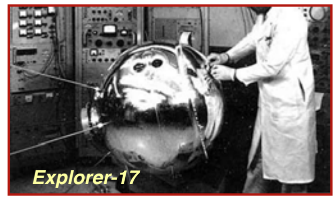
- Constituents at minimum and maximum solar activity
- Different scale heights for different species

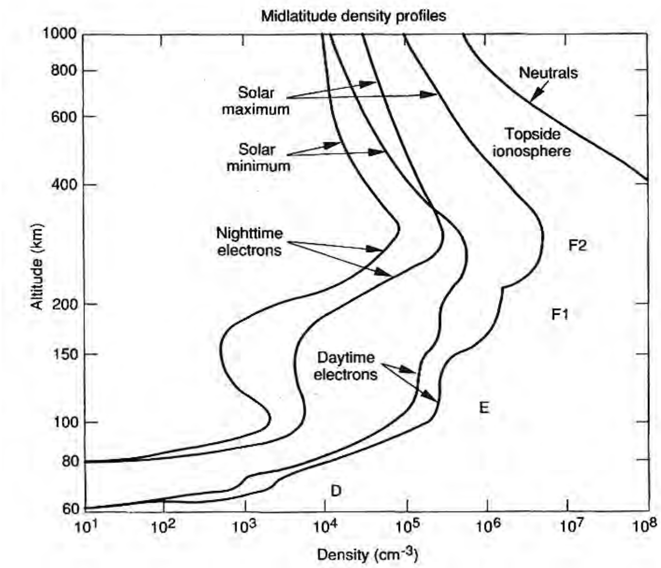




US Std. Atmos., 1976

Atmospheric Ionization Profiles





- Scale heights of electrons, ions, and neutrals vary greatly
- Ionospheric electric field (set by heavy oxygen atoms) dominates gravity field for lighter ions, e.g., hydrogen and helium

US Std. Atmos., 1976

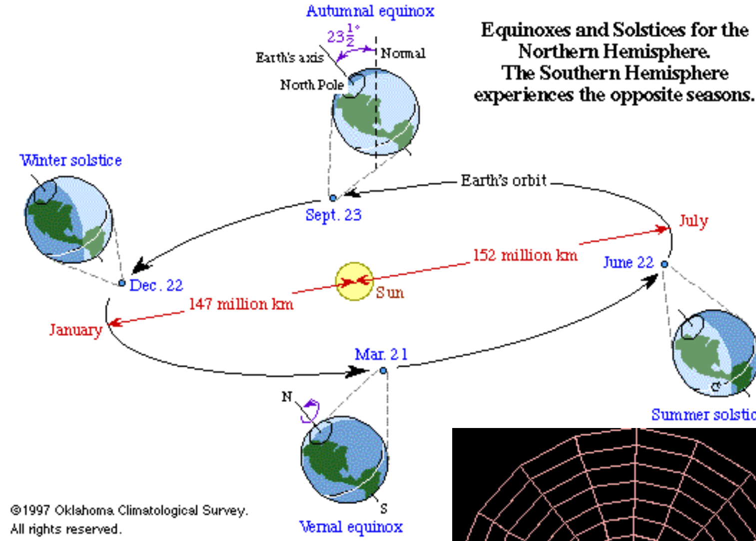
Mean Free Path

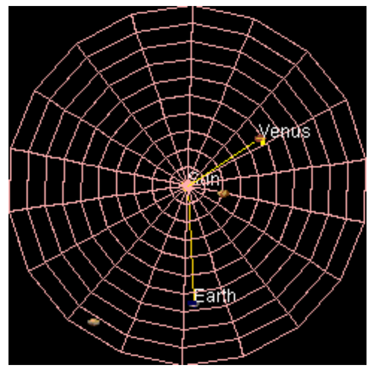
Altitude (km)	λ_0 (m)	Altitude (km)	λ_0 (m)
100	0.142	300	2.6×10^3
120	3.31	400	16×10^3
140	18	500	77×10^3
160	53	600	280×10^3
180	120	700	730×10^3
200	240	800	1400×10^3

- At high altitude, the mean free path of molecules is greater than the dimensions of most spacecraft
  - Aerodynamic calculations should be based on free molecular flow
  - Heat exchange is solely due to radiation

Fortescue, et al, 2011

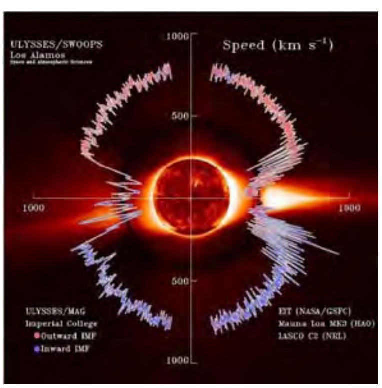
Orbits About the Sun





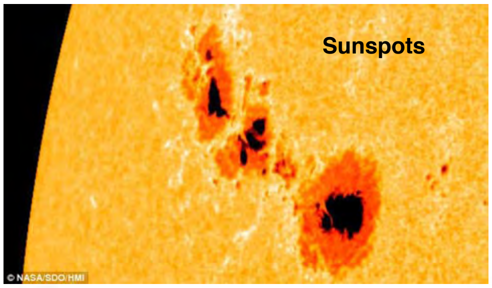
Solar System Environment

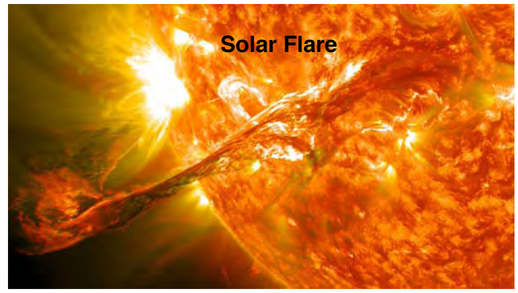
Low- and high-speed particles | **Heliospheric Current Sheet**

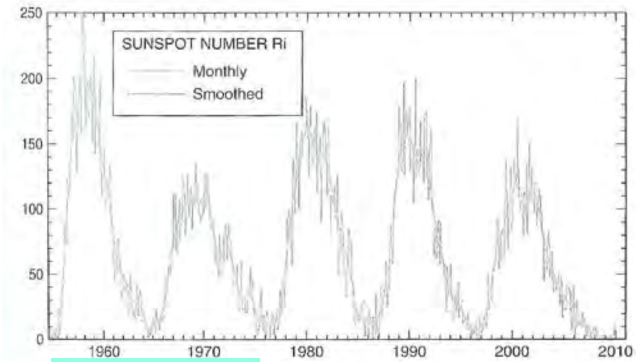


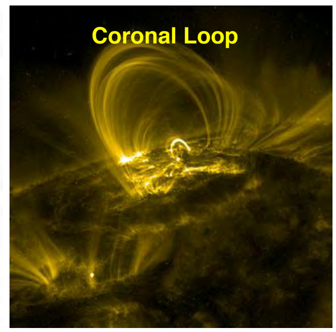
- **Solar wind**
  - **Plasma consisting of electrons, protons, and alpha particles**
  - **Variable temperature, density, and speed**
  - **1.5-10 keV**
  - **Slow (400 km/s) and fast (750 km/s) charged particles**
  - **Geomagnetic storms**

Sunspots and Solar Flares









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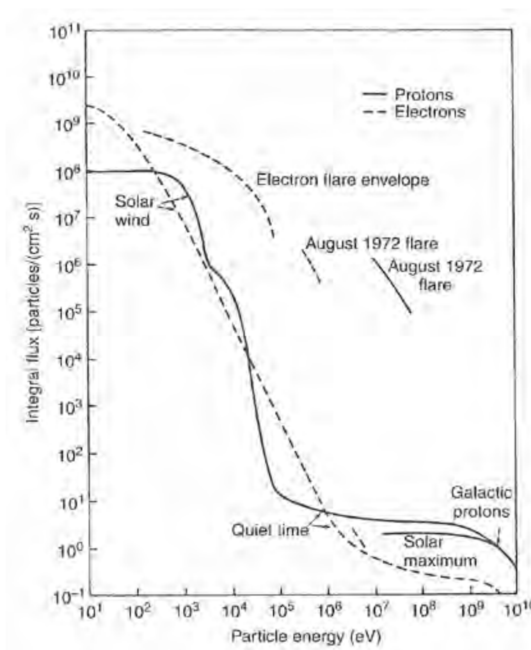
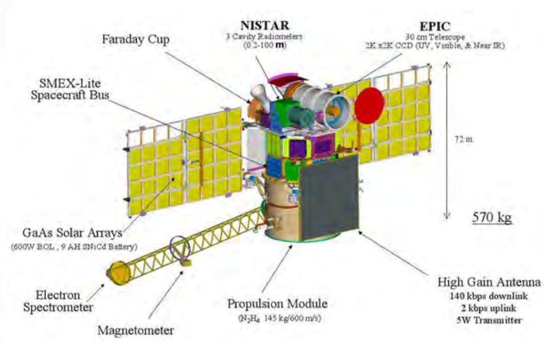
Flux vs. Energy of Electrons and Protons



Deep Space Climate Observatory (DSCOVR) at L1



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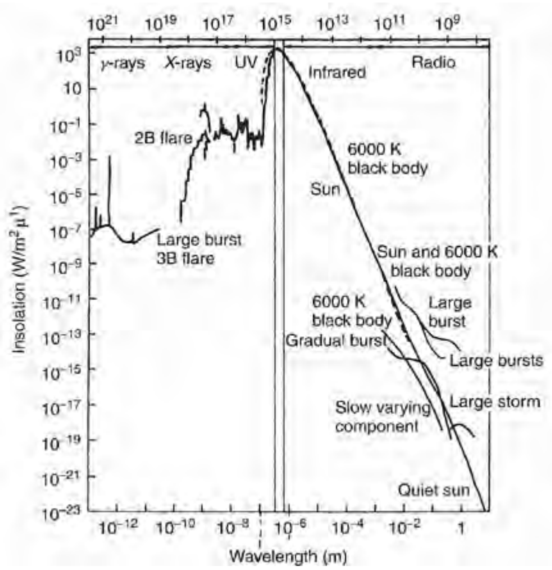
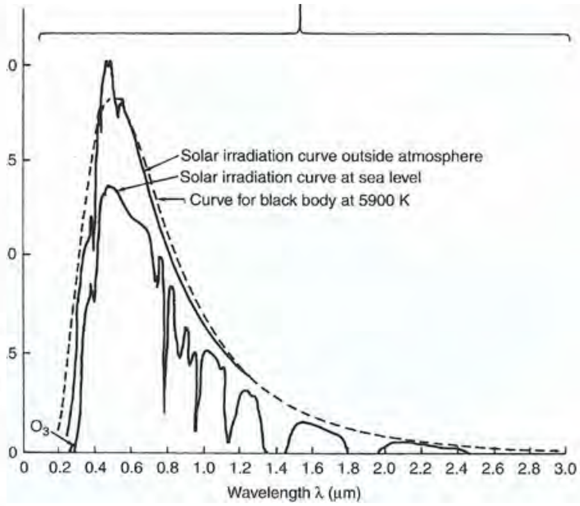
The Solar Spectrum





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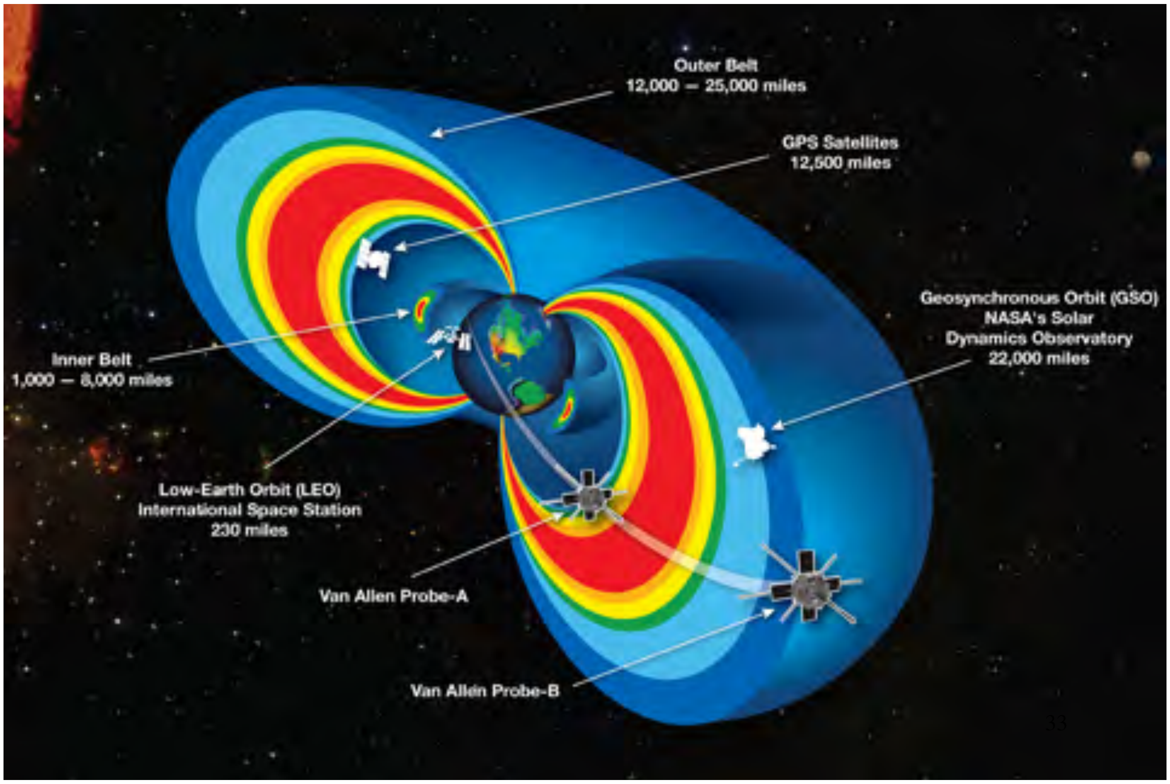
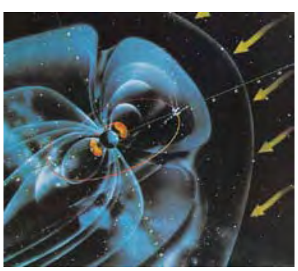
Variability of Solar Radiation

Spectral region	Wavelength	Flux (J/(m^2 s μm))	Variability
Radio	$\lambda > 1$ mm	10^{-11}–10^{17}	×100
Far infrared	1 mm $\geq \lambda > 10$ μm	10^{-5}	Uncertain
Infrared	10 μm $\geq \lambda > 0.75$ μm	10^{-3}–10^{2}	Uncertain
Visible	0.75 μm $\geq \lambda > 0.3$ μm	10^{3}	<1%
Ultraviolet	0.3 μm $\geq \lambda > 0.12$ μm	10^{-1}–10^{2}	1–200%
Extreme ultraviolet	0.12 μm $\geq \lambda > 0.01$ μm	10^{-1}	×10
Soft X-ray	0.01 μm $\geq \lambda > 1$Å	10^{-1}–10^{-7}	×100
Hard X-ray	1Å $\geq \lambda$	10^{-7}–10^{-8}	×10– × 100

Fortescue, et al, 2011

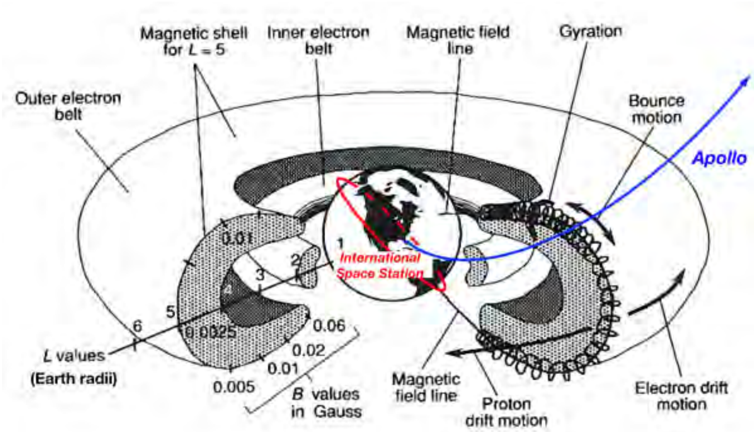
Van Allen Belts



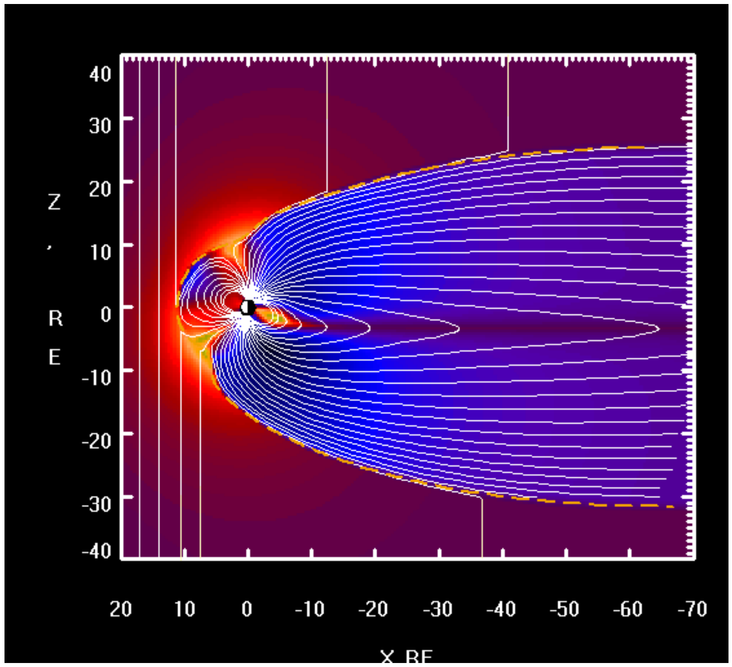


Magnetosphere and Van Allen Belts

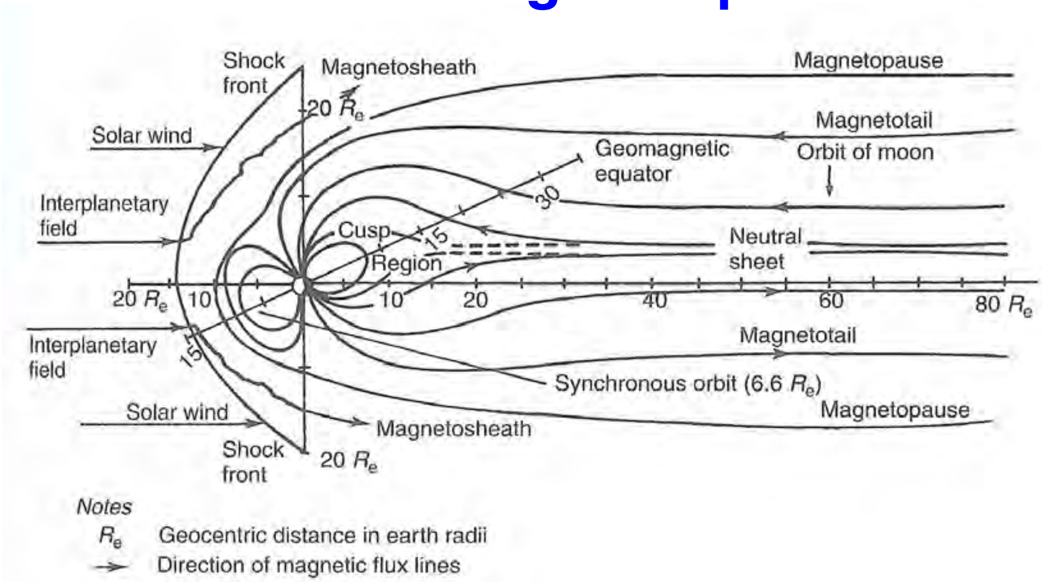
- Trapped Energetic Ions and Electrons
- Light ions form the base population of the magnetosphere



Earth’s Magnetosphere



Earth’s Magnetosphere



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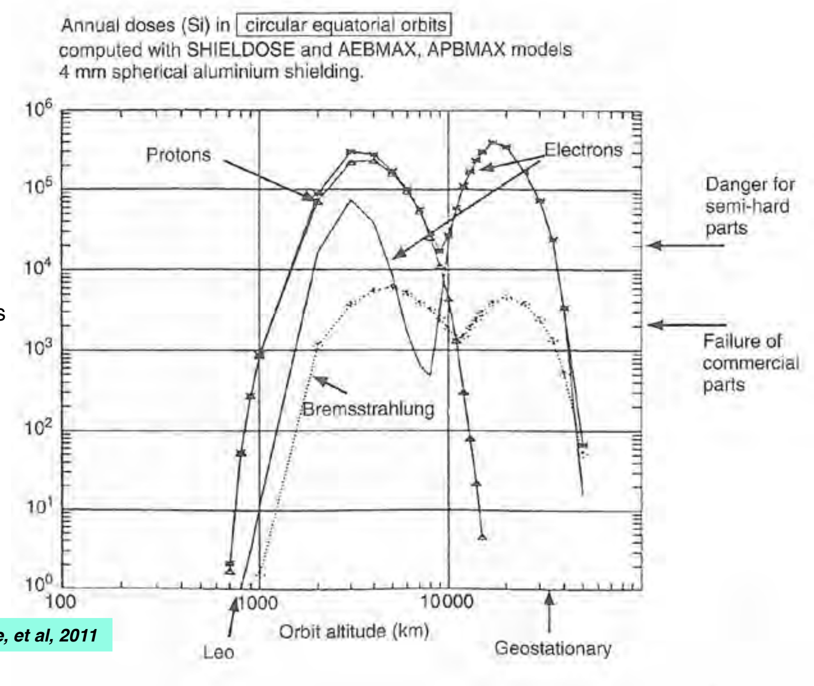
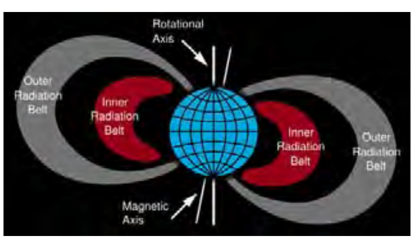
Annual Dose of Ionizing Radiation

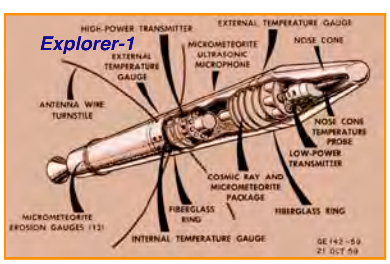
Si: Sieverts

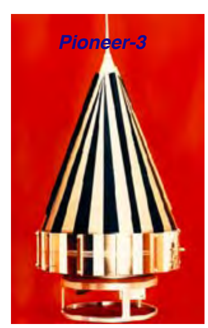


Fortescue, et al, 2011

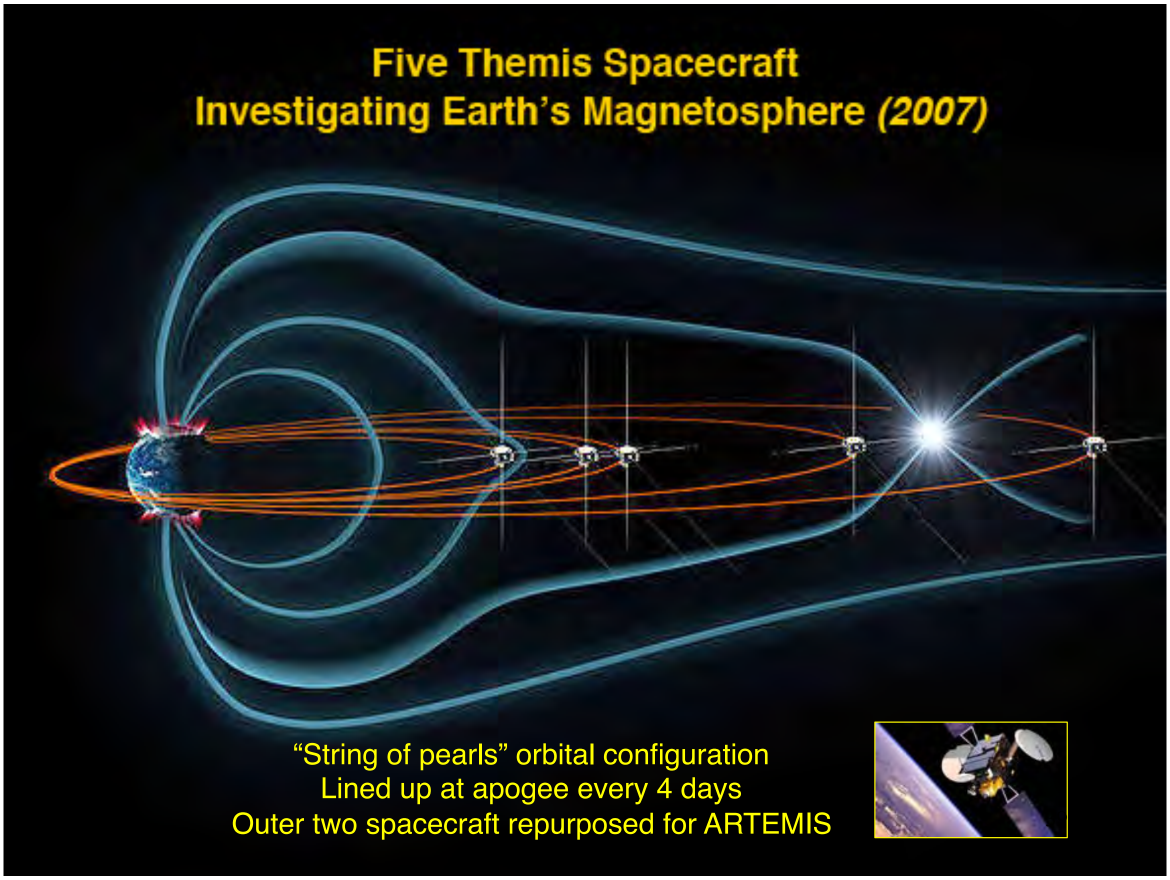
Spacecraft That Defined the Magnetosphere and Van Allen Belts





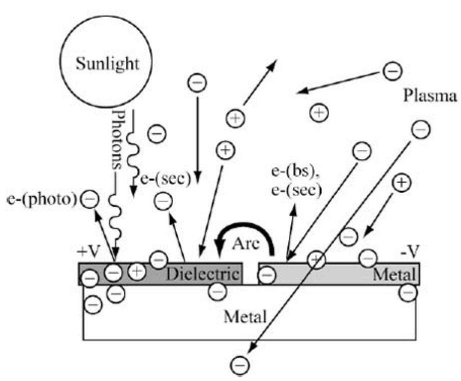


- see *Pisacane* for discussion of mechanics and dynamics
  - plasma frequency
  - Debye length
  - spacecraft charging and ram-wake effects
  - motion of charged particles in a dipole field
  - trapped radiation

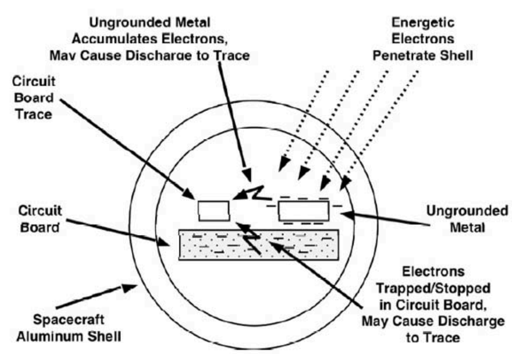


Spacecraft Charging

Interaction of sunlight, space plasma, and spacecraft materials and electronics



Exterior

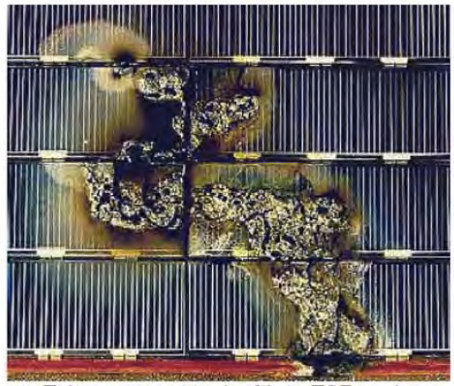


Interior

NASA-HDBK-4002A, 2011

Spacecraft Charging Damage

Interaction of space plasma and spacecraft materials and electronics

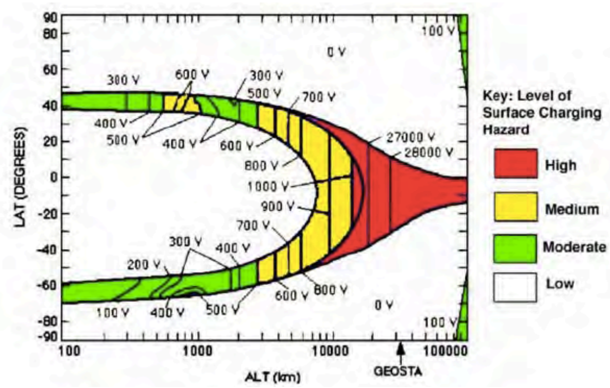


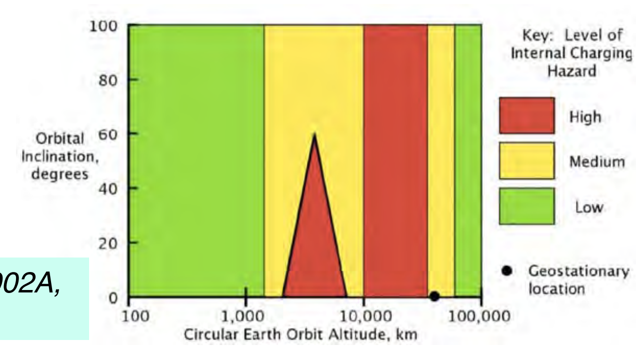
(a) Failure caused by in-flight ESD arcing

SCATHA Satellite, 1979

NASA-HDBK-4002A, 2011

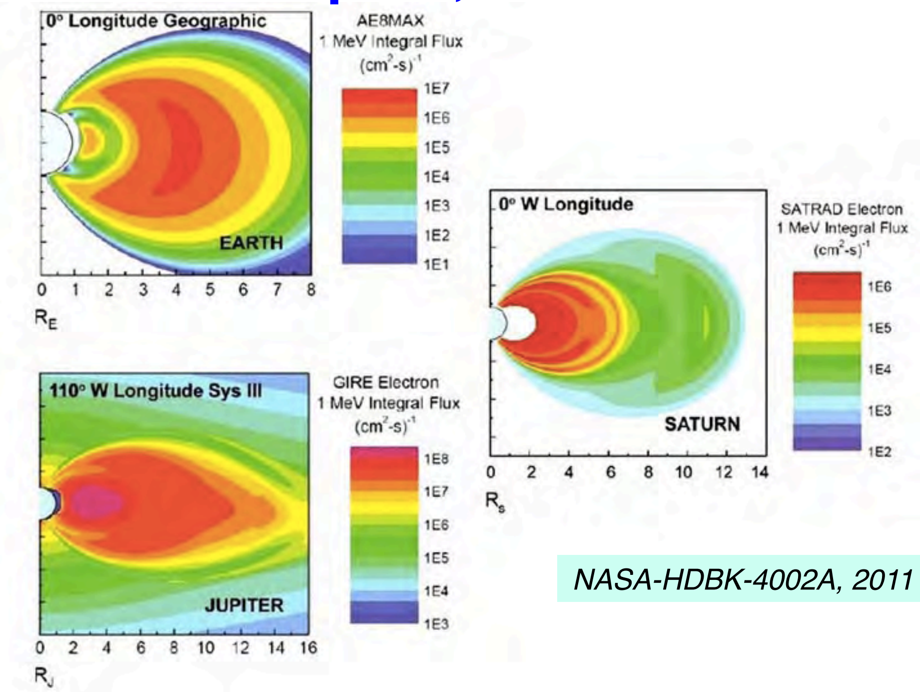
Spacecraft Charging Hazard Zones





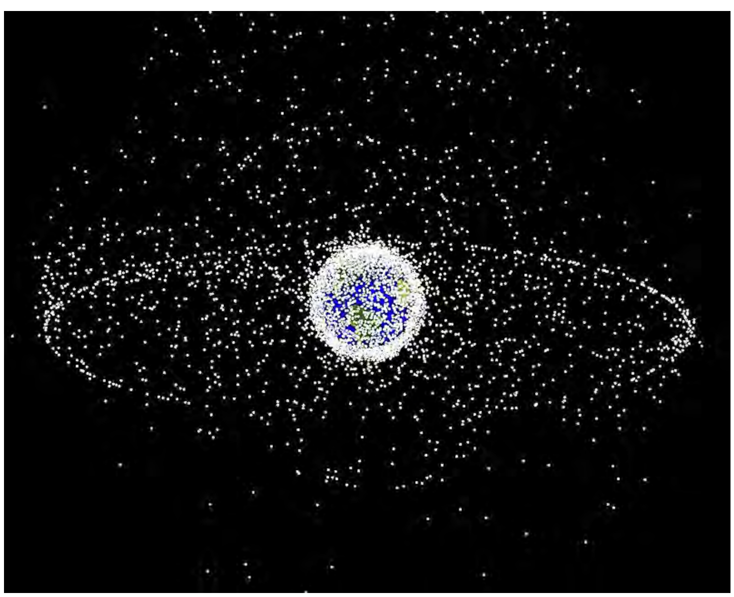
NASA-HDBK-4002A, 2011

Integral Flux Contours at Earth, Jupiter, and Saturn



NASA-HDBK-4002A, 2011

Space Debris

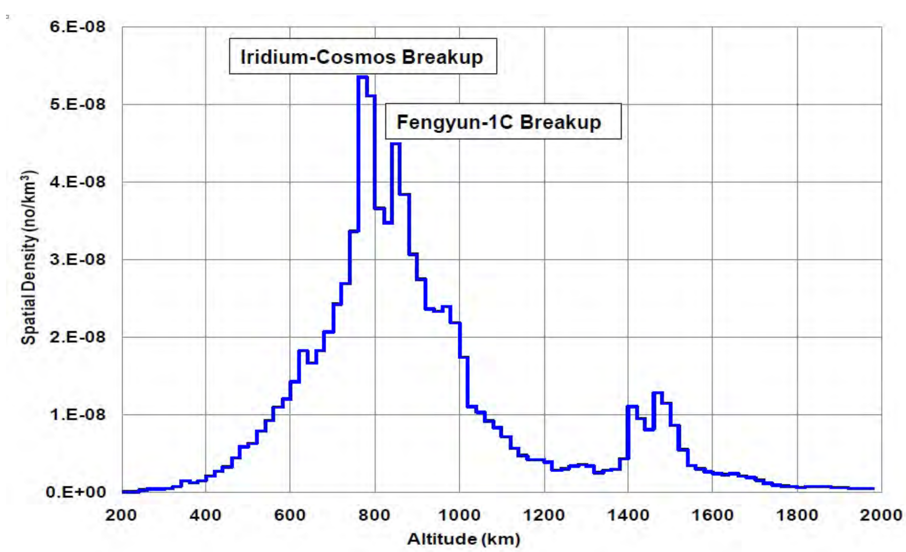


Ring of objects in geosynchronous orbit (GEO) altitudes
Cloud of objects in low-Earth orbit (LEO) altitudes

Micrometeoroids and Space Debris

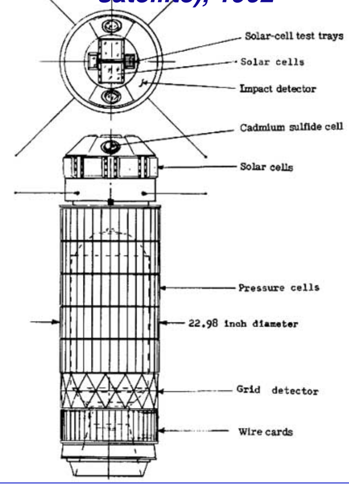
- Nuts, bolts, and other fragments in orbit
- July 2013 estimate
  - 170 million objects {< 1cm}
  - 670,000 objects {1 – 10 cm}
  - 29,000 objects {> 10 cm}
- January 2007: Chinese anti-satellite test destroyed old satellite and added >1,335 remnants larger than a golf ball
- U.S. shot down a failed spy satellite in 2008 -- more debris

Space Debris Density after 2009

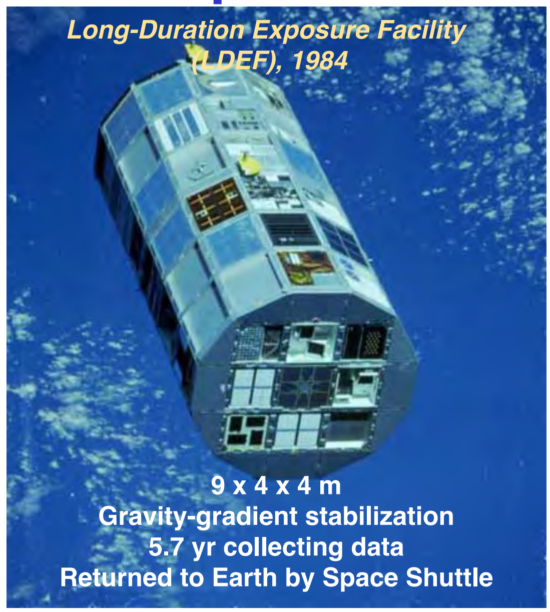


Satellites for Detecting Micrometeoroids and Space Debris

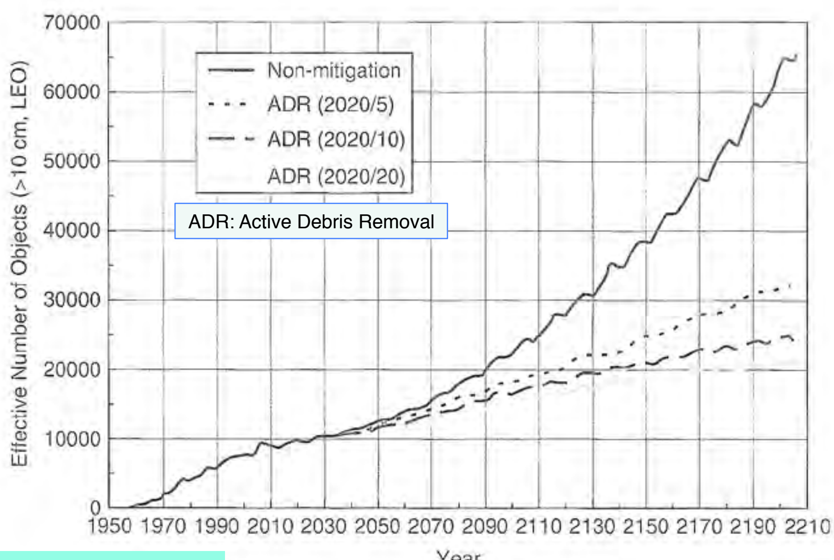
Explorer-16 ("Beer can" satellite), 1962



2 x 0.6 x 0.6 m
Pressurized-cell penetration detectors, impact and other detectors, Scout launch vehicle



Growth Estimate of Low-Earth-Orbit Debris Population



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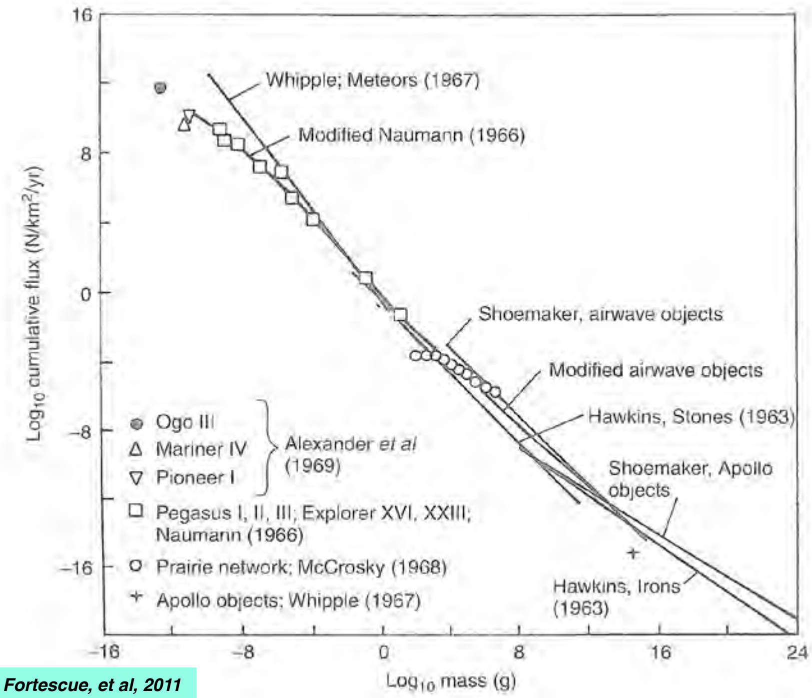
Mass Influx Rates of Micrometeoroids



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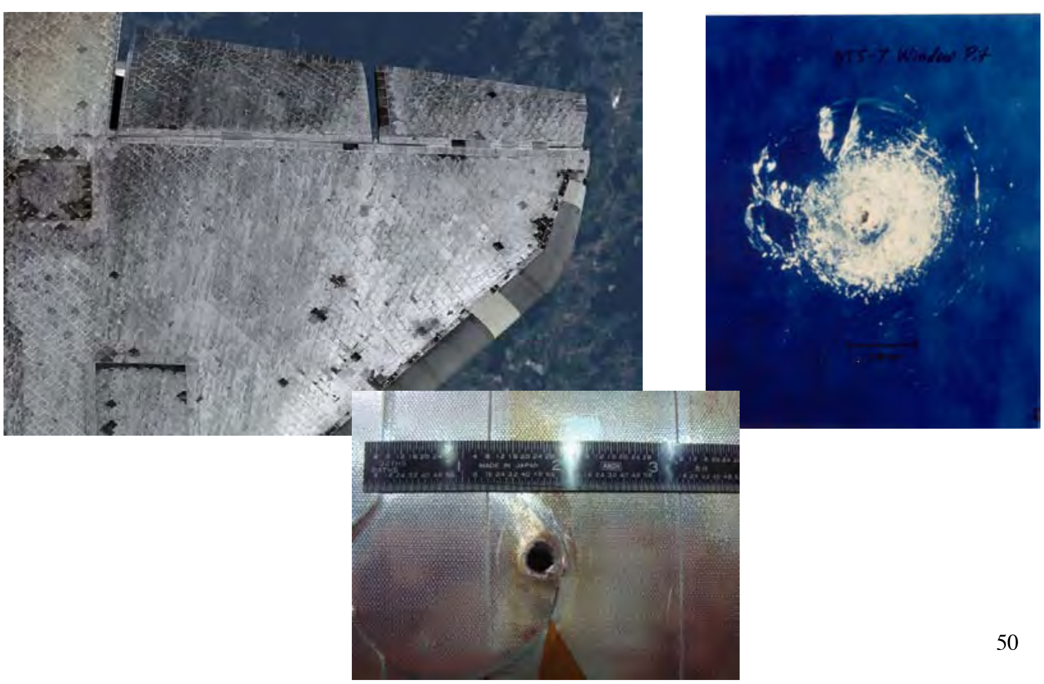
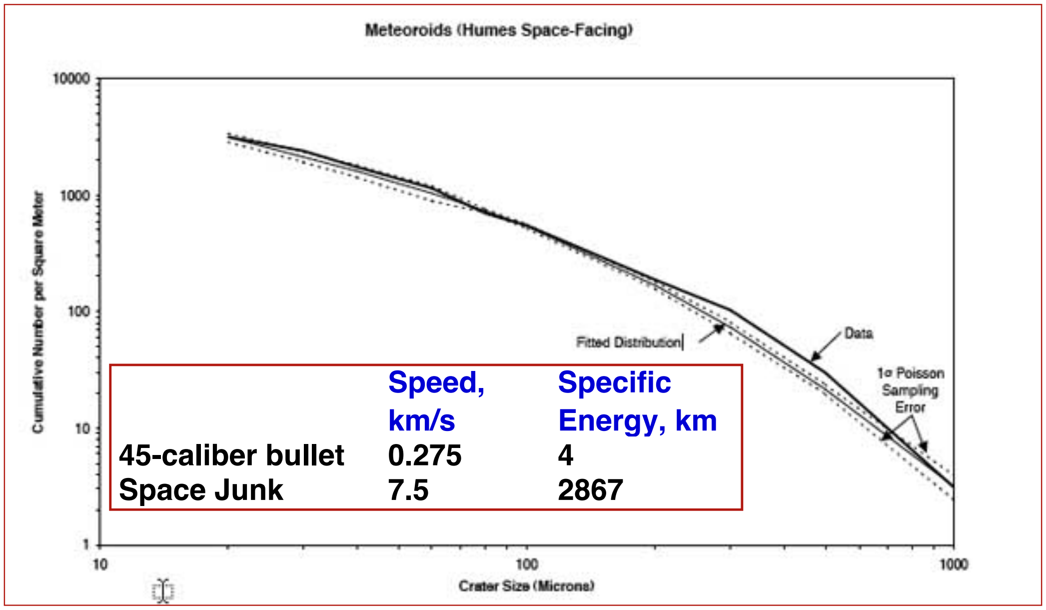
Space Debris/Micrometeoroid Damage to the Space Shuttle

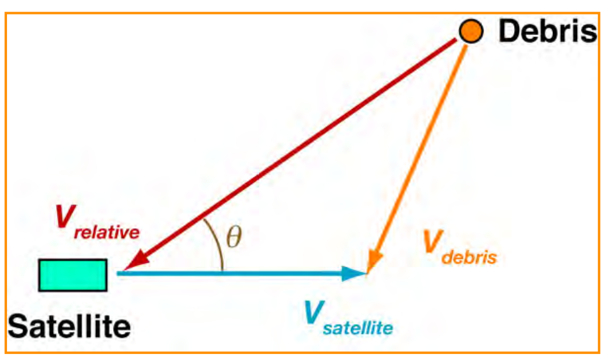


Distribution of Micrometeoroids and Space Debris (from LDEF)



	Speed, km/s	Specific Energy, km
45-caliber bullet	0.275	4
Space Junk	7.5	2867

Effect of Impact Angle on Relative Specific Energy



Impact Angle, deg	Satellite Velocity, km/s	Debris Velocity, km/s	Relative Velocity, km/s	Relative Specific Energy, km
180	7.5	7.5	0	0
45	7.5	7.5	10.6	5734
0	7.5	7.5	15	11468

Atmospheric Composition of the Planets

Planet/ Moon	Composition %	Surface pressure (Bar)	Surface temperature (K)	Temperature @ 200 km (K)	Ionosphere (Electrons/ cm^3)
Mercury	None	—	—	—	
Venus	CO_2 (96); N_2 (3.5)	92	750	100–280	$\sim 10^6$
Earth	N_2 (77); O_2 (21); H_2 (1)	1	285	800–1100	$\sim 10^6$
Mars	CO_2 (95); Ar (1.6); N_2 (2.7)	0.006	220	310	$\sim 10^5$
Jupiter	H_2 (89); CH_4 (0.2); He (11)	Gaseous planet	165[1]		$\sim 10^5$
Saturn	H_2 (93); CH_4 (0.2); He (7)	Gaseous planet	130[1]		
Titan	N_2 (90–99); CH_2 (1–5); Ar (0–6)	1.5	95	150	$\sim 10^3$
Uranus	H_2 (85); CH_4(< 1); He (15)	Gaseous planet	80[1]		
Neptune	H_2 (90); CH_4(< 1); He (10)	Gaseous planet	70[1]		
Pluto	N_2 CH_4/CO (traces only)	—	40	—	—

[1]Temperature quoted where pressure is the same as Earth sea level (P = 1 Bar).
See also Tables 2.5, 2.7 and 4.1.

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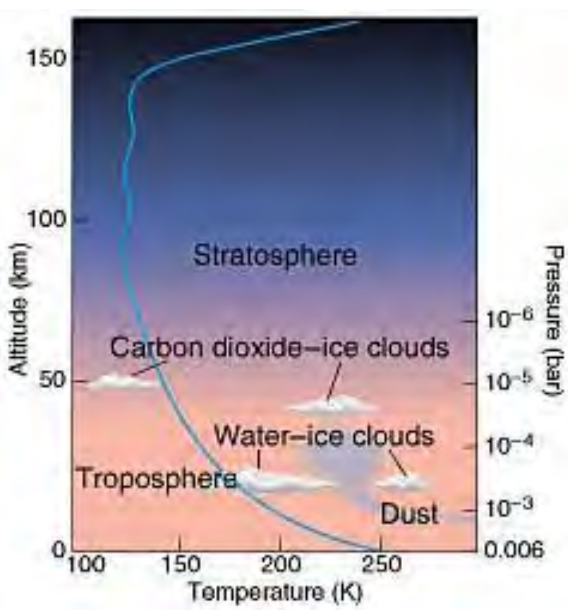
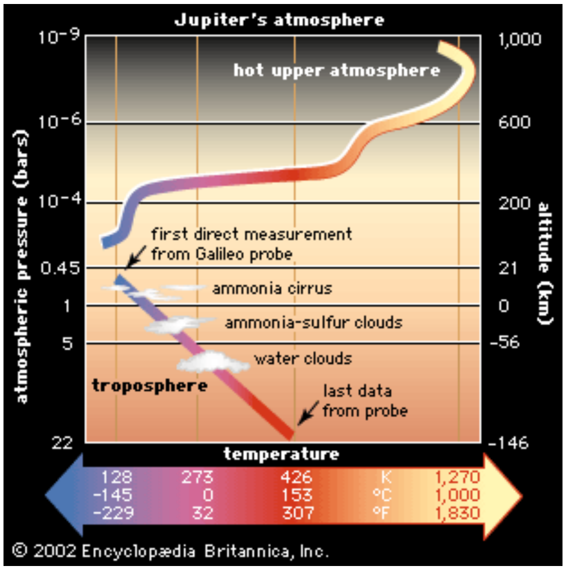
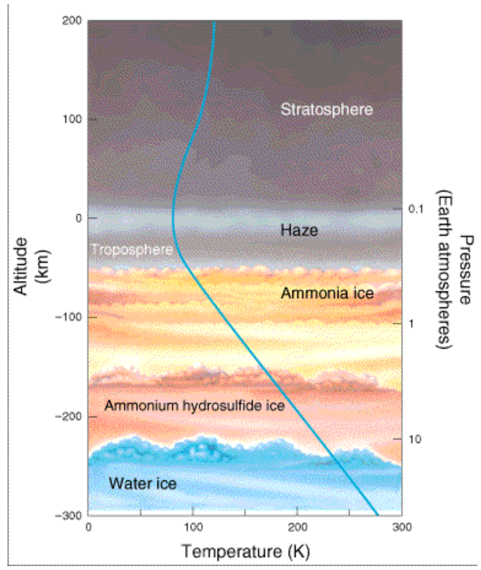
The Atmosphere of Mars

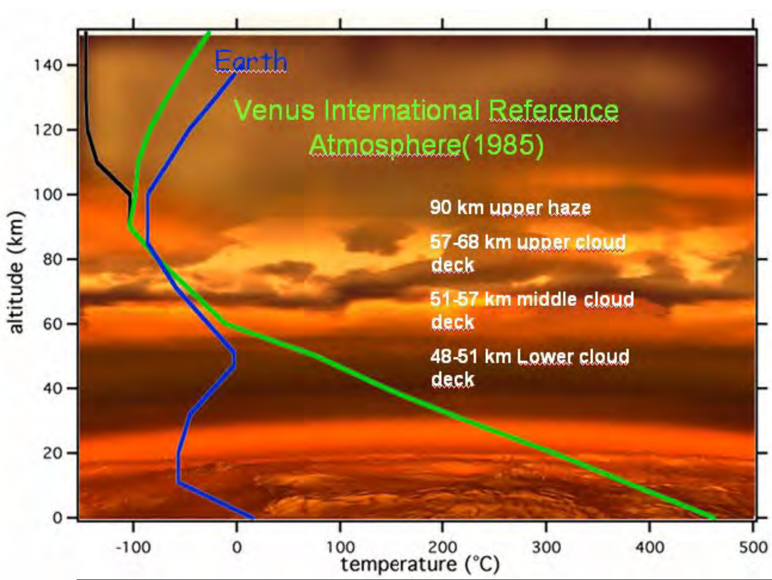


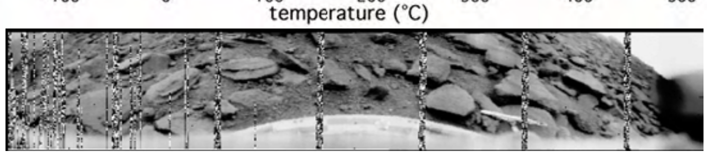
The Atmospheres of Jupiter and Saturn



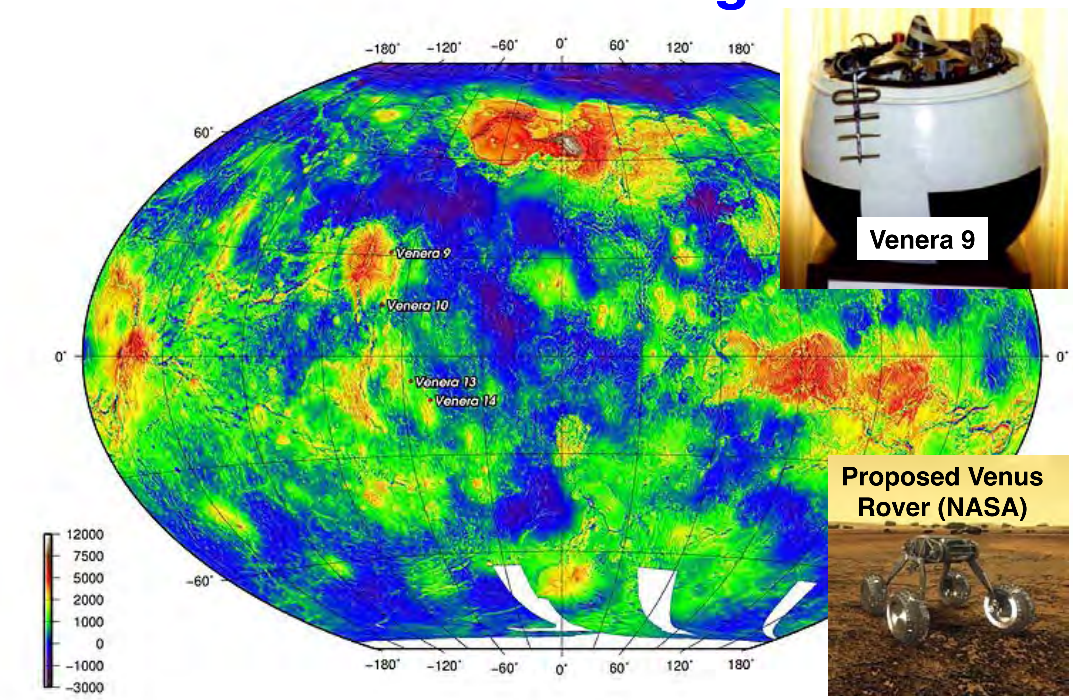


The Atmosphere and Surface of Venus





Venus Landings



Next Time: Chemical/Nuclear Propulsion Systems