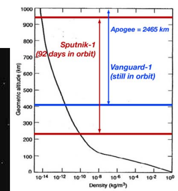
Spacecraft Environment

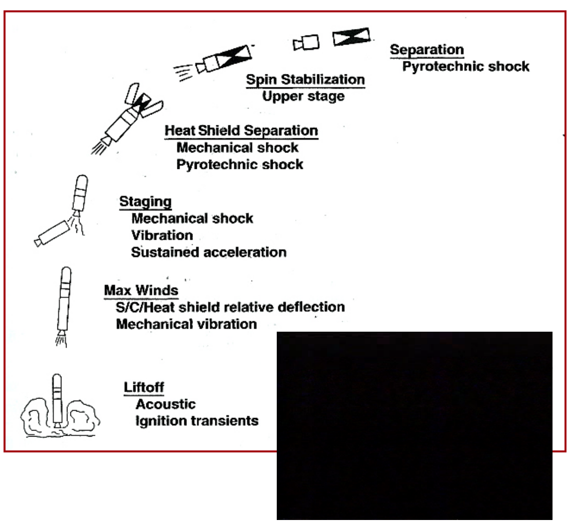
Space System Design, MAE 342, Princeton University
Robert Stengel

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



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

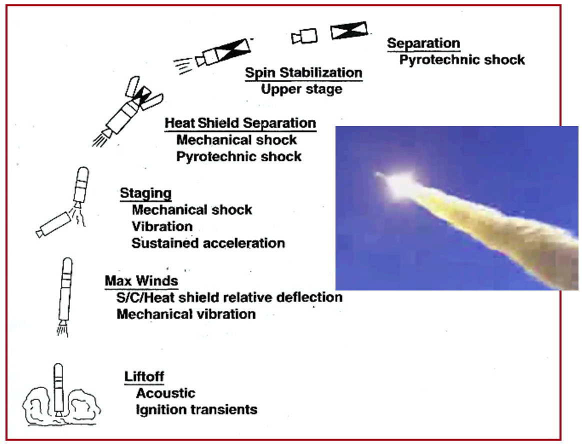
Launch Phases and Loading Issues-1



- 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

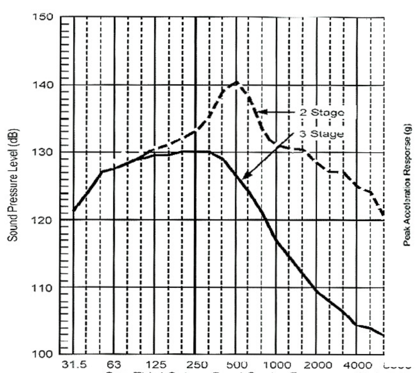


3

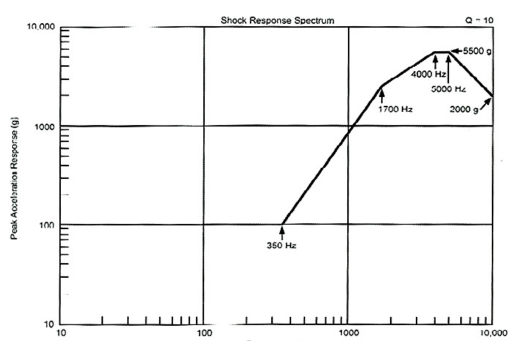
3

Typical Acoustic and Shock Environment (Delta II)

Sound Pressure (dB)



Peak Acceleration (g)



Decibel (dB)

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

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

4

4

Transient Loads at Thrusting Cutoff

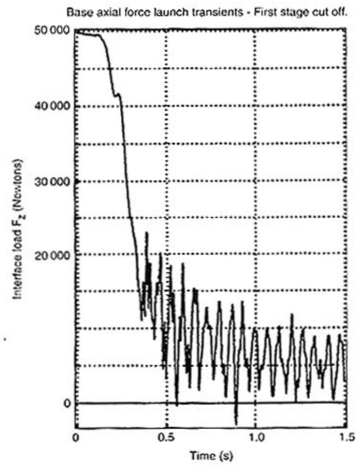


Figure 8.8 Base axial force launch transient for Ariane 4 first stage cut off (Reproduced by permission of Arianespace)

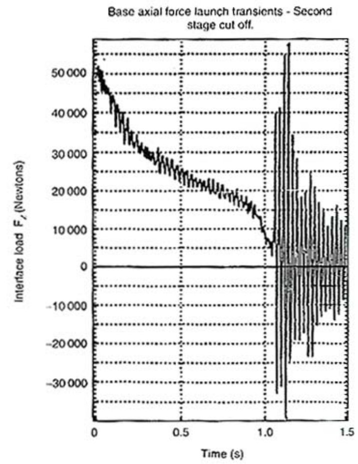


Figure 8.9 Base axial force launch transient for Ariane 4 second stage cut off (Reproduced by permission of Arianespace)

Fortescue, et al, 2003

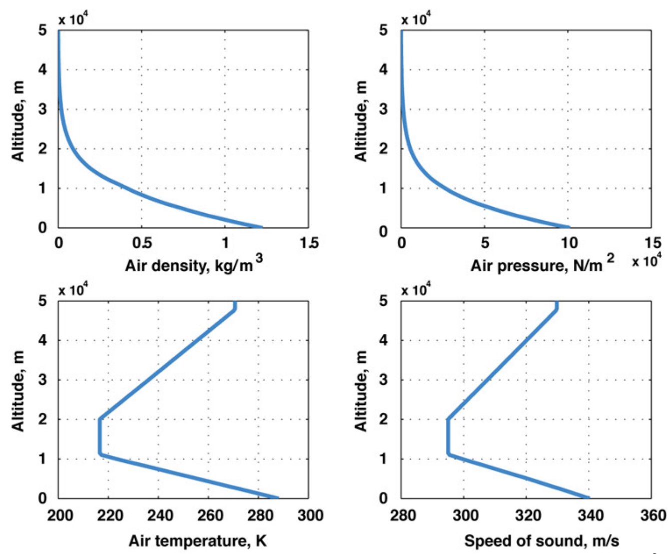
5

5

Properties of the Lower Atmosphere

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

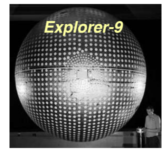
US Standard Atmosphere, 1976



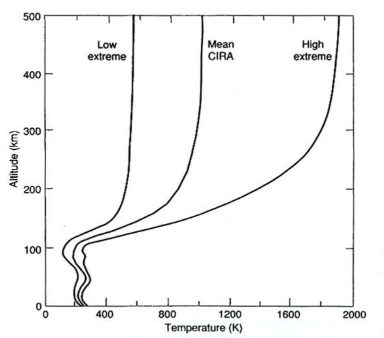
6

6

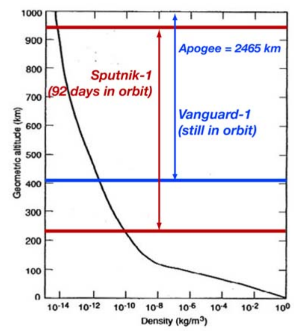
Earth's High-Altitude Atmosphere



Temperature of the Atmosphere



Density of the Atmosphere



Atmosphere not well-represented as a continuum at high altitude

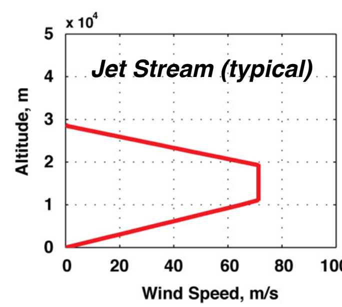
Altitude	Molecules/cc	Mean Free Path
Sea Level	2 x 10^19	7 x 10^-6 cm
600 km	2 x 10^7	10 km

7

7

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

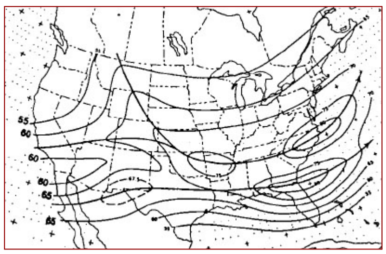


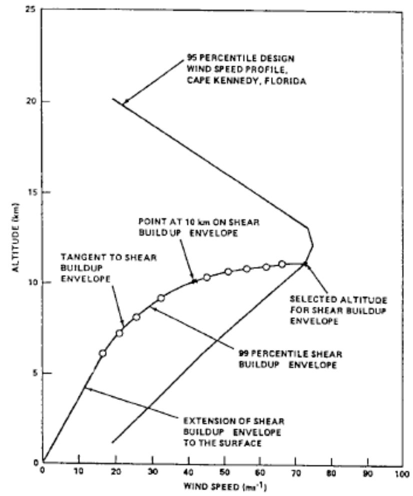
8

8

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

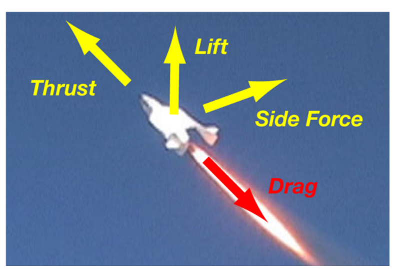




9

9

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

10

10

Aerodynamic Force Parameters

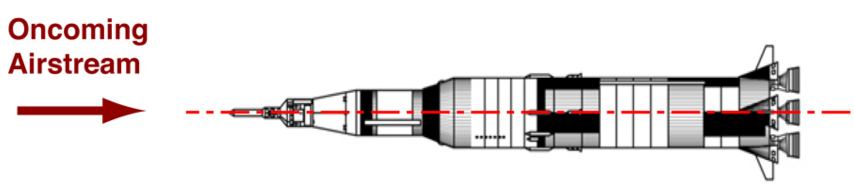
$$\rho = \textbf{air density}, \text{ function of height, } h$$
$$= \rho_{sealevel} e^{-\beta h}$$
$$\rho_{sealevel} = 1.225\, kg/m^3; \quad \beta = 1/9{,}042\, m$$
$$V = \left[v_x^2 + v_y^2 + v_z^2\right]^{1/2} = \left[\mathbf{v}^T \mathbf{v}\right]^{1/2}, m/s$$
$$\textbf{Dynamic pressure} = \bar{q}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

11

11

Aerodynamic Drag

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

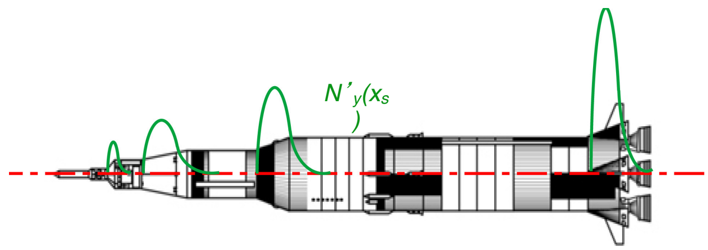


- **Drag components sum to produce total drag**
  - Skin friction
  - Base pressure differential
  - Forebody pressure differential (M > 1)

12

12

Aerodynamic Moment



Lengthwise lift variation causes bending moment

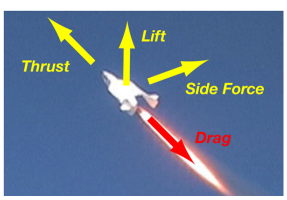
$N'(x) = \text{normal force variation with length} \approx \text{lift variation}$

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

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

13

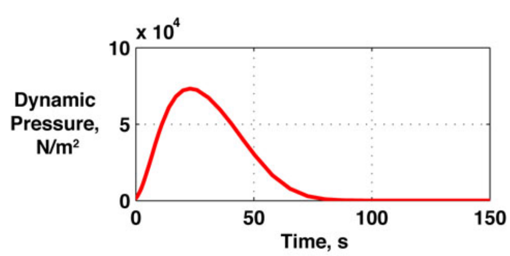
13



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_DS/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



14

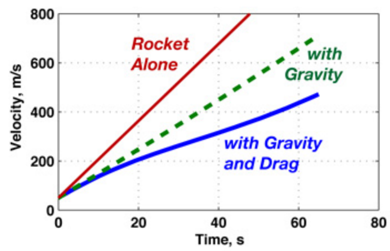
14

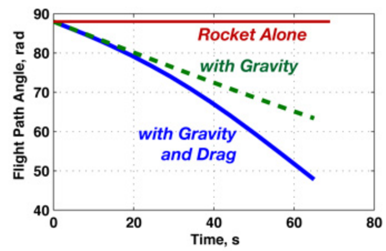
Effects of Gravity and Drag on the Velocity Vector

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

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

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

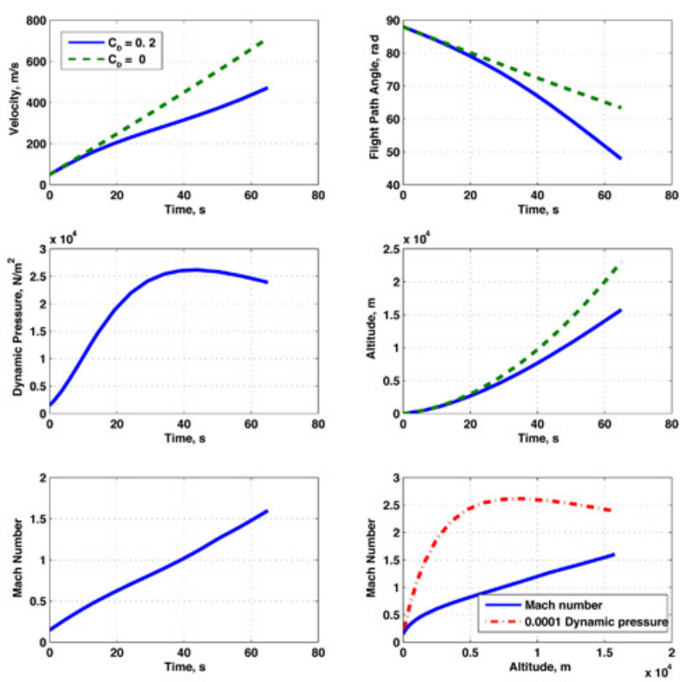




Significant reduction in velocity magnitude
Strong curvature of the flight path

15

15



Typical Properties of Launch Trajectories

Thrust/Weight = 2

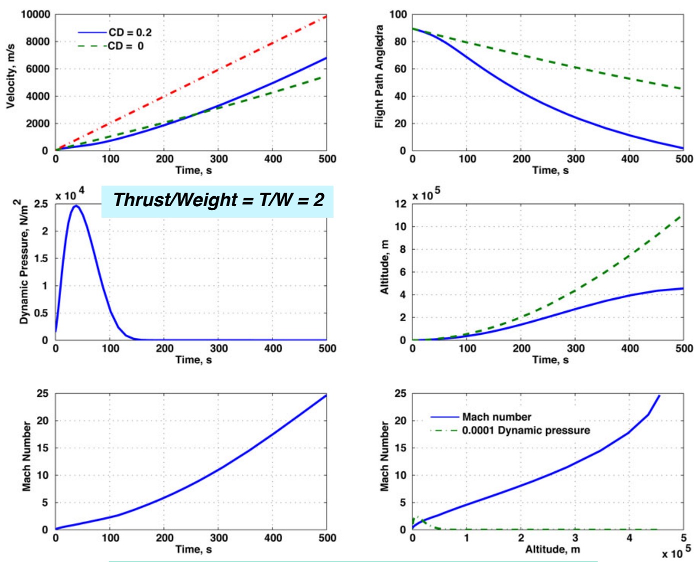
- **Maximum dynamic pressure**
- **Mach = 1**
- **maximum drag**
- **maximum jet stream magnitude**

tend to occur at similar altitudes

16

16

Gravity and Drag Effects during Single-Stage Orbital Launch



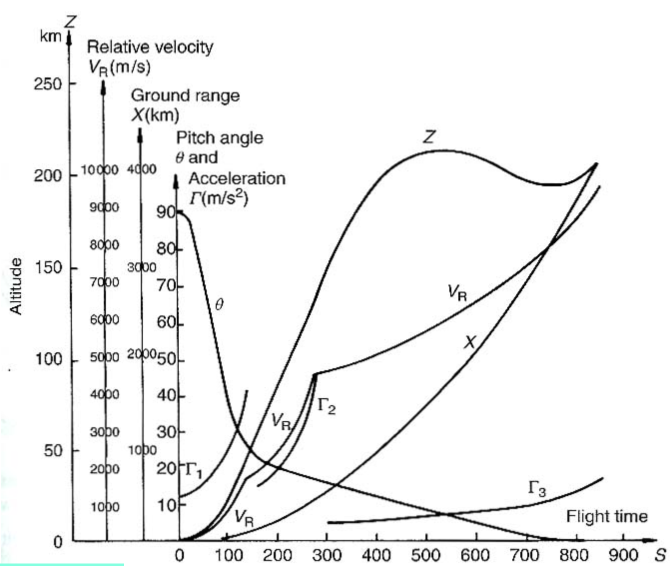
- Launch trajectory using flat-earth model
- Red line signifies velocity due to rocket alone
- Several km/s lost to gravity and drag

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

17

17

Typical Ariane 4 Launch Profile

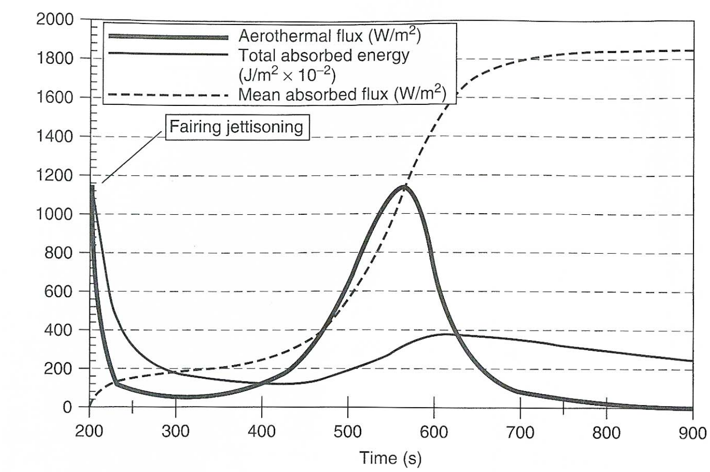


Fortescue, et al, 2003

18

18

Ariane 5 Aerothermal Flux



Fortescue, et al, 2011

19

19

Orbital Lifetime of a Satellite

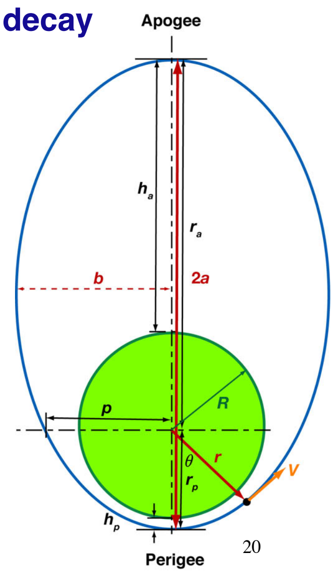
- **Aerodynamic drag causes orbit to decay**

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

- **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**



20

20

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

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

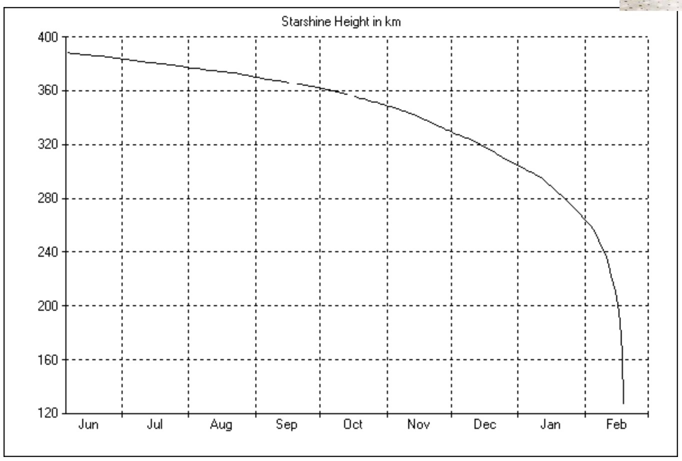
- Time, t_{decay}, to reach earth's surface ($a = R$) from starting altitude, h_0

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

21

21

NRL Starshine 1 Orbital Decay (2003)



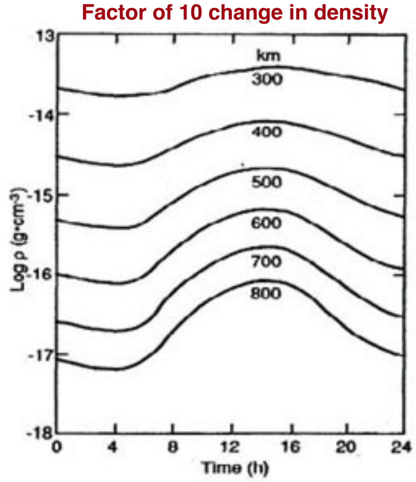
http://www.azinet.com/starshine/descript.htm

22

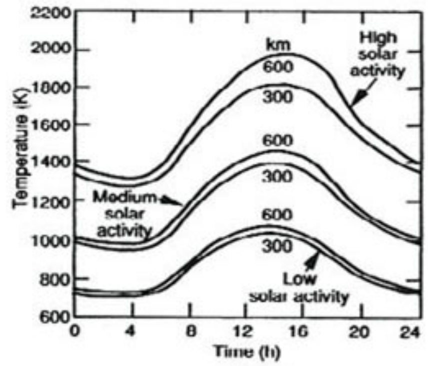
22

Diurnal Variations in Earth's Upper Atmosphere

Factor of 10 change in density



±20% change in temperature
Large effect of solar activity

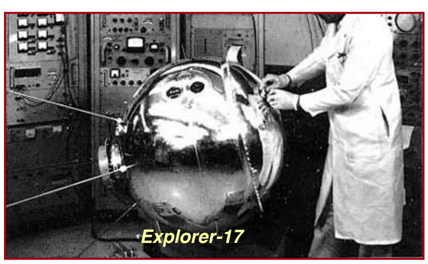


Pisacane, 2005

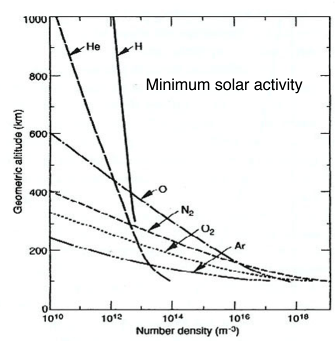
23

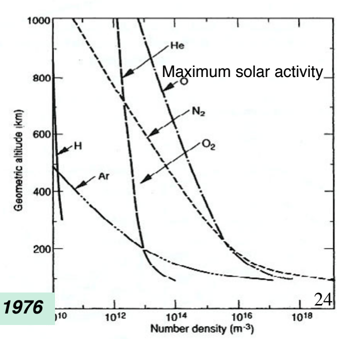
23

Atmospheric Constituents



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



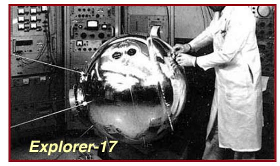


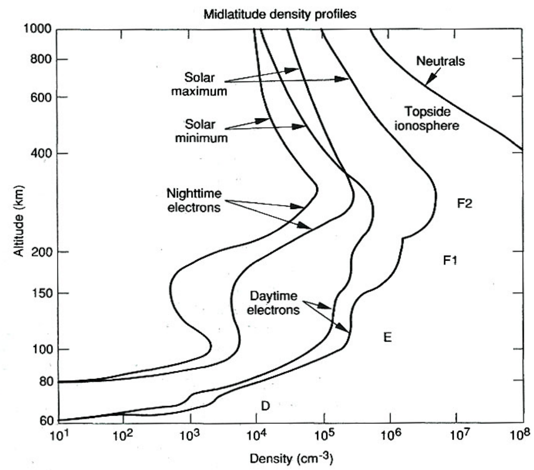
US Std. Atmos., 1976

24

24

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

25

25

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

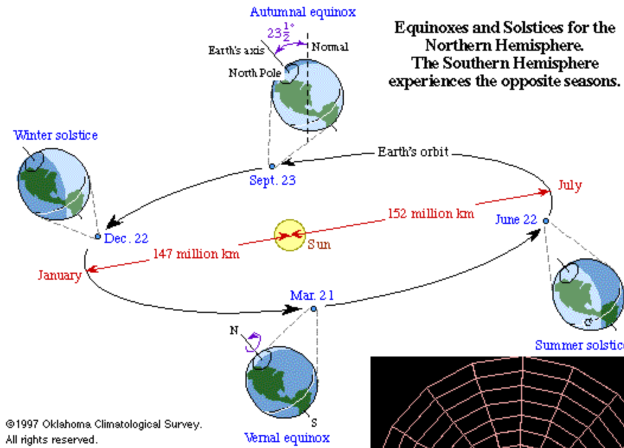
- At high altitude, the mean free path of molecules is greater than the dimensions of most spacecraft
  - Aerodynamic calculations should be based on free molecular flow
  - Heat exchange is solely due to radiation

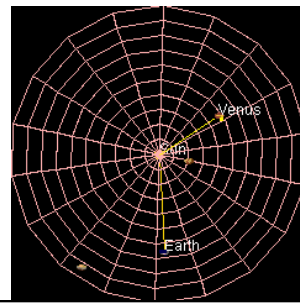
Fortescue, et al, 2011

26

26

Orbits About the Sun



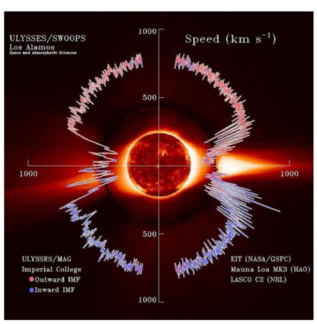


27

27

Solar System Environment

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

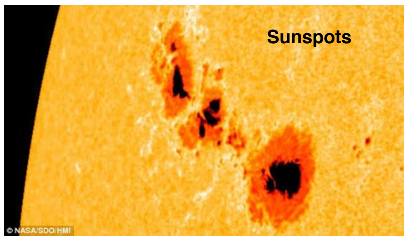


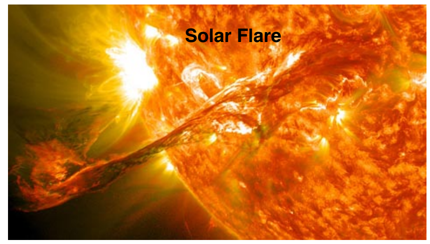
- **Solar wind**
  - **Plasma consisting of electrons, protons, and alpha particles**
  - **Variable temperature, density, and speed**
  - **1.5-10 keV**
  - **Slow (400 km/s) and fast (750 km/s) charged particles**
  - **Geomagnetic storms**

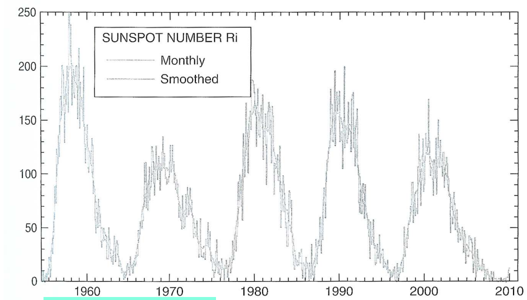
28

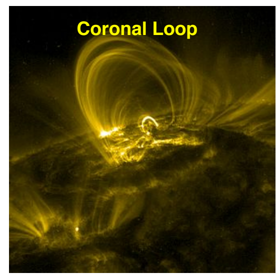
28

Sunspots and Solar Flares







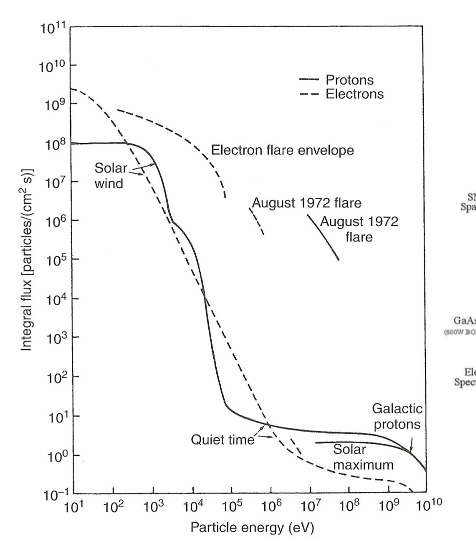


Fortescue, et al, 2011

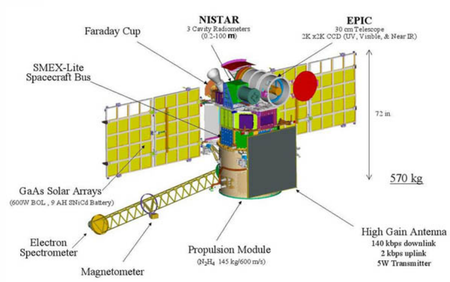
29

29

Flux vs. Energy of Electrons and Protons



Deep Space Climate Observatory (DSCOVR) at L1

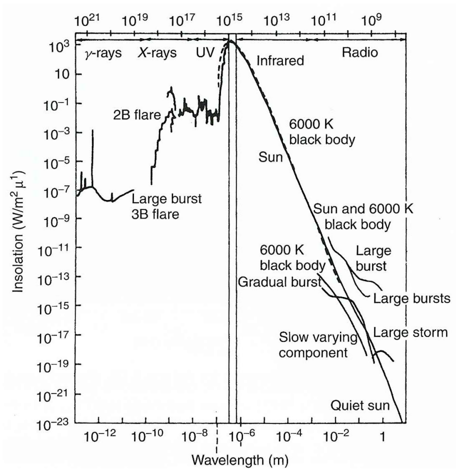


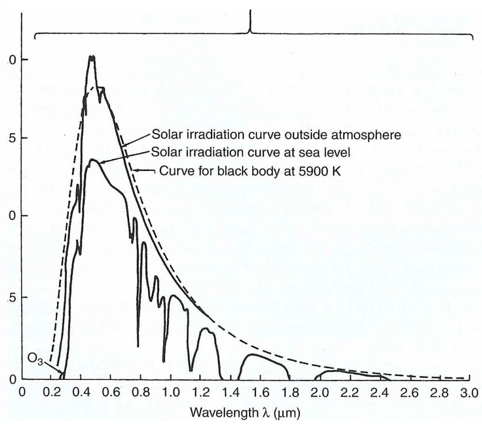
Fortescue, et al, 2011

30

30

The Solar Spectrum





Fortescue, et al, 2011

31

31

Variability of Solar Radiation

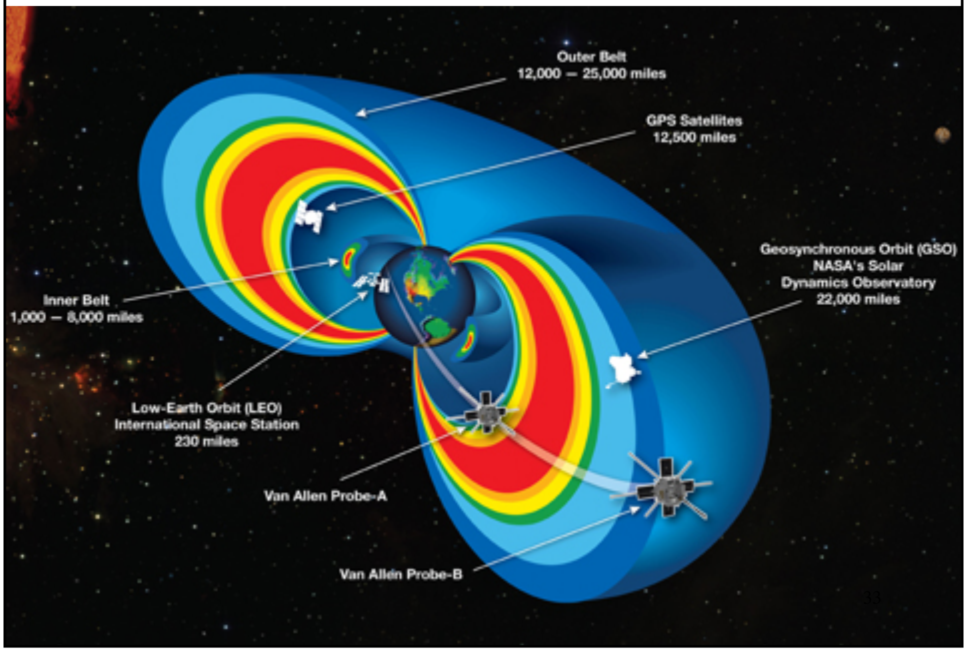
Spectral region	Wavelength	Flux (J/(m² s μm))	Variability
Radio	$\lambda > 1$ mm	10^{-11}–10^{17}	×100
Far infrared	1 mm $\geq \lambda >$ 10 μm	10^{-5}	Uncertain
Infrared	10 μm $\geq \lambda >$ 0.75 μm	10^{-3}–10^{2}	Uncertain
Visible	0.75 μm $\geq \lambda >$ 0.3 μm	10^{3}	<1%
Ultraviolet	0.3 μm $\geq \lambda >$ 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 $\geq \lambda >$ 1Å	10^{-1}–10^{-7}	×100
Hard X-ray	1Å $\geq \lambda$	10^{-7}–10^{-8}	×10– × 100

Fortescue, et al, 2011

32

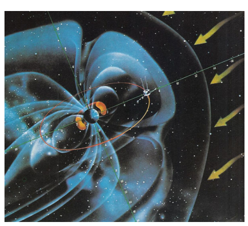
32

Van Allen Belts

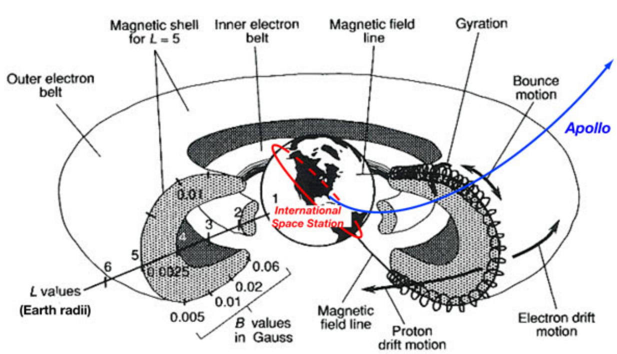


33

Magnetosphere and Van Allen Belts



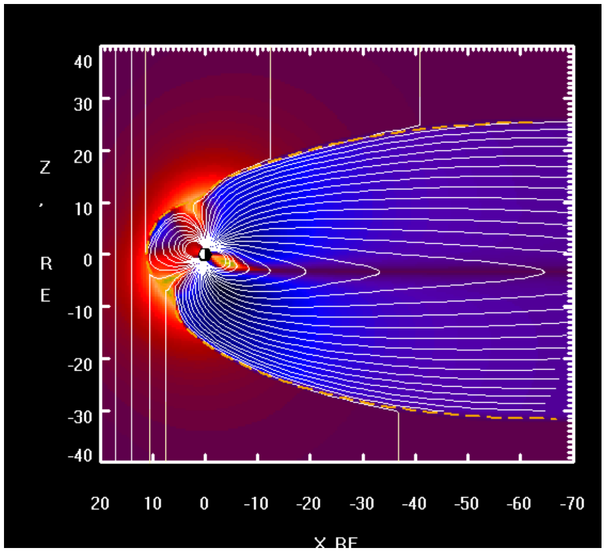
- Trapped Energetic Ions and Electrons
- Light ions form the base population of the magnetosphere



34

34

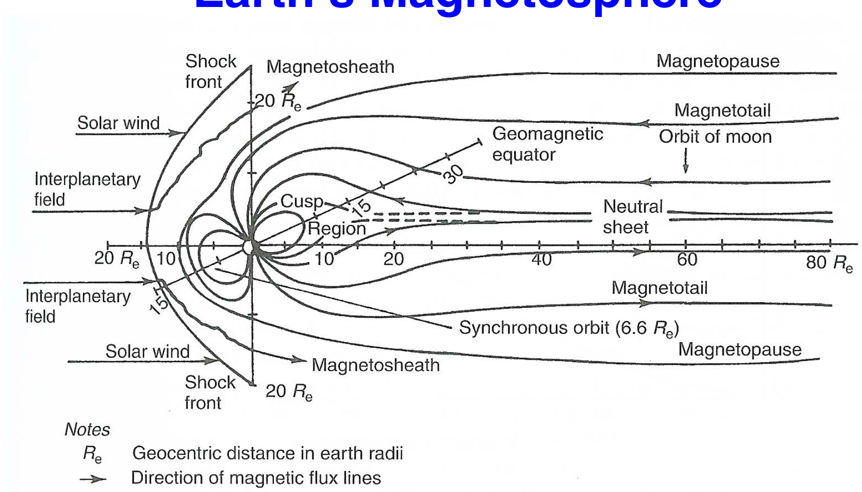
Earth’s Magnetosphere



35

35

Earth’s Magnetosphere

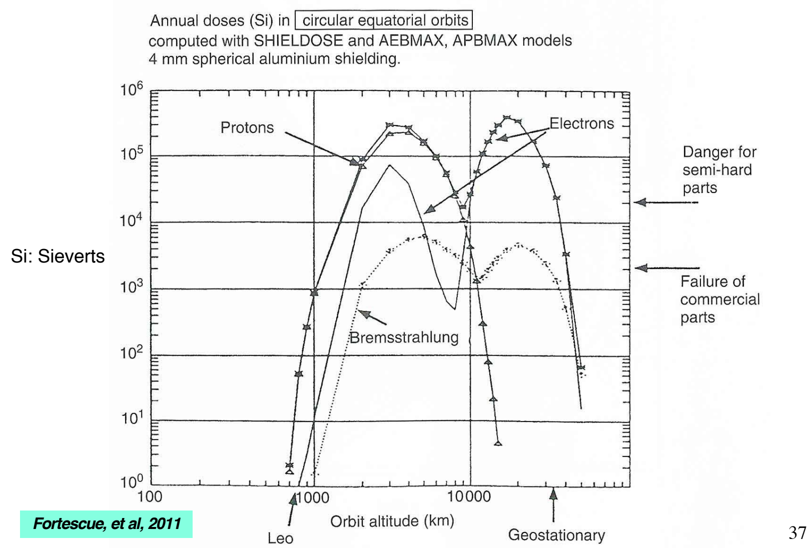


Fortescue, et al, 2011

36

36

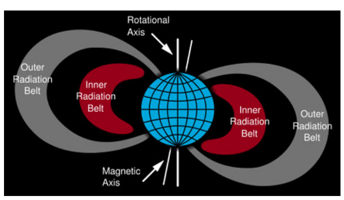
Annual Dose of Ionizing Radiation



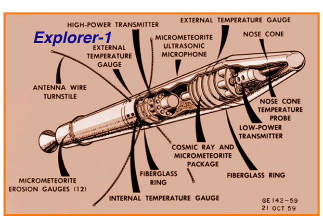
Fortescue, et al, 2011

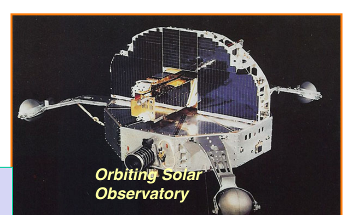
37

37



Spacecraft That Defined the Magnetosphere and Van Allen Belts

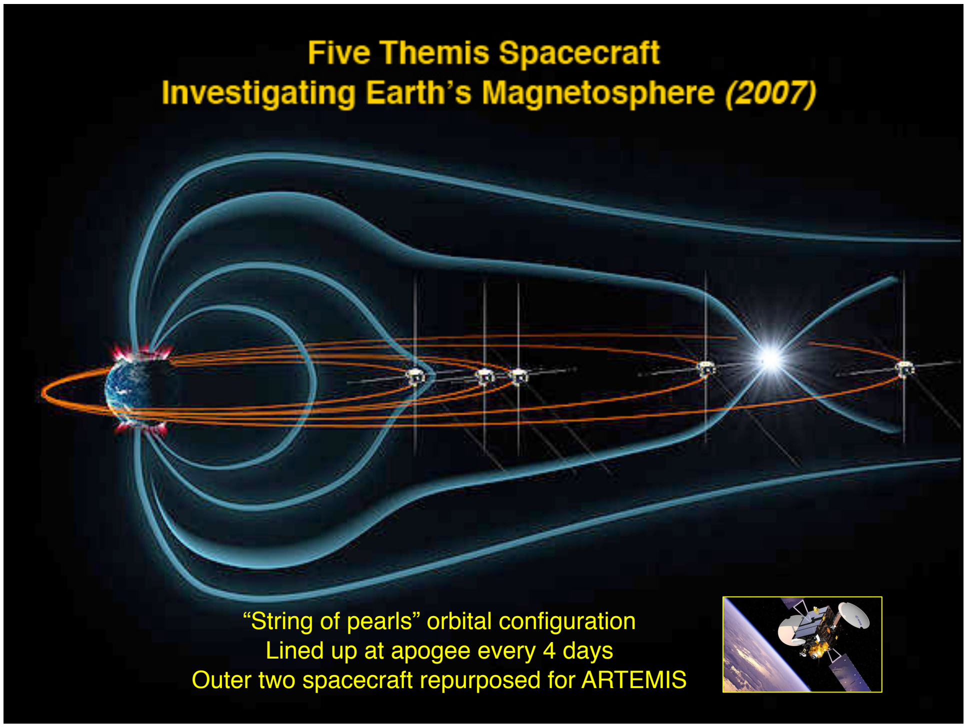




- see *Pisacane* for discussion of mechanics and dynamics
  - plasma frequency
  - Debye length
  - spacecraft charging and ram-wake effects
  - motion of charged particles in a dipole field
  - trapped radiation

38

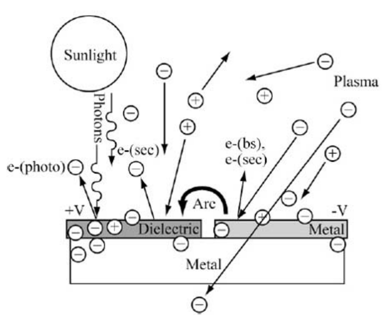
38



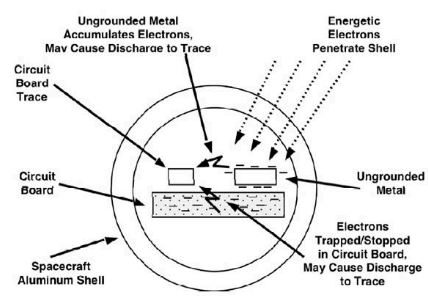
39

Spacecraft Charging

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



Exterior



Interior

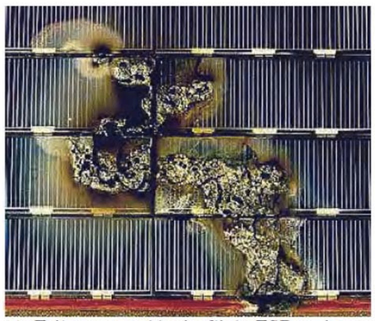
NASA-HDBK-4002A, 2011

40

40

Spacecraft Charging Damage

Interaction of space plasma and spacecraft materials and electronics



(a) Failure caused by in-flight ESD arcing

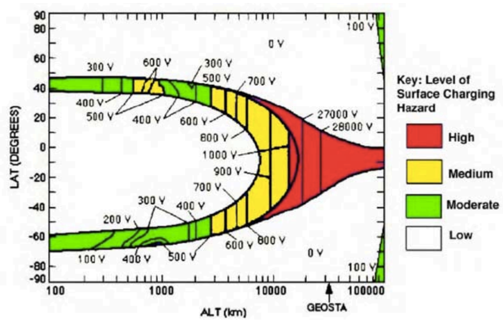
SCATHA Satellite, 1979

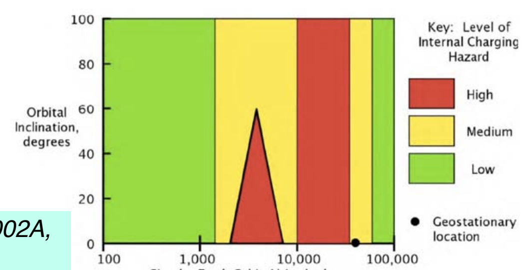
NASA-HDBK-4002A, 2011

41

41

Spacecraft Charging Hazard Zones



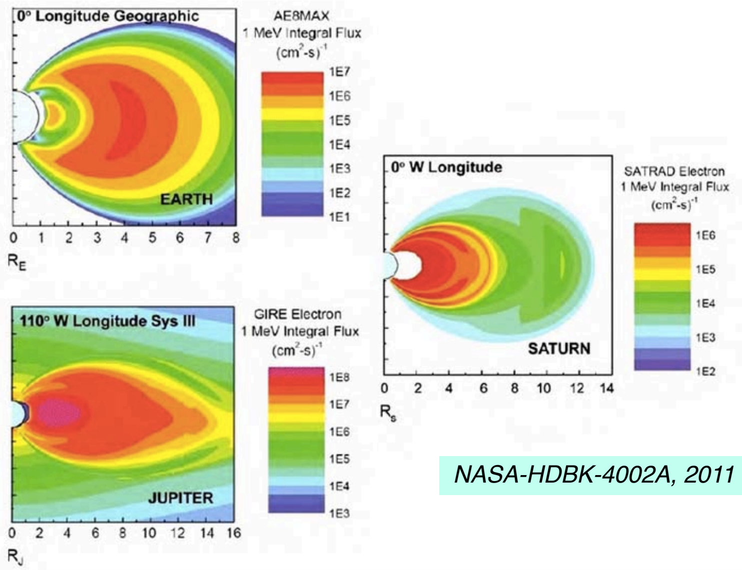


NASA-HDBK-4002A, 2011

42

42

Integral Flux Contours at Earth, Jupiter, and Saturn

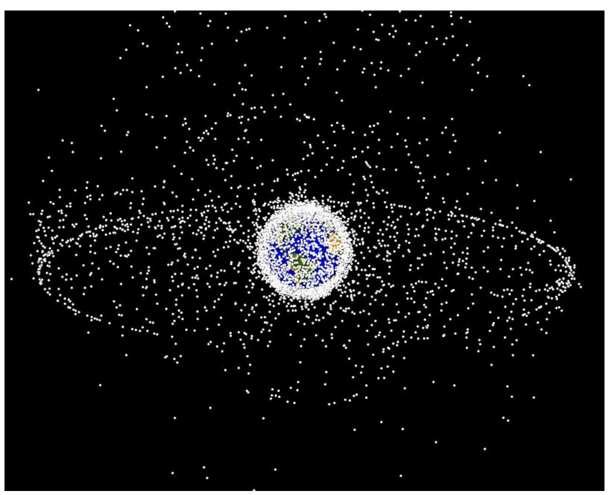


NASA-HDBK-4002A, 2011

43

43

Space Debris

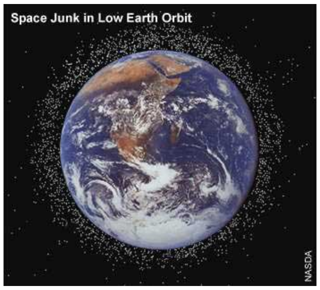


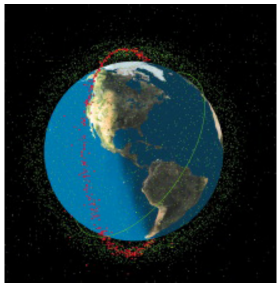
Ring of objects in geosynchronous orbit (GEO) altitudes
Cloud of objects in low-Earth orbit (LEO) altitudes

44

44

Micrometeoroids and Space Debris



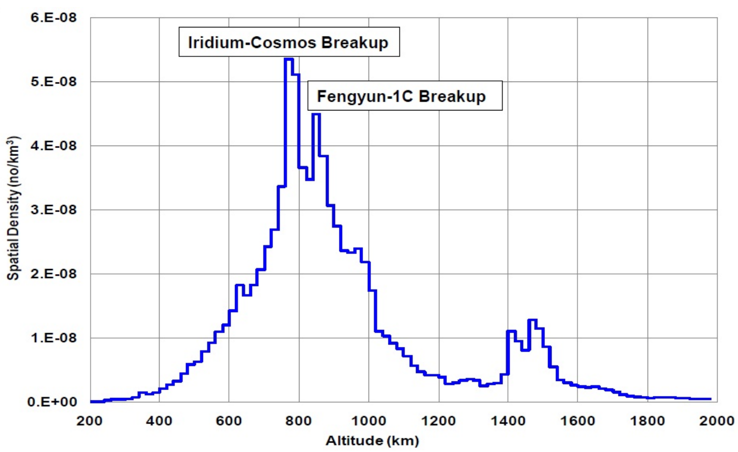


- Nuts, bolts, and other fragments in orbit
- July 2013 estimate
  - 170 million objects {< 1cm}
  - 670,000 objects {1 – 10 cm}
  - 29,000 objects {> 10 cm}
- January 2007: Chinese anti-satellite test destroyed old satellite and added >1,335 remnants larger than a golf ball
- U.S. shot down a failed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

45

45

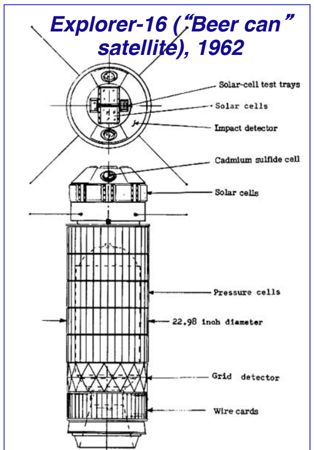
Space Debris Density after 2009



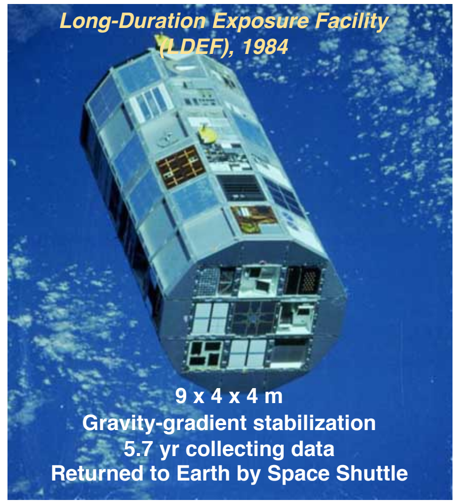
46

46

Satellites for Detecting Micrometeoroids and Space Debris



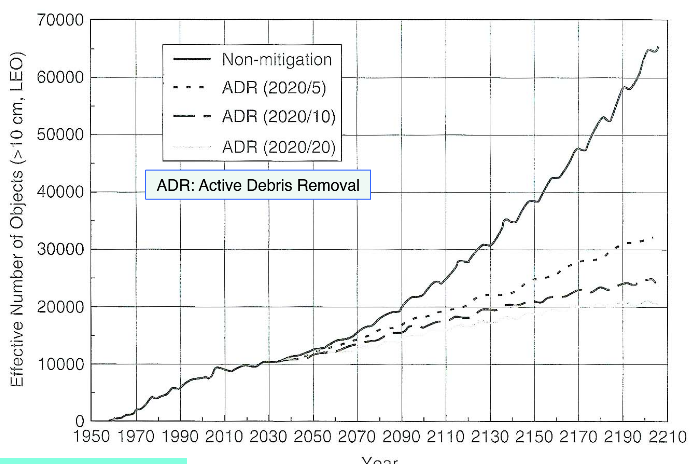
2 x 0.6 x 0.6 m
Pressurized-cell penetration detectors, impact and other detectors, Scout launch vehicle



47

47

Growth Estimate of Low-Earth-Orbit Debris Population

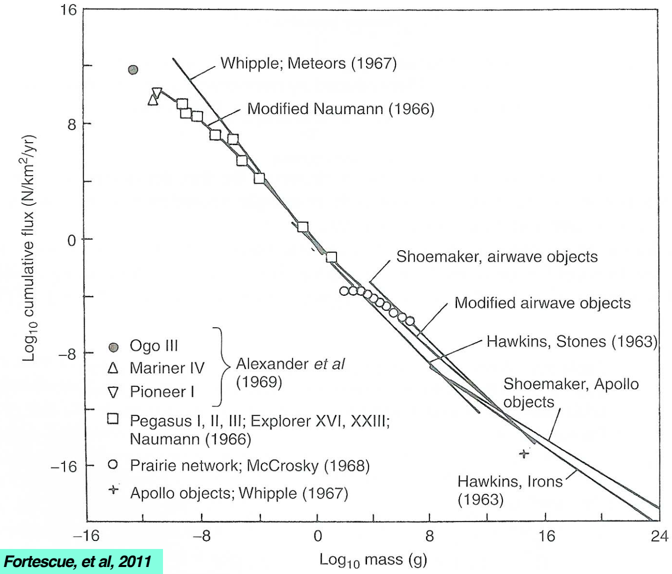


Fortescue, et al, 2011

48

48

Mass Influx Rates of Micrometeoroids

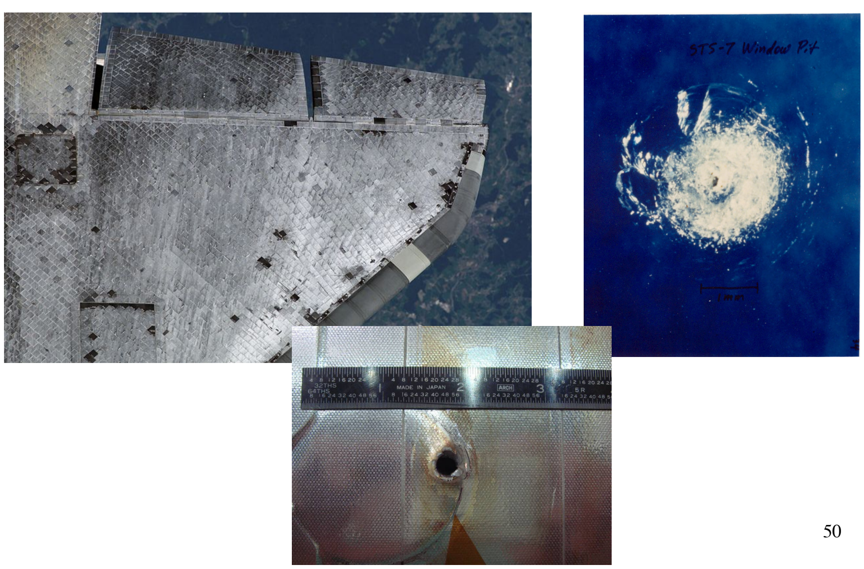


Fortescue, et al, 2011

49

49

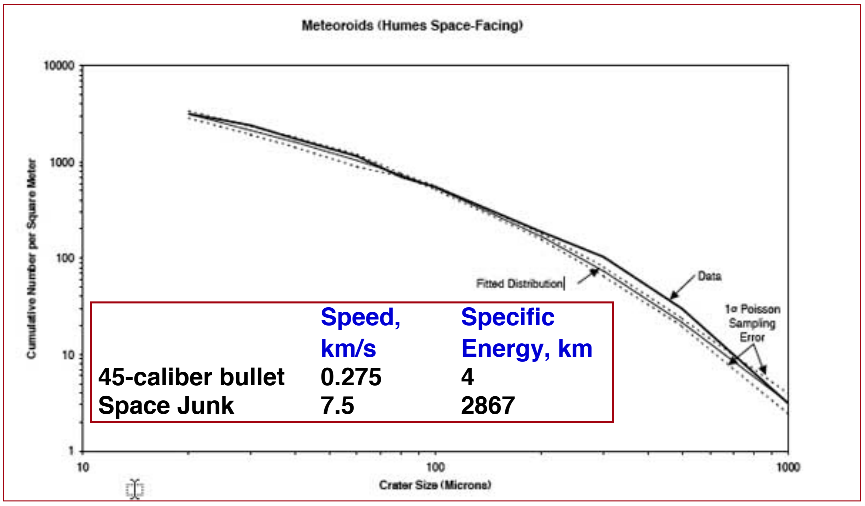
Space Debris/Micrometeoroid Damage to the Space Shuttle



50

50

Distribution of Micrometeoroids and Space Debris (from LDEF)

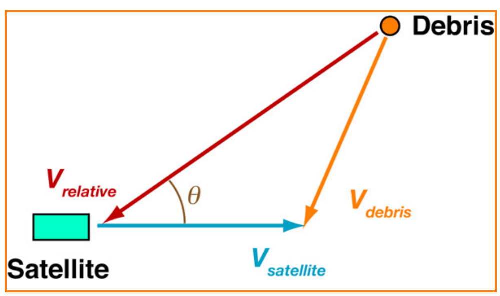


	Speed, km/s	Specific Energy, km
45-caliber bullet	0.275	4
Space Junk	7.5	2867

51

51

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

52

52

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	—	—

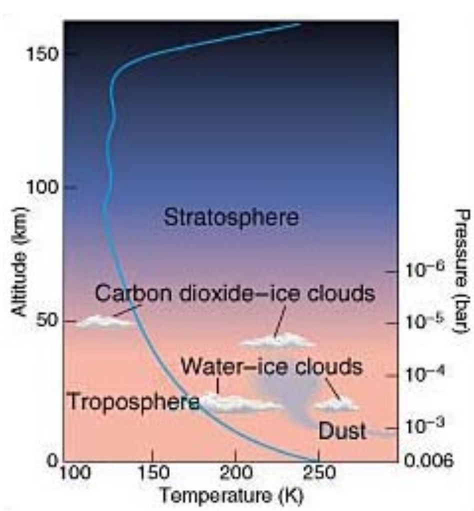
[1]Temperature quoted where pressure is the same as Earth sea level (P = 1 Bar).
See also Tables 2.5, 2.7 and 4.1.

Fortescue, et al, 2011

53

53

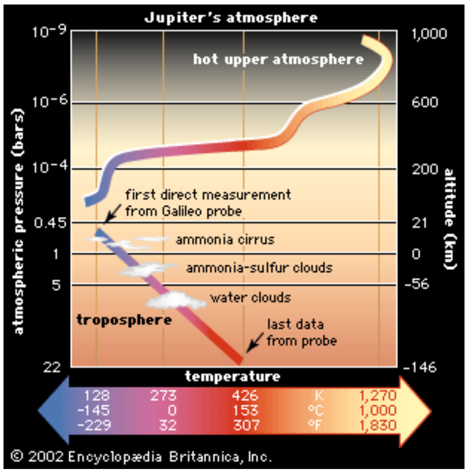
The Atmosphere of Mars

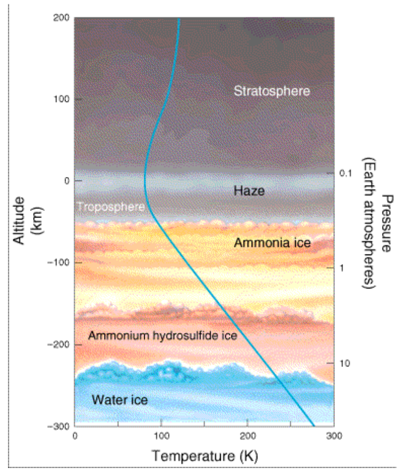


54

54

The Atmospheres of Jupiter and Saturn

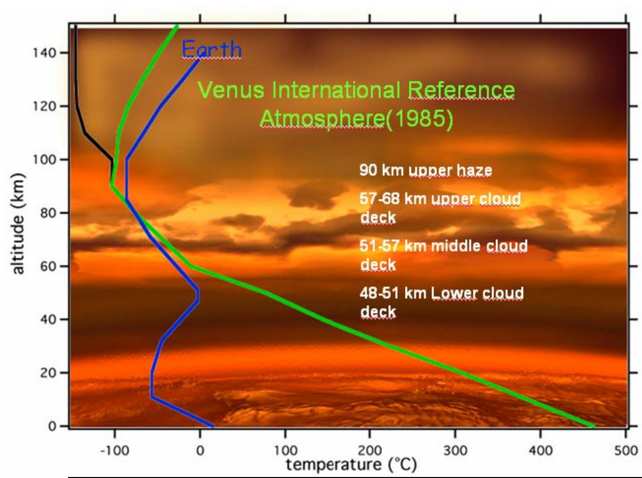


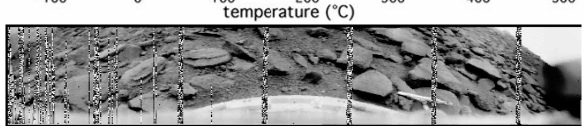


55

55

The Atmosphere and Surface of Venus

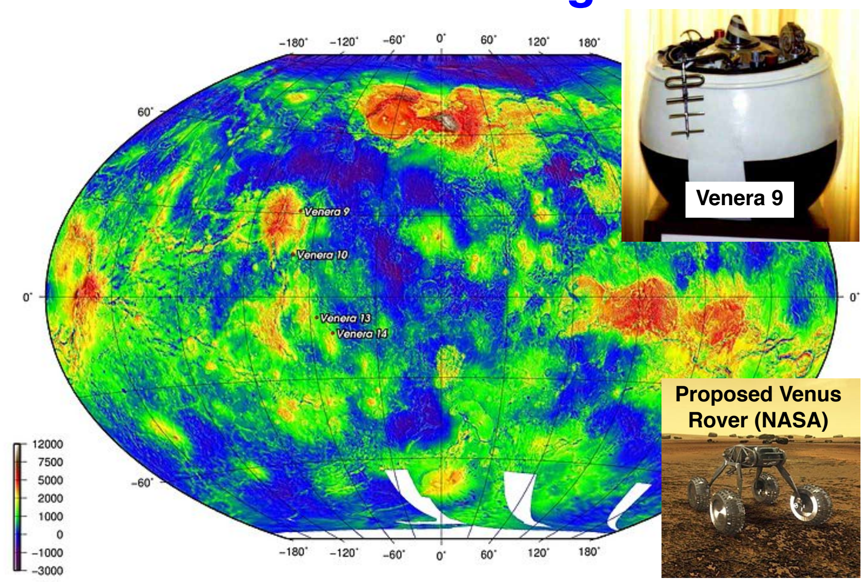




56

56

Venus Landings



57

57

Next Time: Chemical/Nuclear Propulsion Systems

58

58