Micrometeoroid and Orbital Debris (MMOD) environment

Lecture 12

W.K. Tobiska

Space Environment Technologies

Announcements

Contributions

- Cluster: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=8 (This website is on the ESA network (homepage: http://sci.esa.int), which has excellent links to other spacecraft and instruments, and background science)
- WIND: http://www-spof.gsfc.nasa.gov/istp/wind
- FAST: http://sprg.ssl.berkeley.edu/fast/
- Radiation Belt Mapper: http://lws.gsfc.nasa.gov/documents/mission_requir_ws_2_2000/hesse_020900.pdf

Announcements

Contributions

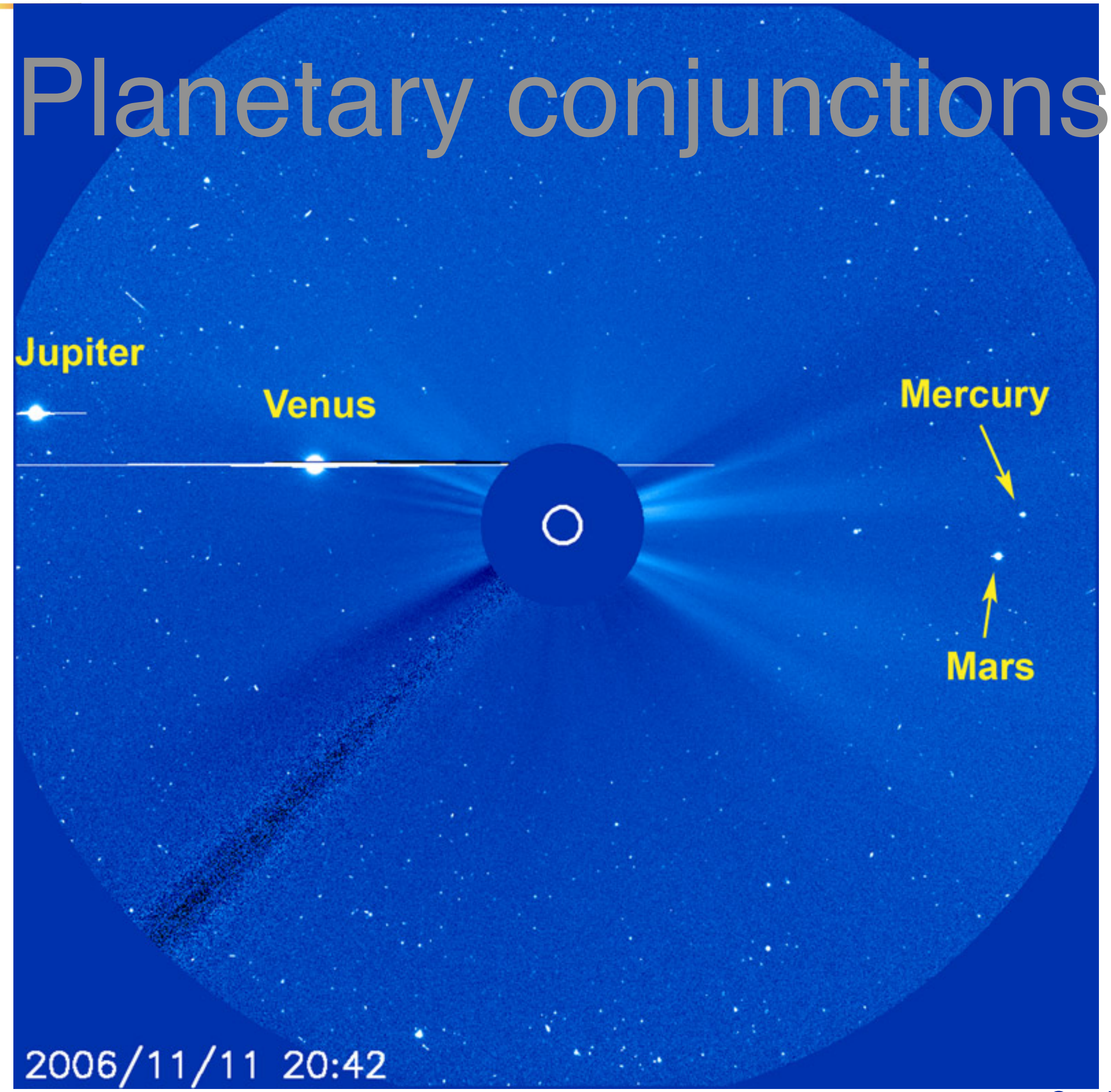
- **Wikipedia Space Tourism (with links to other space tourism sites):** http://en.wikipedia.org/wiki/Space_hotel
- **Space Adventures Tourism Company:** www.spaceadventures.com
- **Space-Future profile of a space hotel:** http://www.spacefuture.com/archive/space_elevators_space_hotels_and_space_tourism.shtml
- **Bigelow-Aerospace Space Hotel:** http://www.lasvegasmercury.com/2004/MERC-Jul-08-Thu-2004/24250261.html
- **Hilton Space Hotel:** http://news.bbc.co.uk/1/hi/sci/tech/293366.stm
- A MeV = Mega electron Volt per Mass Number, where A is the mass number of an atom. A is the number of nucleons (protons + neutrons) in an atom and A MeV is therefore the energy per single nucleon.

Announcements

Contributions

- **Helium-3 fuel source on the moon:** http://en.wikipedia.org/wiki/Helium-3
- **Sounds of meteors** http://www.space.com/scienceastronomy/generalscience/iridium_sound_000328.html
- **Lutetia: a Rare Survivor from the Birth of the Earth** **http://stardustnext.jpl.nasa.gov/mission/Lutetia_rareSurvivor1.html**
- **SOFIA galactic studies** http://www.sofia.usra.edu/News/news_2006/07_21_06/index.html
- **Someone's actually thought about removing the the inner Van Allen Belt** **http://en.wikipedia.org/wiki/HiVolt**
- **Heliosphere** http://photojournal.jpl.nasa.gov/archive/PIA12310.mov
- **Philae finds organic molecules on Comet 67P** http://www.theguardian.com/science/2014/nov/18/philae-lander-comet-surface-detects-organic-molecules

Planetary conjunctions



Credit: SOHO

Announcements

Credit: John Ashley

Contributions

- *Lecture items of interest*
  - **Geminid meteor shower** peaks Dec. 13-14
  - **Interstellar dust** http://antwrp.gsfc.nasa.gov/apod/ap961119.html
  - **Earth's Magnetic Field Weakens 10 Percent** http://www.space.com/scienceastronomy/earth_magnetic_031212.html

Credit: Thomas

Credit: Casado & Graboleda

Lecture Overview

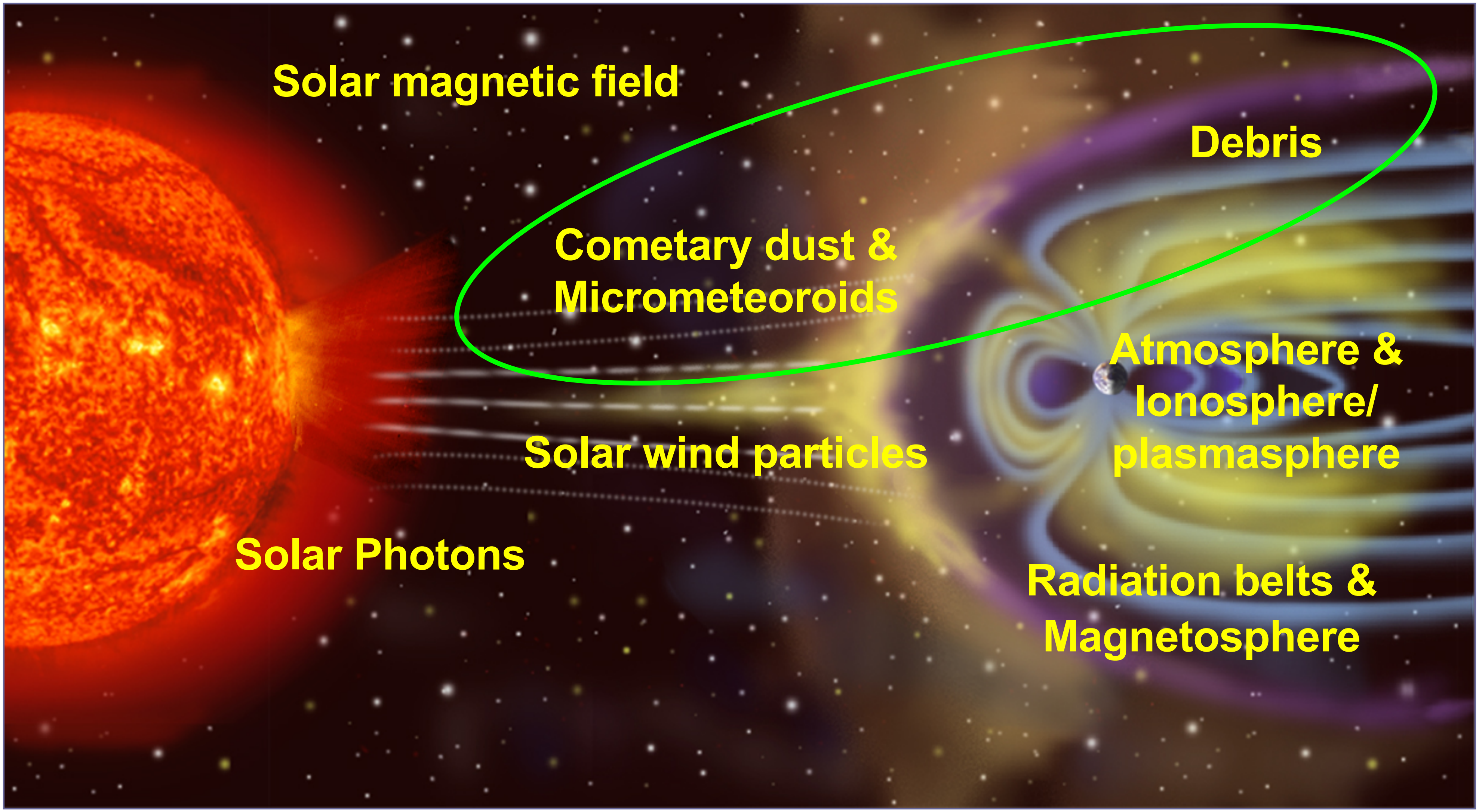
Micrometeoroid and orbital debris environment

- Micrometeoroid (MM) environment
  - Sources, terrestrial effects, fluences, directionality
- Orbital Debris (OD) environment
  - Population/sources, types, detectability, fluences, perturbations/lifetime
- Effects
  - Hypervelocity impacts (cratering, spallation, penetration, perforations, cracks), thickness of materials
- Mitigation paths for debris
  - ISO TC20/SC14 ODCWG
- Standards, guidelines, models

Homework

The planetary space environment

The space environment



Credit: Steele Hill/NASA

Micrometeoroid (MM) environment

Micrometeoroid environment

- Micrometeoroids are a naturally occurring environmental condition - part of solar system particle and dust environment
- Meteors are >10 m
- Meteoroids are <10 m ("shooting stars" when they enter atmosphere)
- Micrometeoroids or interplanetary dust particles tend to be <1 mm

Meteor showers

Micrometeoroid environment

- Their source is usually cometary material
  - Meteoric and dust constituents
    - Sodium, lithium
    - Ions: iron, magnesium, aluminum, calcium
    - Observed using resonance dayglow and lidar
    - Dust and micrometeoroid particles provide nucleation centers for formation of noctilucent clouds and for sporadic ionosphere E layer
- Meteor and "shooting star" effect occurs as particles pass into higher density atmosphere regions, i.e., the lower thermosphere and mesosphere (120 to 60 km)
- Particles >100 μm do not ablate but remain intact and settle to surface
- Ionization creates sporadic E layer (Es) which affects HF/VHF radio communications
- Velocities range from ~2–25 km s^{-1} with a mean value of 17 km s^{-1}
- Effects on spacecraft surfaces includes surface degradation by kinetic energy impact removal of surface material (atoms, molecules)

Meteor showers

Table 13.10. *Principal meteor showers.*[a]

Shower name[b]	Activity period	Solar long.[c]	Radiant RA	Radiant Dec	Diurnal drift RA	Diurnal drift Dec	Local time of transit	V_g^d	r^e	Peak ZHR	Number density[f]
Quadrantids	Jan 01–05	283.3	230	+49	+0.4	−0.2	08.5	39	2.2	120	80
Lyrids[g]	Apr 16–25	32.1	271	+34	+1.1	0.0	04.0	48	2.9	20	8–10
η Aquarids	Apr 19–May 28	43.1	336	−02	+0.9	+0.4	07.6	65	2.7	50	4–5
Arietids[h]	May 29–Jun 19	77	44	+23	+0.7	+0.6	09.9	35	—	—	—
ζ Perseids[h]	Jun 01–17	77	62	+23	+1.1	+0.4	11.0	25	—	—	—
β Taurids[h]	Jun 07–Jul 07	97	86	+19	+0.8	+0.4	11.2	28	—	—	—
α Capricornids	Jul 03–Aug 19	127	307	−10	+0.9	+0.3	00.0	20	2.5	10	150
S δ Aquarids	Jul 15–Aug 28	126	339	−16	+0.7	+0.2	02.2	39	3.2	20	20–25
Perseids[i]	Jul 17–Aug 24	139.9	46	+58	+1.3	+0.1	05.7	58	2.6	100	10–20
κ Cygnids	Aug 03–31	146	286	+59	+0.3	+0.1	21.3	22	3.0	5	125
S Taurids	Sep 15–Nov 25	221	50	+14	+0.8	+0.2	00.5	25	2.3	10	50
N Taurids	Sep 15–Nov 25	231	60	+23	+0.9	+0.2	00.5	27	2.3	8	30
Orionids	Oct 02–Nov 07	208	95	+16	+0.7	+0.1	04.3	65	2.9	25	2
Draconids[j]	Oct 06–10	197.0	262	+54	+0.4	0	16.1	17	2.6	—	—
Leonids[k]	Nov 14–21	235.2	152	+22	+0.7	−0.4	06.4	70	2.5	25	1–2
Geminids	Dec 07–17	262.0	112	+33	+1.0	−0.1	01.9	33	2.6	110	290
Ursids[l]	Dec 17–26	270.9	217	+75	0	0	08.4	31	3.0	20	80

Notes

[a] Courtesy J. Rendtel, M. Gyssens, P. Roggemans, and P. Brown, International Meteor Organization. All angles are in degrees, and referred to the 1950.0 equinox.

[b] See Table 13.11 for parent comet identifications.

[c] The solar longitude is that at the time of peak shower activity.

[d] V_g is the geocentric velocity of the meteoroid; the velocity at the top of the atmosphere after acceleration by the Earth is given by $V^2 = V_g^2 + 125$ (in km/s).

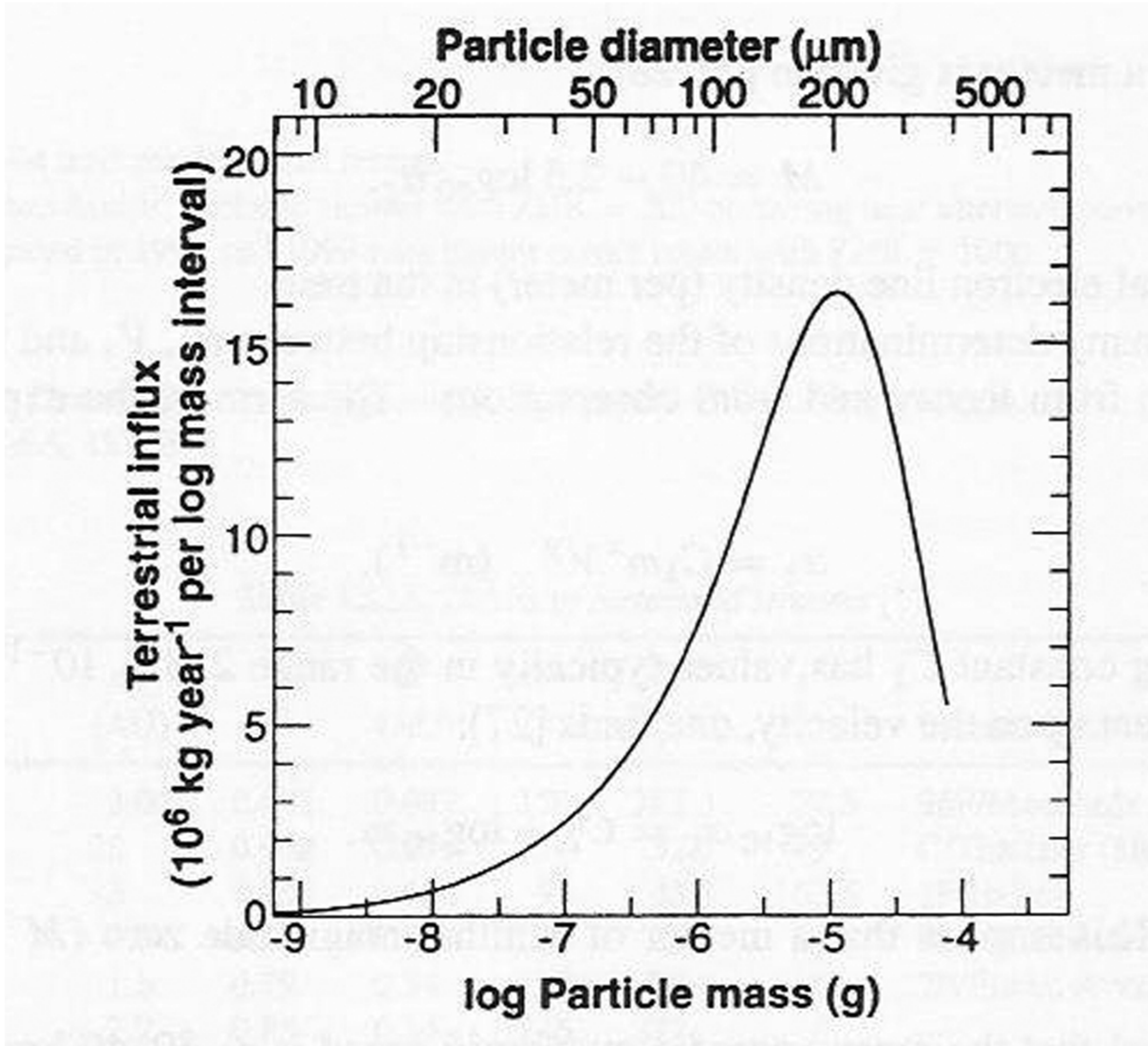
[e] The mass index s is related to the population index r by $s = 1 + 2.3 \log_{10} r$ (see [1] for details).

[f] The number density gives the number of particles of $m > 10^{-3}$ g per 10^9 km^3 [2].

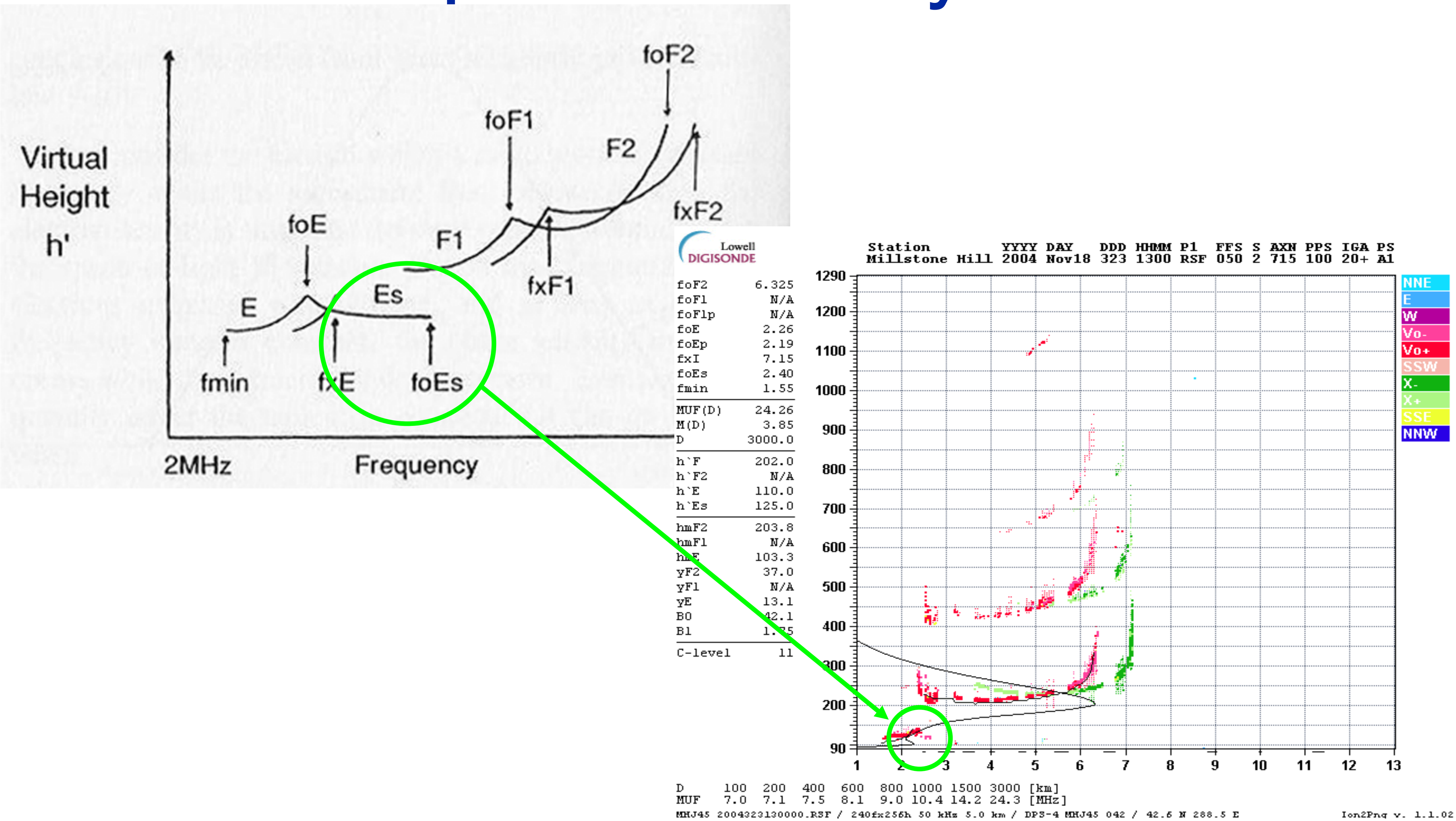
Interplanetary dust size/mass

Peak influx is at ~1E-5 g

The integral under the curve is ~40,000 tons/year



Sporadic E-layer



Micrometeoroid environment

- Micrometeoroid (MM) interplanetary background flux is estimated from (12-1) – (12-4)

$$F_{MM} = 3.156 \times 10^{7} (A^{-4.38} + B + C) \quad \textbf{(12-1)}$$

$$A = 15 + 2.2 \times 10^{3} m^{0.306} \quad \textbf{(12-2)}$$

$$B = 1.3 \times 10^{-9} (m + 10^{11} m^{2} + 10^{27} m^{4})^{-0.306} \quad \textbf{(12-3)}$$

$$C = 1.3 \times 10^{-16} (m + 10^{6} m^{2})^{-0.85} \quad \textbf{(12-4)}$$

where flux units are particles m^{-2} yr^{-1} and m is the MM mass in grams.

Micrometeoroid environment

- Gravitational focusing (the closer to the Earth, the greater the MM flux) (R_e is Earth radius and h is spacecraft height) enhances the flux by a scaling factor and is given by

$$F_{grav} = 1 + \frac{R_e + 100}{R_e + h} \qquad \textbf{(12-5)}$$

- Earth shielding protects the spacecraft from flux coming out of Earth-side direction and the flux reducing factor is

$$F_{shield} = \frac{1 + \cos\eta}{2} \qquad \textbf{(12-6)}$$

$$\eta = \sin^{-1}\left(\frac{R_e + 100}{R_e + h}\right) \qquad \textbf{(12-7)}$$

Micrometeoroid environment

- The Earth-facing and space-facing sides of a spacecraft will encounter differing flux rates depending upon direction; Earth-facing sees a reduction of 10, the ram or side surfaces see a reduction factor of

$$F_{dir} = \frac{1.8 + 3\sqrt{1 - \left(\frac{R_e + 100}{R_e + h}\right)^2}}{4} \qquad \textbf{(12-8)}$$

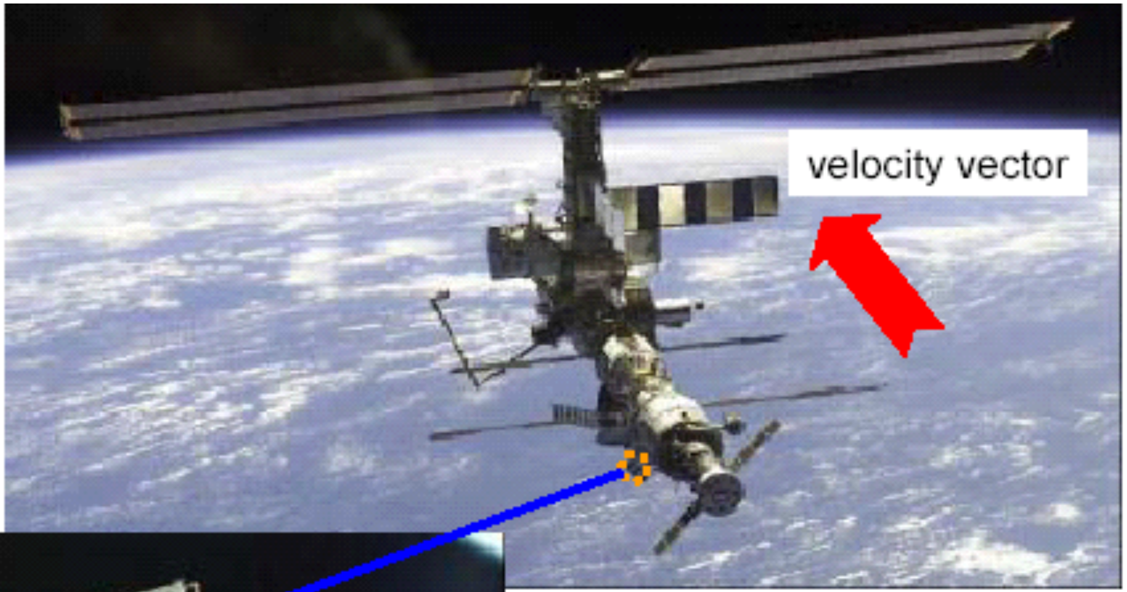
- The MM flux to a spacecraft component is the product of (12-1), (12-5), (12-6) and (12-8)
- Note that the observed MM flux on ISS versus calculated flux rates from recent work may not agree
- The $F_{total\_MM} = F_{mm}\, F_{grav}\, F_{shield}\, F_{dir}$ hits year^{-1} m^{-2}

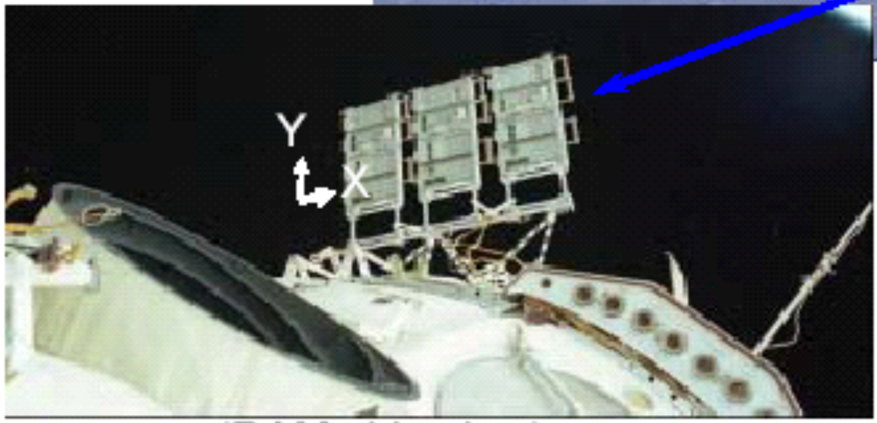
Micrometeoroid environment

- Micrometeoroid mass densities, ρ, with a mass of m, are parameterized as follows
  - 1) $\rho = 2.0$ g cm^3 ($m < 10^{-6}$ g) **(12-9)**
  - 2) $\rho = 1.0$ g cm^3 ($10^{-6} \leq m < 10^{-2}$ g) (H_2O) **(12-10)**
  - 3) $\rho = 0.5$ g cm^3 ($m > 10^{-2}$ g) **(12-11)**

- MM velocities follow an Erickson (normalized) speed distribution, f(v), where v is the MM velocity, and
  - 1) $f(v) = 0.112$ ($11.1 \leq v < 16.3$ km s^{-1}) **(12-12)**
  - 2) $f(v) = 3.328\times10^5\ [v^{-5.34}]$ ($16.3 \leq v < 55$ km s^{-1}) **(12-13)**
  - 3) $f(v) = 1.695\times10^{-4}$ ($55 \leq v < 72.2$ km s^{-1}) **(12-14)**

MM flux directional dependence





(RAM side view)

- Dust Particle Measurements on ISS
  - Estimation of Influences on ISS surface
  - Debris Monitoring from ISS
    (Estimation of influences on other exposed devices)
- Three SM/MPAC&SEED units were launched aboard Progress M-45 on 21 August 2001.
- Three units were attached on the outside of the Russian Service Module.

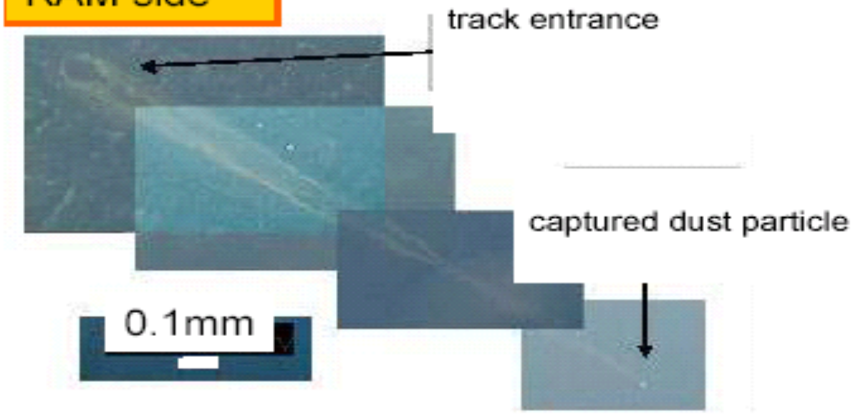
A view of the three SM/MPAC&SEED units during exposure.

Credit: Kitazawa

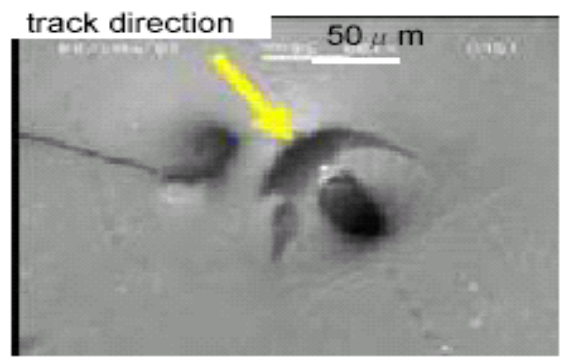
MM flux directional dependence

5. Inspection Results (Examples of Tracks)

RAM side

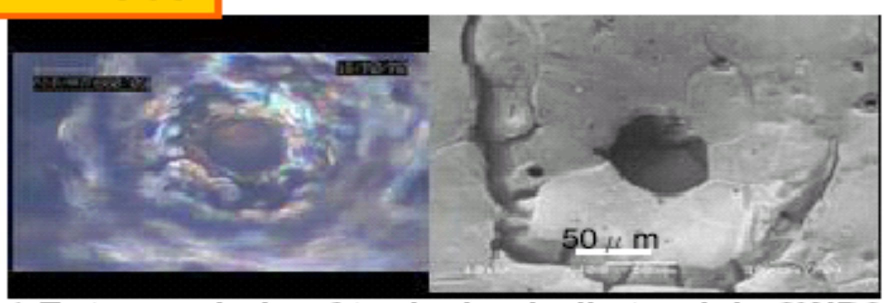


(a) Typical carrot-shaped track in 3RA1(CCD image)



(b) Entrance hole of typical carrot-shaped track in 3RA3 (SEM image)

WAKE side



(c) Entrance hole of typical spindle track in 3WD3 (Left: CCD image, Right: SEM image)

Typical impact features which were found by detailed examination.

Credit: Kitazawa

MM flux directional dependence

5. Inspection Results (Estimated Impact Flux)

Comparison with estimated impact flux by detail inspection results and calculated results of MASTER-2001

Ram Side

Particle Dia. (μm)	Inspection Results[*1,*2] (hits / m^2 / year)	Analysis Results[*2,3] (hits / m^2 / year)
5	5.1×10^3	1×10^3
10	1.6×10^3	4×10^2
20	6.3×10^2	2×10^2

Wake Side

ParticleDia. (μm)	Inspection Results[*1,*2] (hits / m^2 / year)	Analysis Results[*2,3] (hits / m^2 / year)
5	4.2×10^4	2×10^2
10	2.2×10^3	7×10^1
20	1.4×10^2	2×10^1

*1：Estimated based on calibration experiments（Kitazawa et al.,1999） *2：Cumulative flux
*3：Estimated using MASTER-2001（Neish *et al.*, 2003）

The causes of elevated flux levels may be;
1) uncertainties in MASTER-2001
2) elevated flux values from dust swarms (dust clouds)
3) contaminants emitted from the ISS, Soyuz or the Shuttle
4) secondary debris.

Credit: Kitazawa

Orbital Debris (OD) environment

Hollywood's "Gravity"

Credit: "Gravity"

Debris environment

- The debris environment is human-generated from non-operational objects (e.g., breakup material, refuse, rocket bodies, non-op satellites)
- There are concentrations of orbital populations in different regions
  - <2000 km LEO satellites
    - <600 km most human spaceflight
    - 900 – 1000 km sun synchronous navigation and weather satellites
    - 1400 – 1500 km (Russian communication satellites)
  - Circular semi-synchronous (GPS and Russian navigation)
  - Molniya type (Russian military and communication)
  - ~36000 km GEO spacecraft
- Of >41,870 space objects (>10 cm) catalogued by USSPACECOM since 1957 almost 1/3 remain in orbit (17,854); new material (including 2007 Chinese ASAT and 2009 COSMOS-Iridium collisions) has elevated the levels to an estimated 20,000 objects >10 cm diameter
- ~670,000 objects >1cm in the debris population
- ~170 million objects <1cm

Debris sources

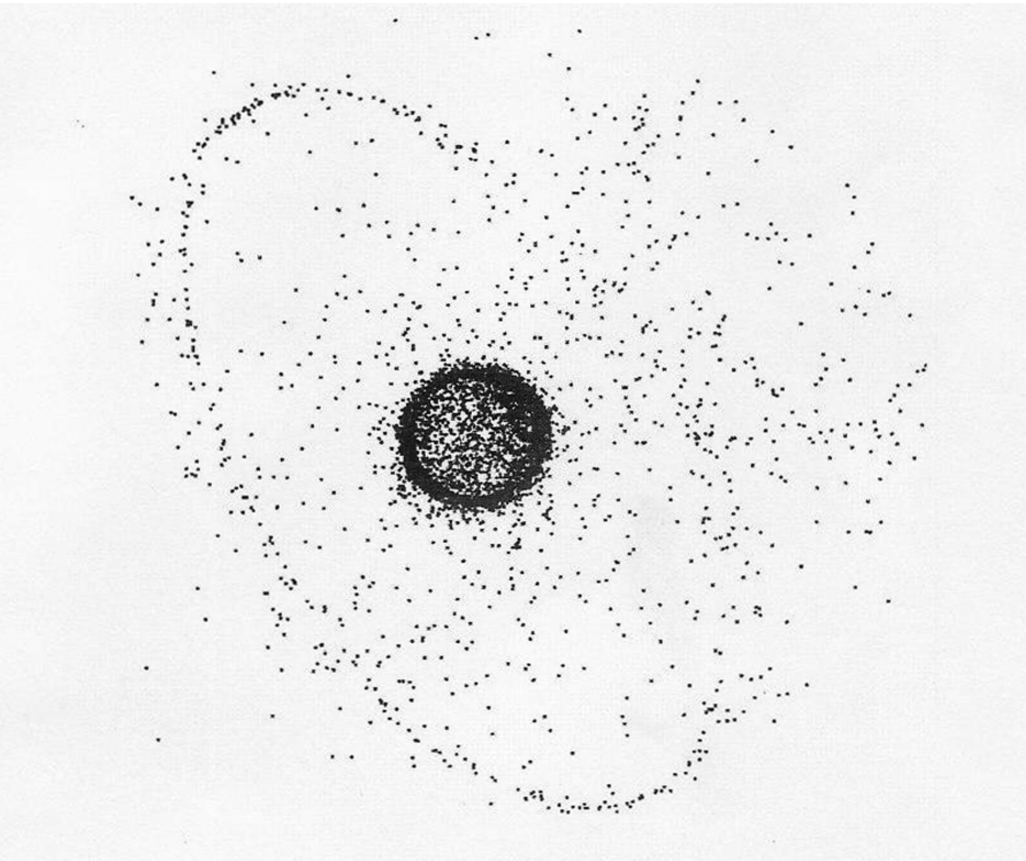
- Debris is generated by a number of processes
  - **Vehicle-released objects**
    - hardware intentional release such as explosive bolt parts, spring release mechanisms, spin-up devices, camera covers
    - intentional waste products from MIR, Shuttle, and ISS
  - **Fragmentation**
    - explosions created by residual propellant in tanks
    - deterioration of materials
    - collisional impacts with other bodies
  - **Mission operations and maneuvers**
    - solid rocket motor operation where Al_2O_3 particles with velocities around 4 km s^{-1} and particle sizes not larger than 10 μm but up to 10^{20} particles created during one motor firing
    - unplanned or non-operational disposal of vehicle at EOL

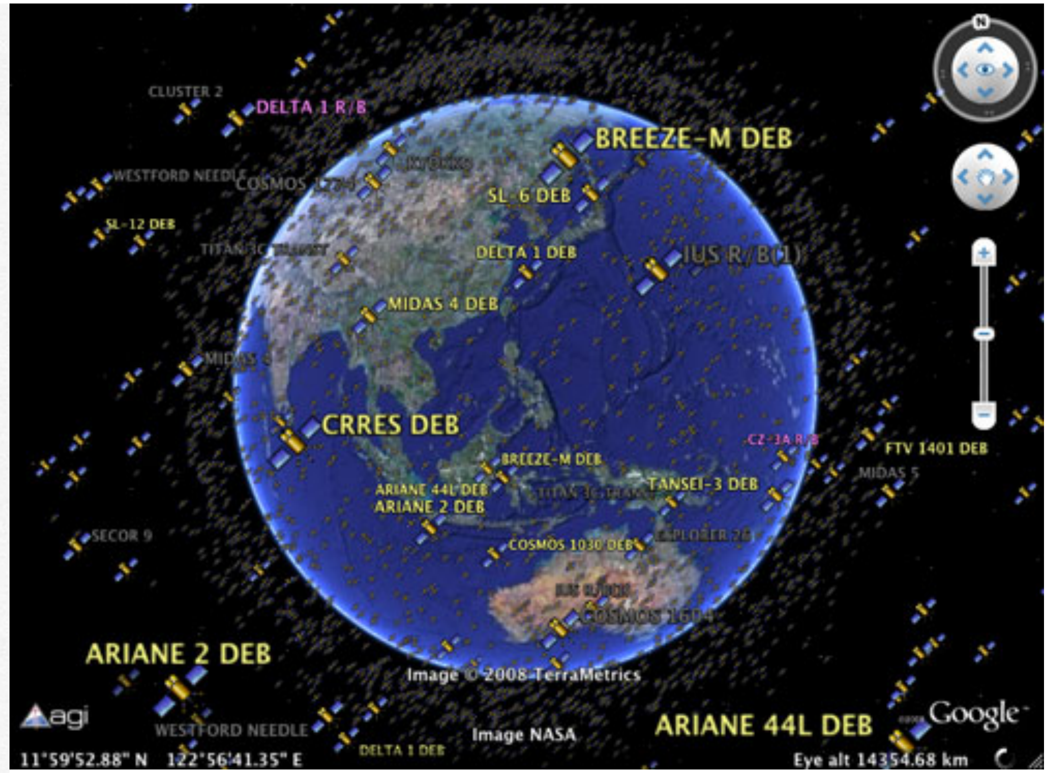
Debris sources

- Fragmentation is the single largest source of the debris population
- Breakups are destructive events that release a distribution of particles with a wide range of initial velocities
- In the first 30 years of spaceflight, there was 120 known breakups with 8100 catalogued items of fragmented debris; 3100 remained in orbit as of late 1990's; today there are ~20,000 debris objects
- The expanding debris cloud from a breakup starts with a toroidal shape and expands until bounded only by its maximum inclinations and altitudes

Credit: Ketsdever

OD distribution





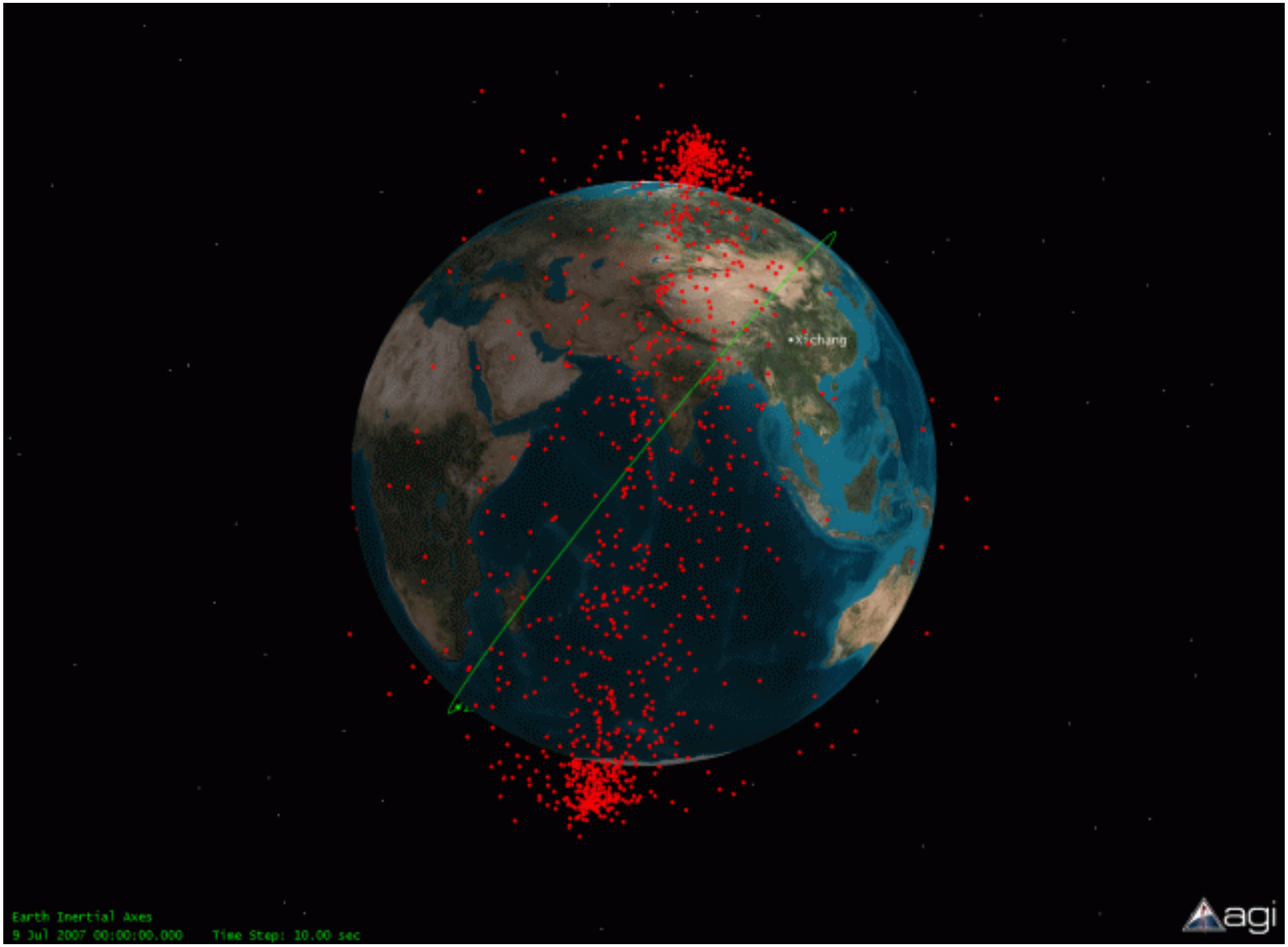
Real-time satellite database KMZ file from AGI for Google Earth can be downloaded from http://spacewx.com Innovations:Visualizing Space Weather with KML link

Credit: AGI

Debris sources

- Chinese FENGYUN 1C polar-orbiting weather satellite on 2007 January 11 (ASAT test) produced 35,000 objects > 1 cm and at least 2,247 pieces large enough to be tracked by NORAD (>10 cm)
- The most intensive breakup prior to FENGYUN 1C is the 1987 Kosmos 1813 which generated ~850 fragments observable from Earth
- Small and medium-sized debris is known to have been generated by the degradation of surfaces on LDEF before retrieval
- Debris fragments from deterioration events usually separate at low velocities from the spacecraft/rocket body which tends to remain intact

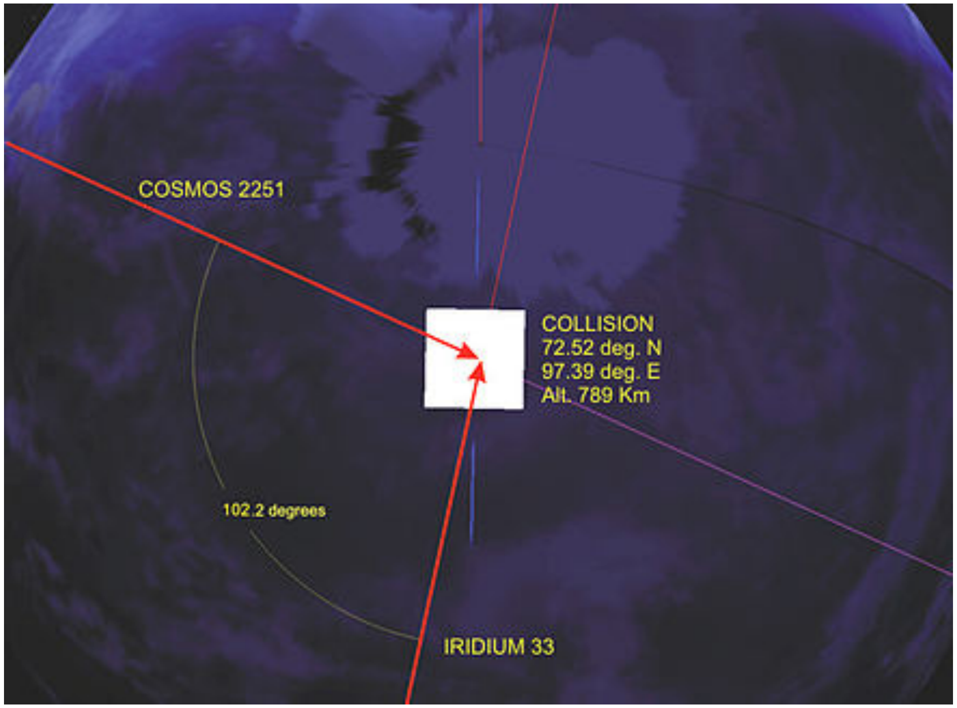
Chinese ASAT debris & ISS



Credit: AGI CSSI

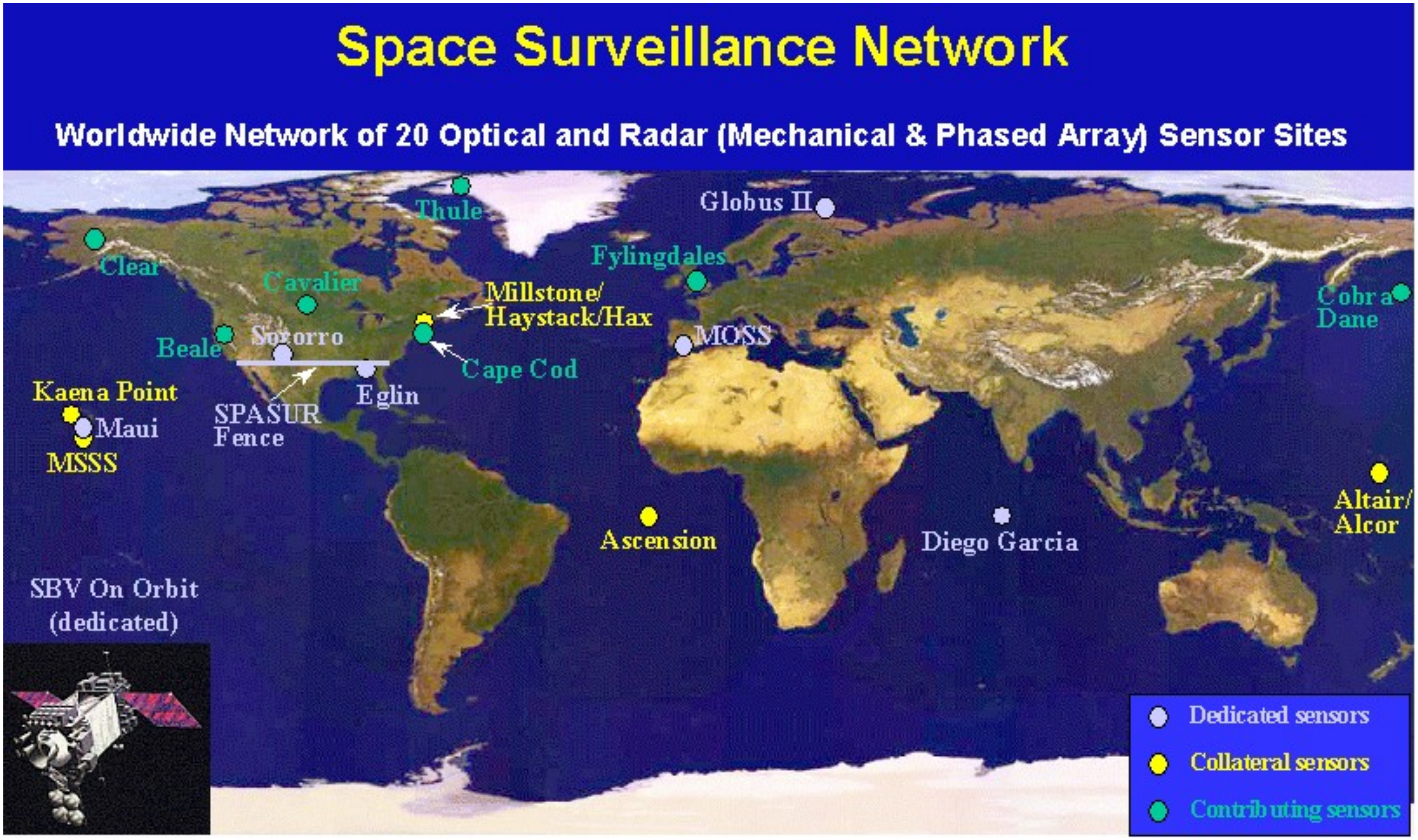
Debris sources

- The first accidental hypervelocity collision between two intact satellites on Feb 10, 2009 between Iridium 33 and Kosmos-2251.
- Speed of collision was 42,120 km/hr
- NASA estimated 1000 debris objects >10 cm at time of collision and Space Surveillance Network (SSN) catalogued in July 2011 over 2000 large debris fragments.



http://www.youtube.com/watch?v=_o7EKlqCE20

SSN



Space Surveillance Network
Worldwide Network of 20 Optical and Radar (Mechanical & Phased Array) Sensor Sites
Thule
Globus II
Clear
Fylingdales
Cavalier
Millstone/
Haystack/Hax
Cobra
Dane
Beale
Socorro
MOSS
Cape Cod
Kaena Point
Eglin
SPASUR
Fence
Maui
MSSS
Ascension
Diego Garcia
Altair/
Alcor
SBV On Orbit
(dedicated)
Dedicated sensors
Collateral sensors
Contributing sensors

Debris issues

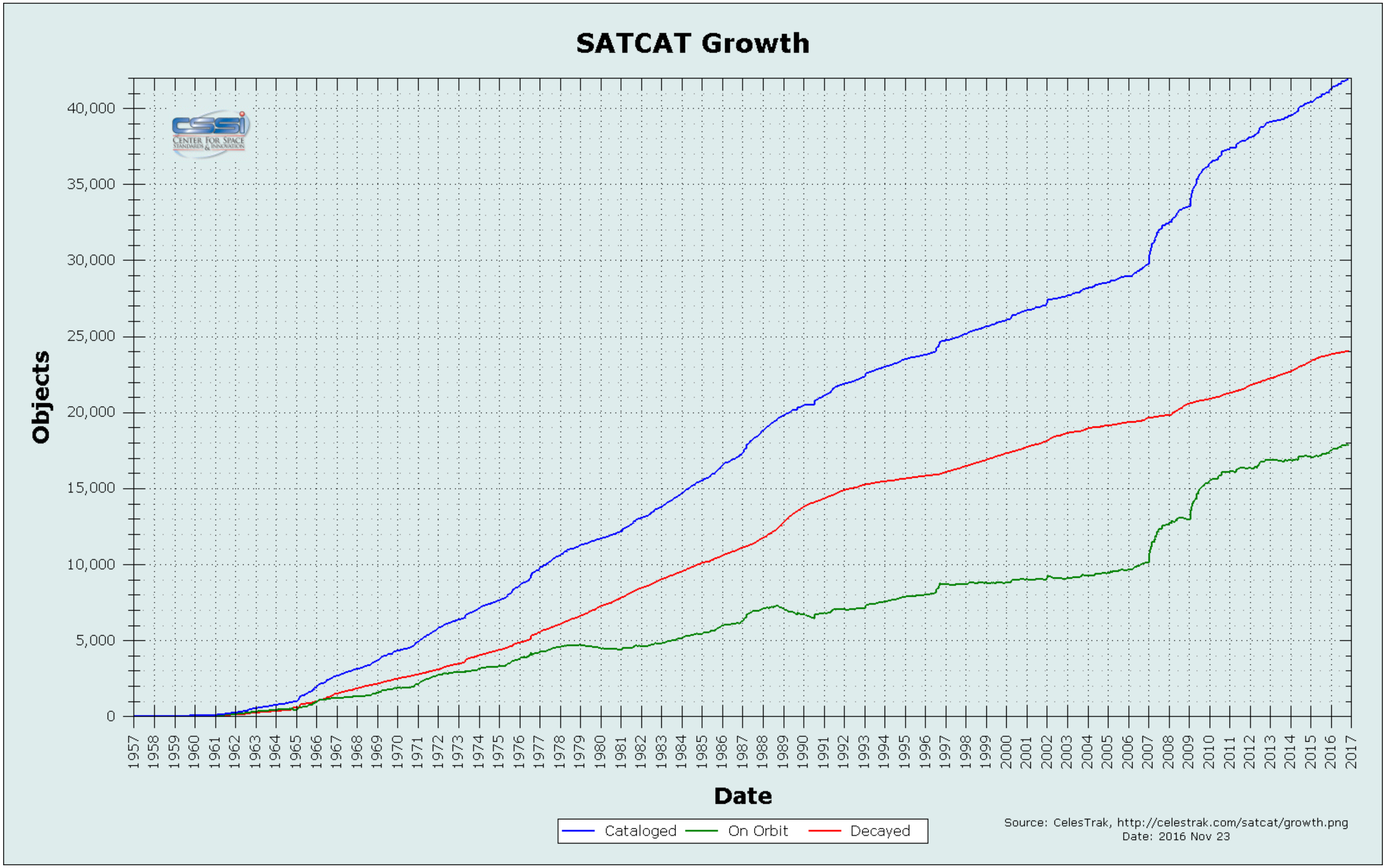
- Functional spacecraft account for <10% of the spacecraft population in orbit
- Spacecraft reach end-of-life (EOL) and are left in their orbits or are transferred to slightly higher or lower altitudes
- EOL re-orbiting maneuvers are typically performed for only GEO or semi-synchronous spacecraft and by LEO spacecraft carrying nuclear materials
- EOL re-orbiting typically increases the lifetime of the non-functional spacecraft
- Majority of spacecraft are accompanied to orbit by one or more stages; for LEO missions usually 1 rocket body is left in orbit; for higher orbits, up to 3 rocket bodies can be left along the way

Credit: Ketsdever

Debris issues

- LEO orbit debris has velocities ~7-8 km s^{-1}
- Collisions with debris particles tend to be on surfaces other than wake
- For LEO debris, it is most affected by atmospheric drag which is modulated by solar activity
- Questions that remain outstanding for the community
  - **What is the actual size of the debris population?**
    - Use optical, radar, lidar measurements for detection and cataloging
    - Use modeling based on updated populations to extend information to unobserved regimes; include spatial density and collision flux
  - **How does it impact operational and planned space programs (effects)?**
  - **How can debris effects be mitigated?**
    - Use IADC guidelines
    - Implement international standards (ISO TC20SC14 ODCWG)

Debris growth



Credit: Talent & Celestrak

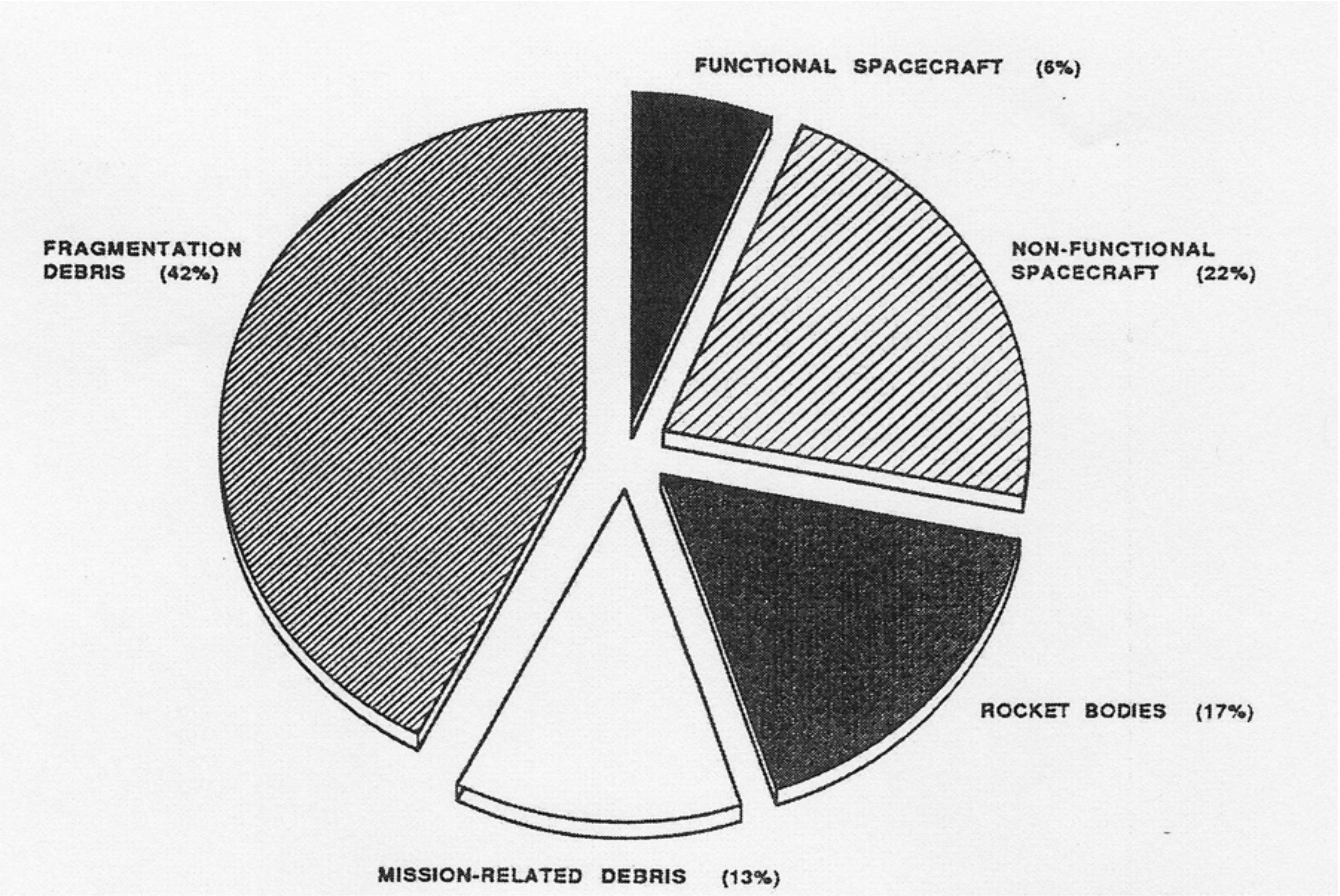
BREAK

Debris types

- There are generally 3 types of debris
  - Non-functional spacecraft
  - Rocket bodies
  - Mission-related debris and fragmentation debris
- Collision objects <0.5 mm dominated by meteoric; >1 mm dominated by debris
  - Size categories, diameters, mass, detectability, and probable damage

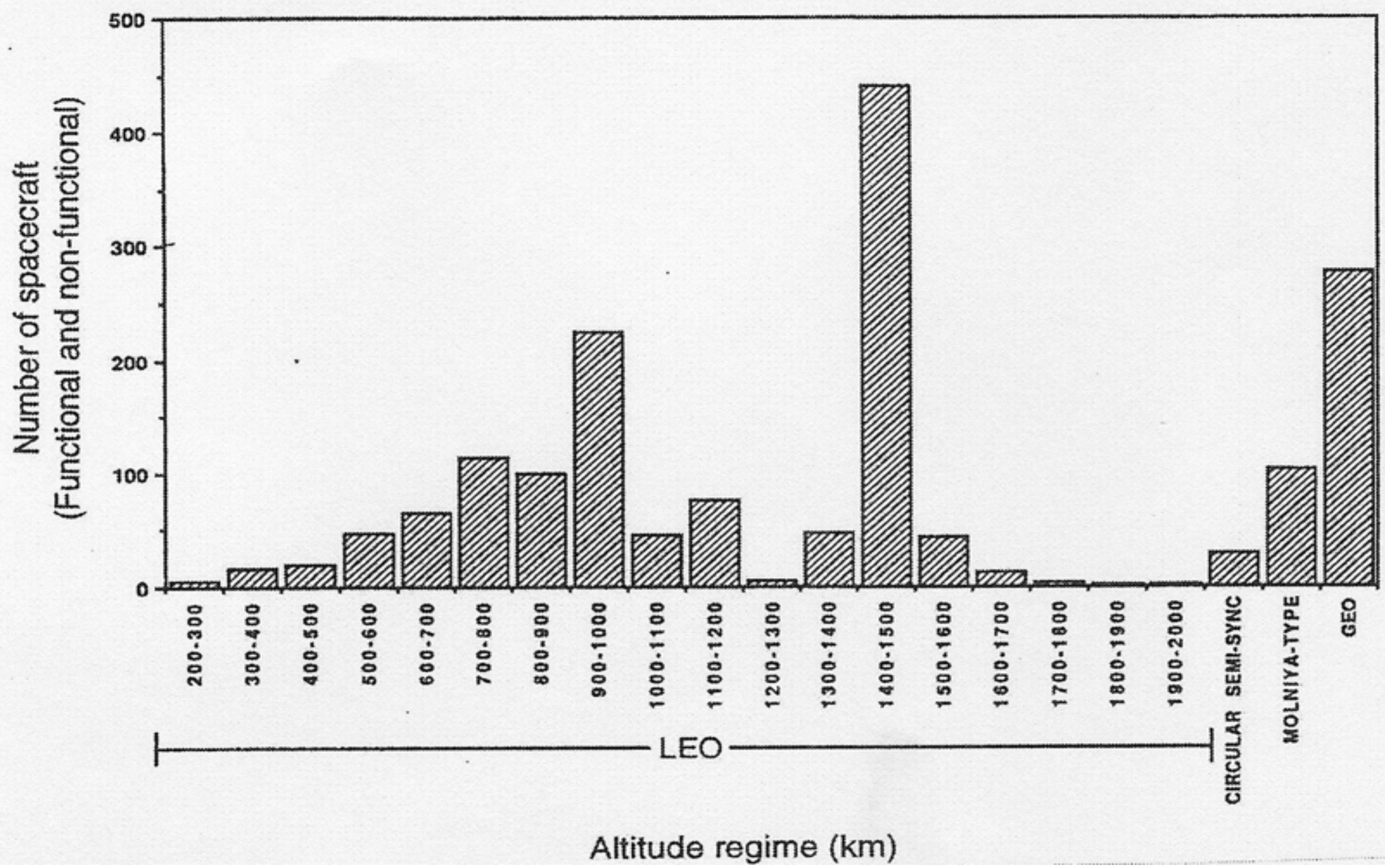
Size Category	Approximate Diameter	Approximate Mass	Detectability	Probable Damage to Spacecraft
Large	> 10 cm	> 1 kg	Catalogable in LEO	Loss of Spacecraft, Catastrophic Breakup
Medium	1 mm - 10 cm	1 mg - 1 kg	Too Small to Catalog, Too Few for In Situ Detection	Surface Degradation, Component Loss, Loss of Spacecraft Capability
Small	< 1 mm	< 1 mg	Detectable by In Situ Sampling	Surface Degradation, Component Damage

OD types



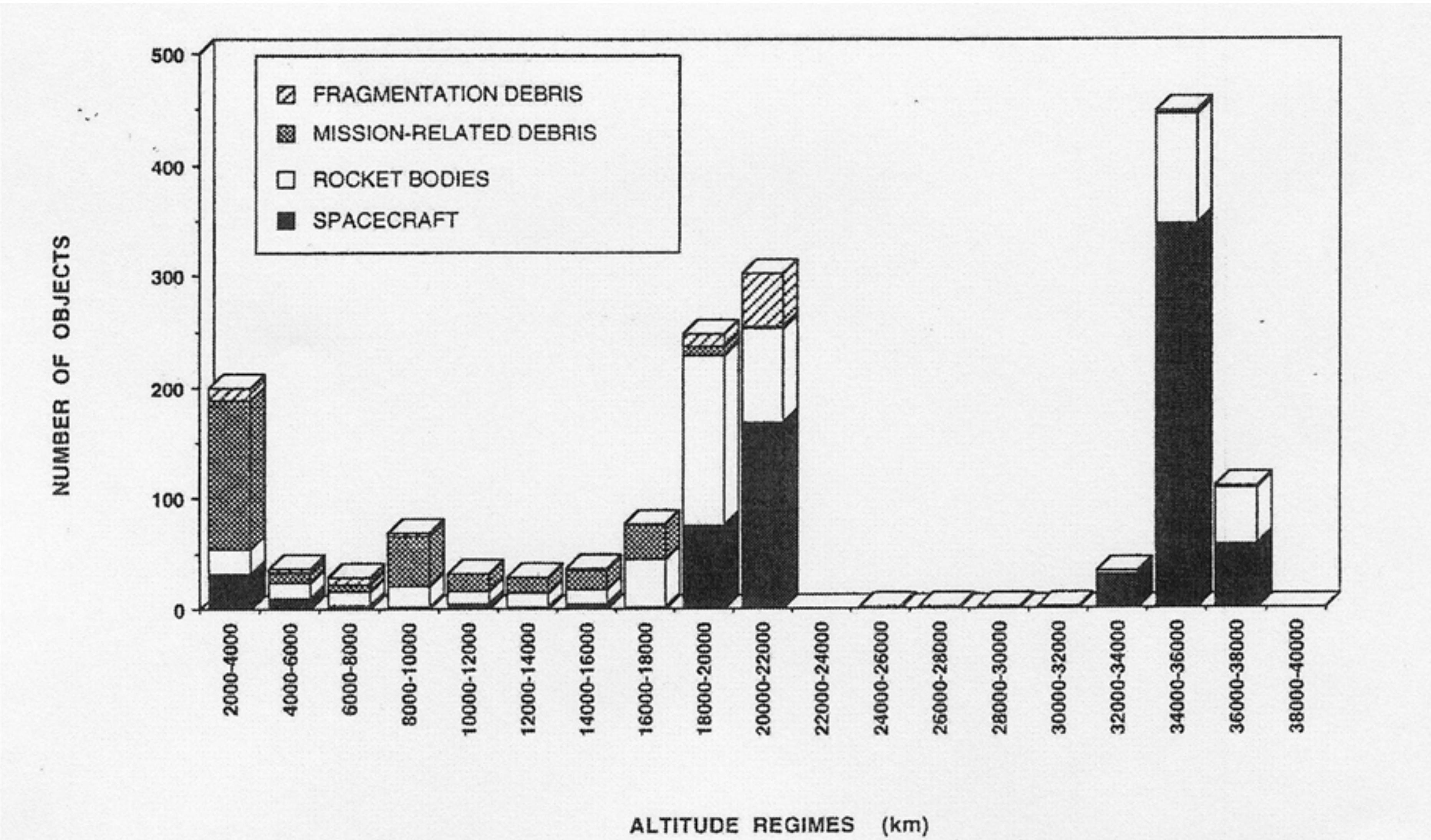
Credit: Ketsdever

Spacecraft population

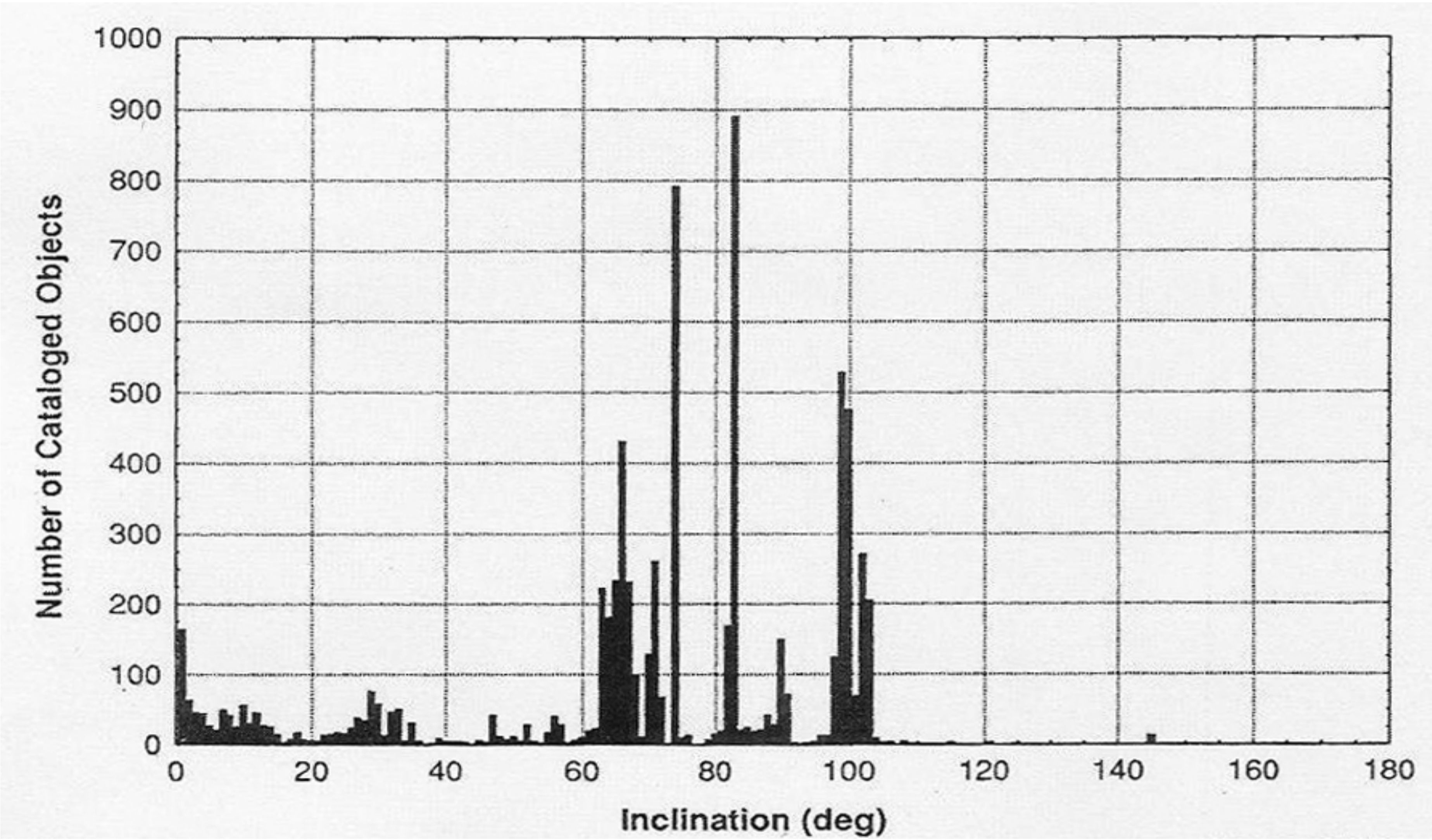


Credit: Ketsdever

OD high altitude types

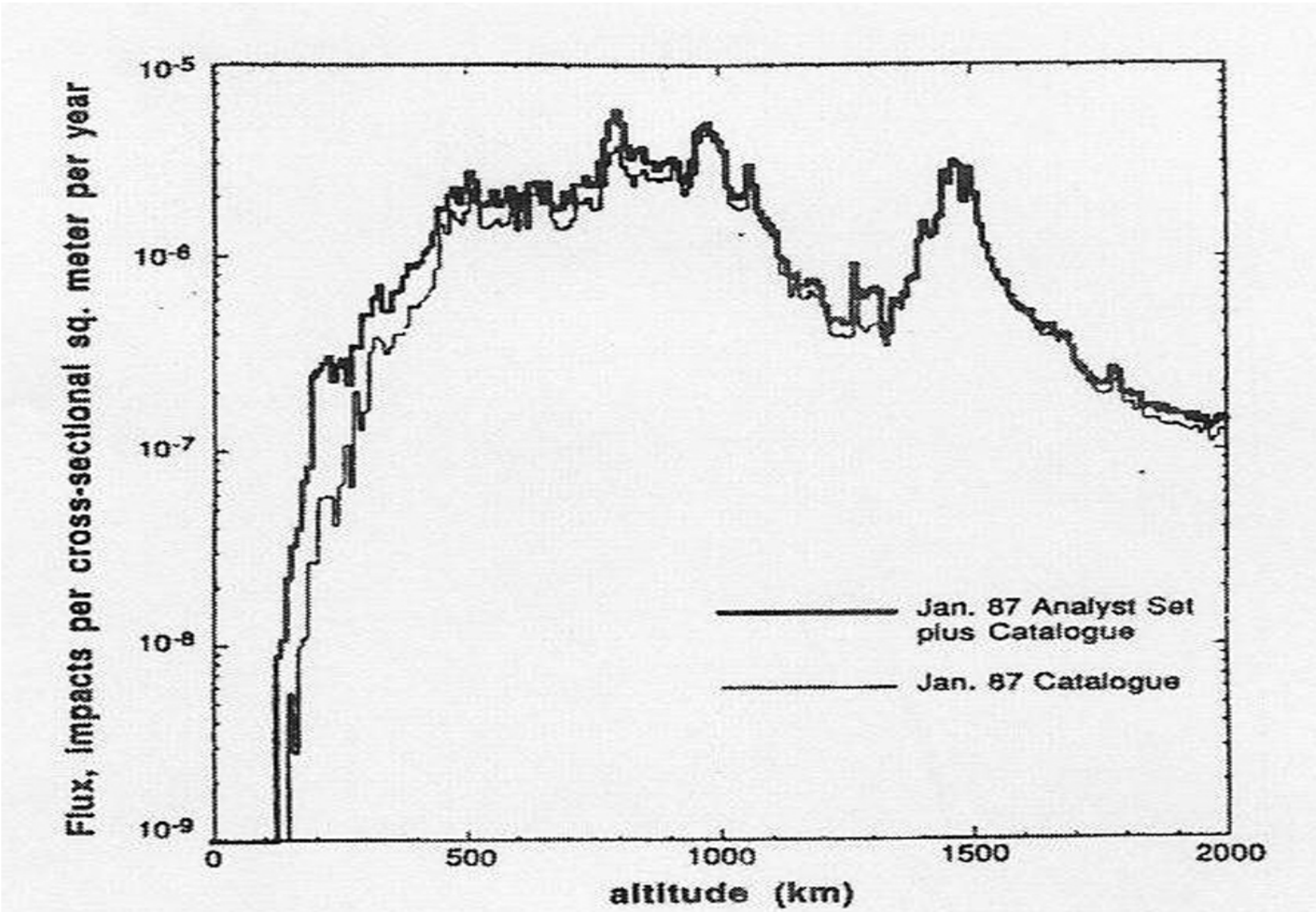


OD inclination types



Credit: Ketsdever

LEO OD flux



Credit: Ketsdever

Debris types

- Orbit inclination is also a discriminator in debris object populations
- Most catalogued objects are in high inclination orbits
- The relative collision velocities for these orbit debris objects is higher in general
- Molniya orbits have an inclination of 63° - 65°
- Most GEO spacecraft have an inclination near 0°
- Most nonfunctional spacecraft at GEO and other debris will oscillate around a plane tilted 7.3° from the equator due to the Earth's oblateness and third-body gravitational perturbations

Credit: Ketsdever

Debris types

- Orbital Debris objects larger than 10 cm comprise only 0.5% of the total LEO debris population
- Yet, these objects contain 99.9% of the total debris mass
- <2000 km most debris objects are from upper stage breakups
- 2000 – 16,000 km mission-related debris dominates the catalog
- >16,000 km spacecraft and rocket bodies dominate debris population
- Populations at higher altitudes may be underrepresented due to observing limitations
- LEO (lower altitude) populations are constantly changed by re-entry from atmospheric drag

Credit: Ketsdever

Debris flux rates

- The OD flux rate in particles (hits) m^{-2} yr^{-1} of diameter, d (cm), depends upon the 13-month smoothed solar activity (S=F10.7), orbital altitude (h), orbit inclination (i), and year (t < 2007); it is given by

$$F_{OD} = H(d)\phi(h,S)\Psi(i)[F_1(d)g_1(t) + F_2(d)g_2(t)] \quad \textbf{(12-15)}$$

where

$$H(d) = \left\{ 10^{\exp\left[-\left((\log d - 0.78) / 0.637 \right)^2\right]} \right\}^{1/2} \quad \textbf{[note: exp = "e"] (12-16)}$$

$$\phi(h,S) = \frac{\phi_1(h,S)}{\phi_1(h,S)+1}, \phi_1(h,S) = 10^{\left[\frac{h}{200} - \frac{S}{140} - 1.5\right]} \quad \textbf{(12-17a,b)}$$

$$F_1(d) = \left(1.22 \times 10^{-5}\right) d^{-2.5}, F_2(d) = \left(8.1 \times 10^{10}\right)(d + 700)^{-6} \quad \textbf{(12-18a,b)}$$

$$g_1(t) = (1+q)^{(t-1988)}, g_2(t) = 1 + p(t - 1988) \quad \textbf{(12-19a,b)}$$

Debris flux rates

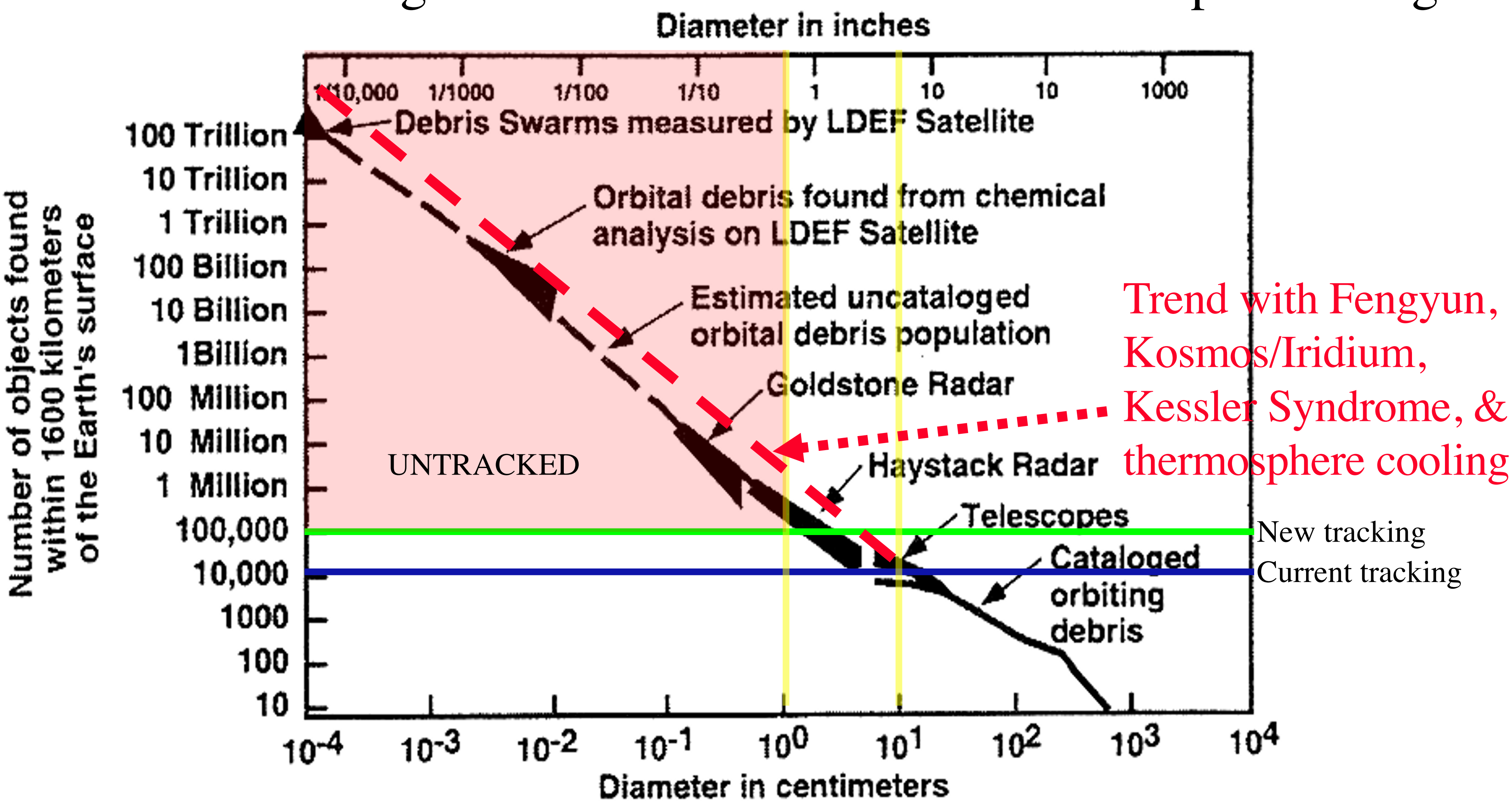
- The value of p ~ 0.05 is the growth rate assumed for intact objects (as of the early 1990's), q~0.02 is the estimated fragment growth rate (also as of the early 1990's), and Ψ(i) is the function describing the relationship between flux and orbit inclination
- The mass density of debris (diameter) d < 0.62 cm is ~4 g cm^{-3} and for d > 0.62 cm is ~2.8d$^{-0.74}$ g cm^{-3}

The Inclination Dependence of Orbital Debris

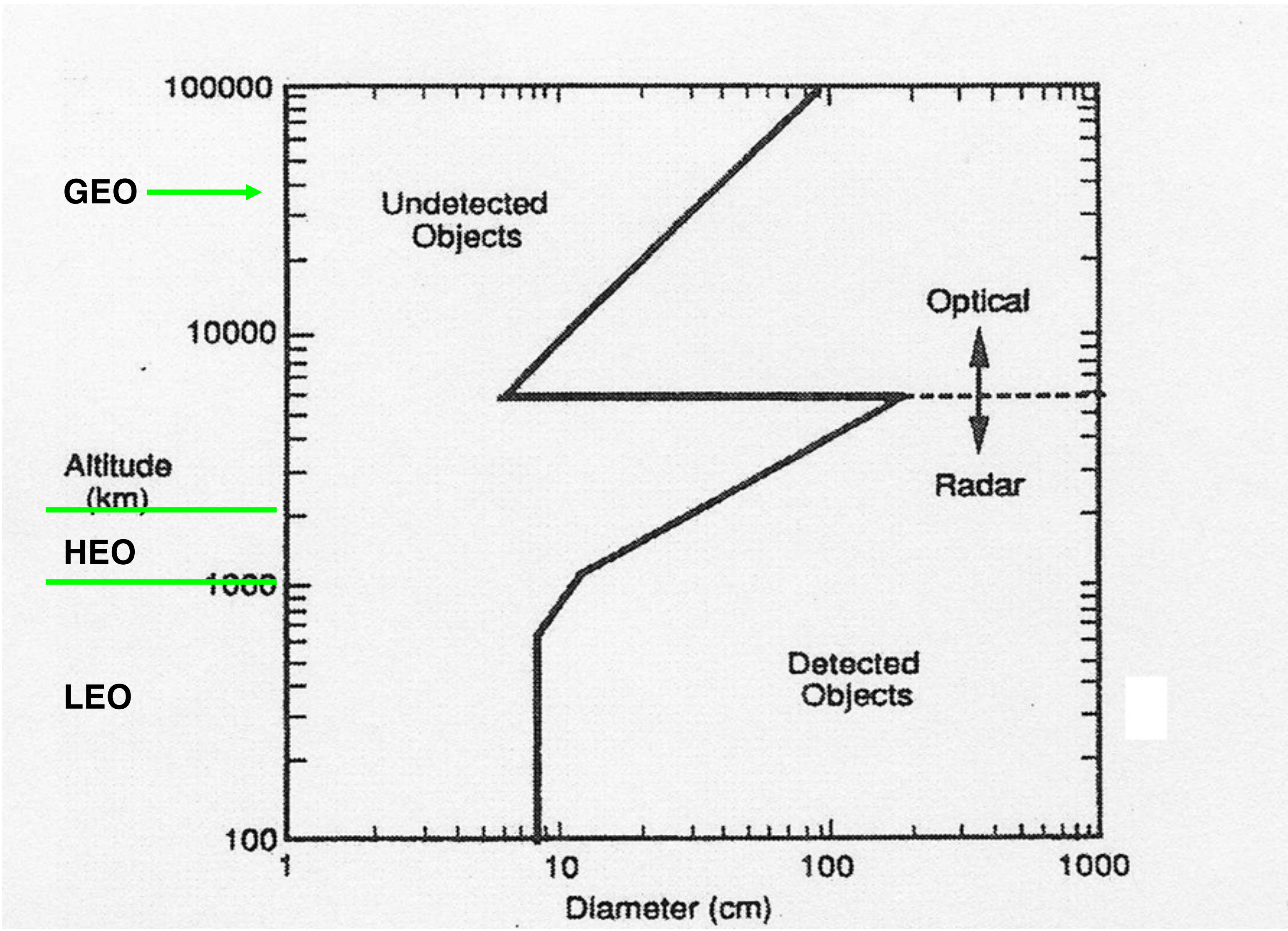
i (deg)	$\Psi(i)$
28.5	0.91
30	0.92
40	0.96
50	1.02
60	1.09
70	1.26
80	1.71
90	1.37

Orbit Debris LEO population

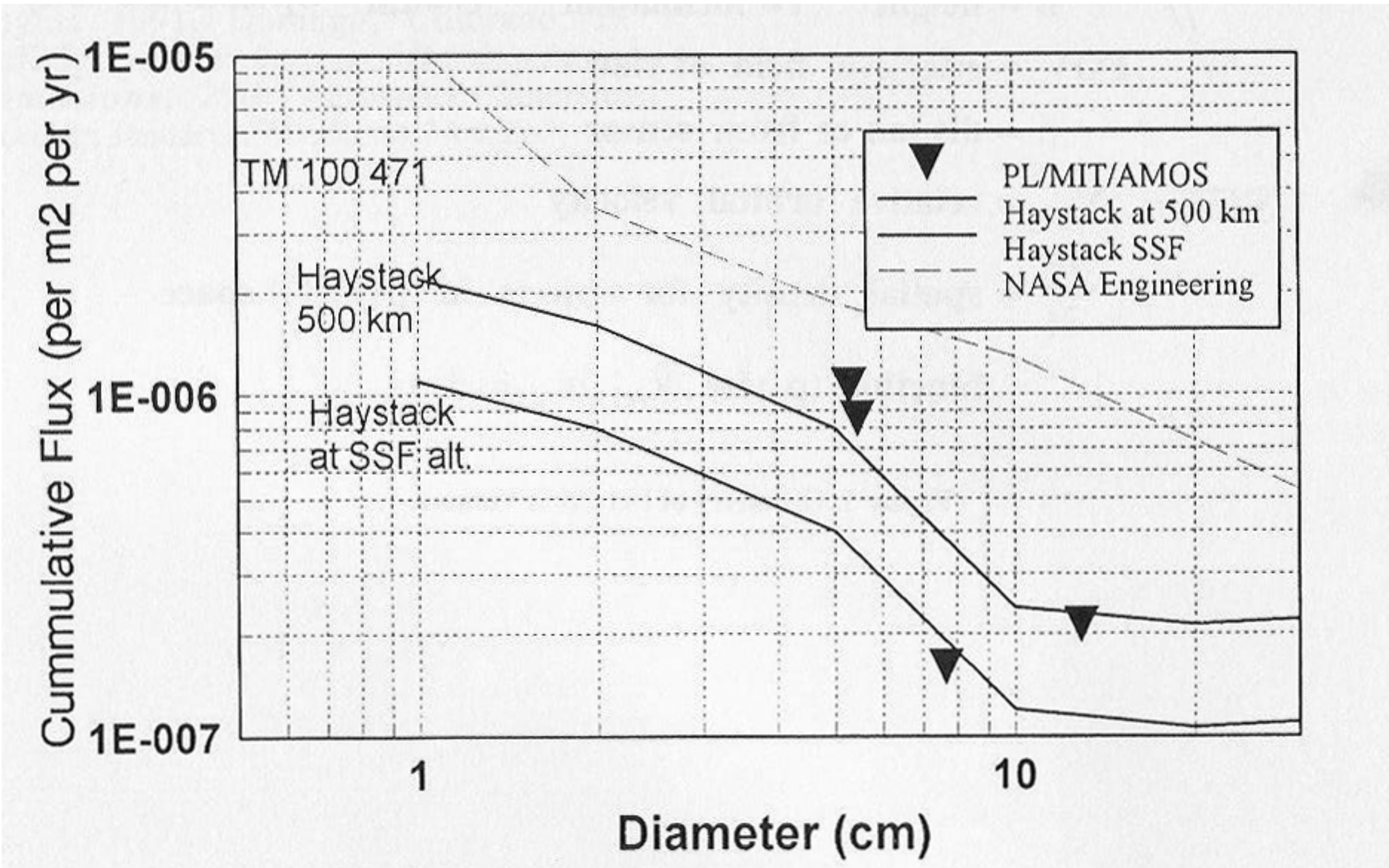
Surface degradation----> unit loss <---- catastrophic damage



OD detectability



OD detectability

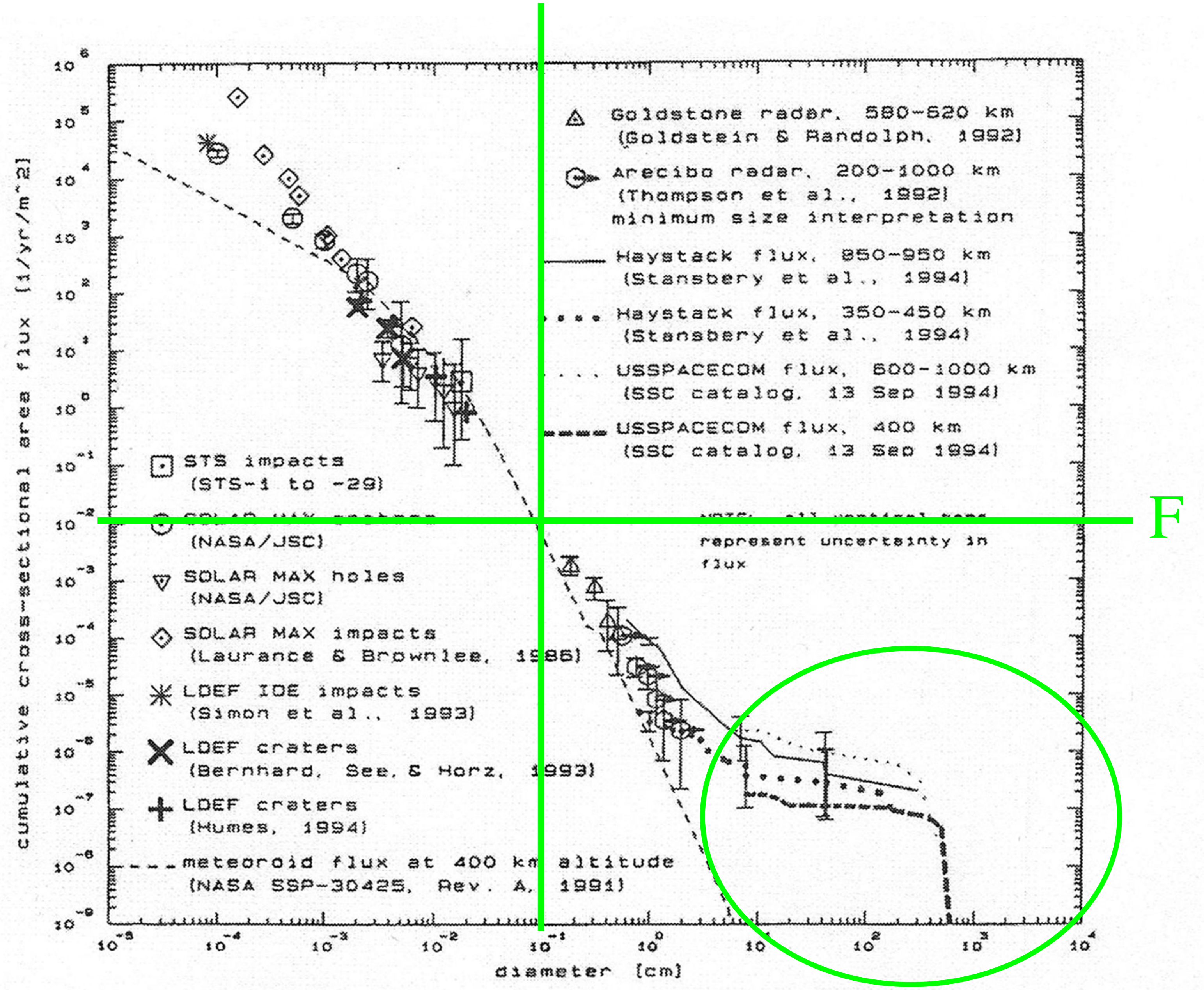


Debris types

- Objects which cause immediate, catastrophic damage have diameters above 10 cm and, in LEO, debris objects in this size range dominate over micrometeoroids
- From next slide, one estimates that a 10 m^2 cross sectional spacecraft with a LEO orbital lifetime of 10 years will be struck by ~1 particle of 1 mm diameter in its operational lifetime and by 100 – 1000 particles of 0.1 mm diameter

Credit: Ketsdever

MMOD flux in LEO



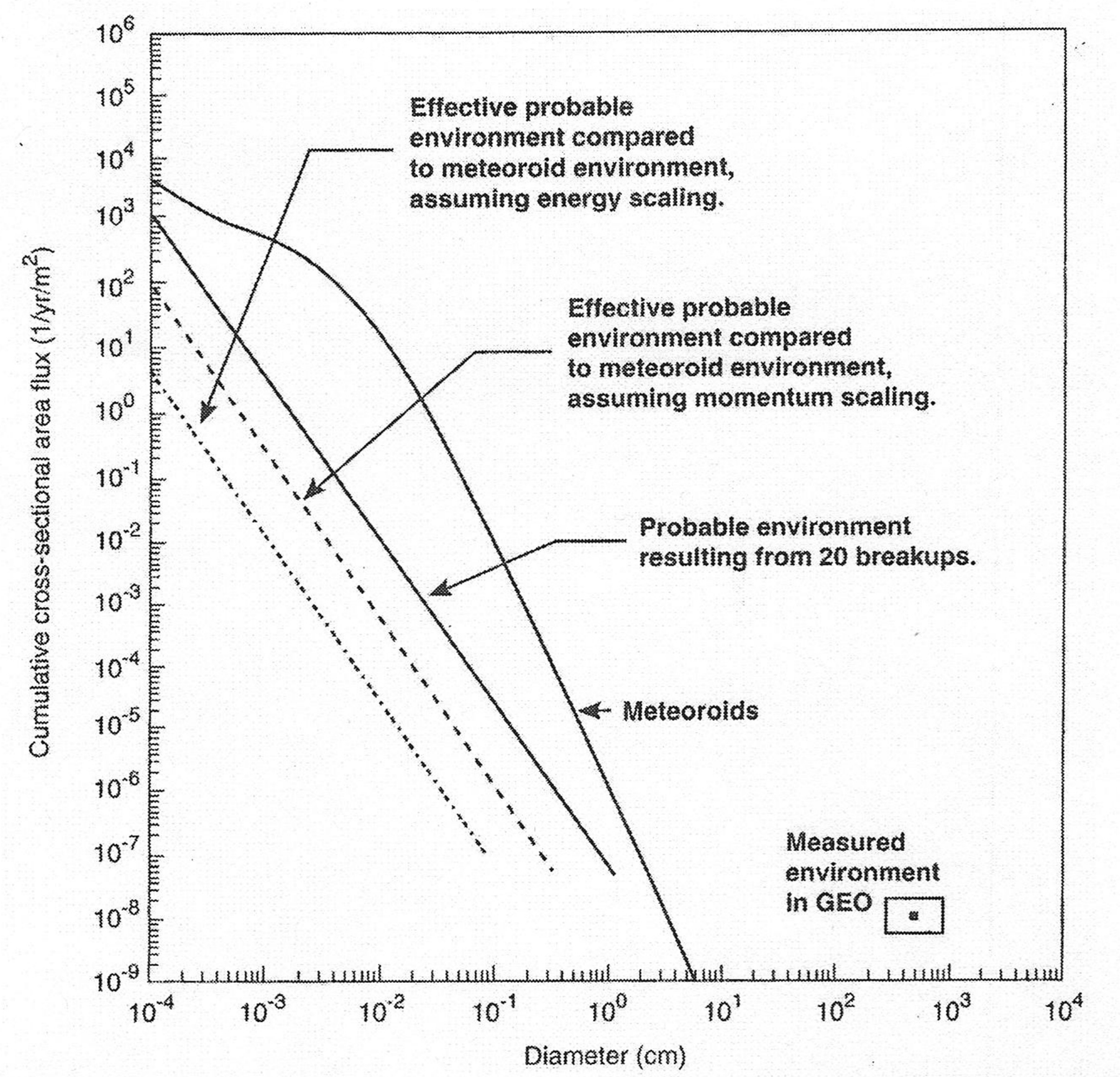
Credit: Ketsdever

Debris hits

- Example for use of previous slide:
  - estimate number of hits by 1 mm diameter particle on a 10 m^2 cross sectional spacecraft with an orbital lifetime of 10 years:
    - 1 mm = 0.1 cm diameter on x-axis for particle size
    - F (cumulative cross section area flux) = 10^{-2} on y-axis for hits yr^{-1} m^{-2} as the value for 1 mm
    - Hits = F * (10 yrs * 10 m^2) = (10^{-2} * 10 * 10) = 1
    - Therefore 1 particle hit in operational lifetime

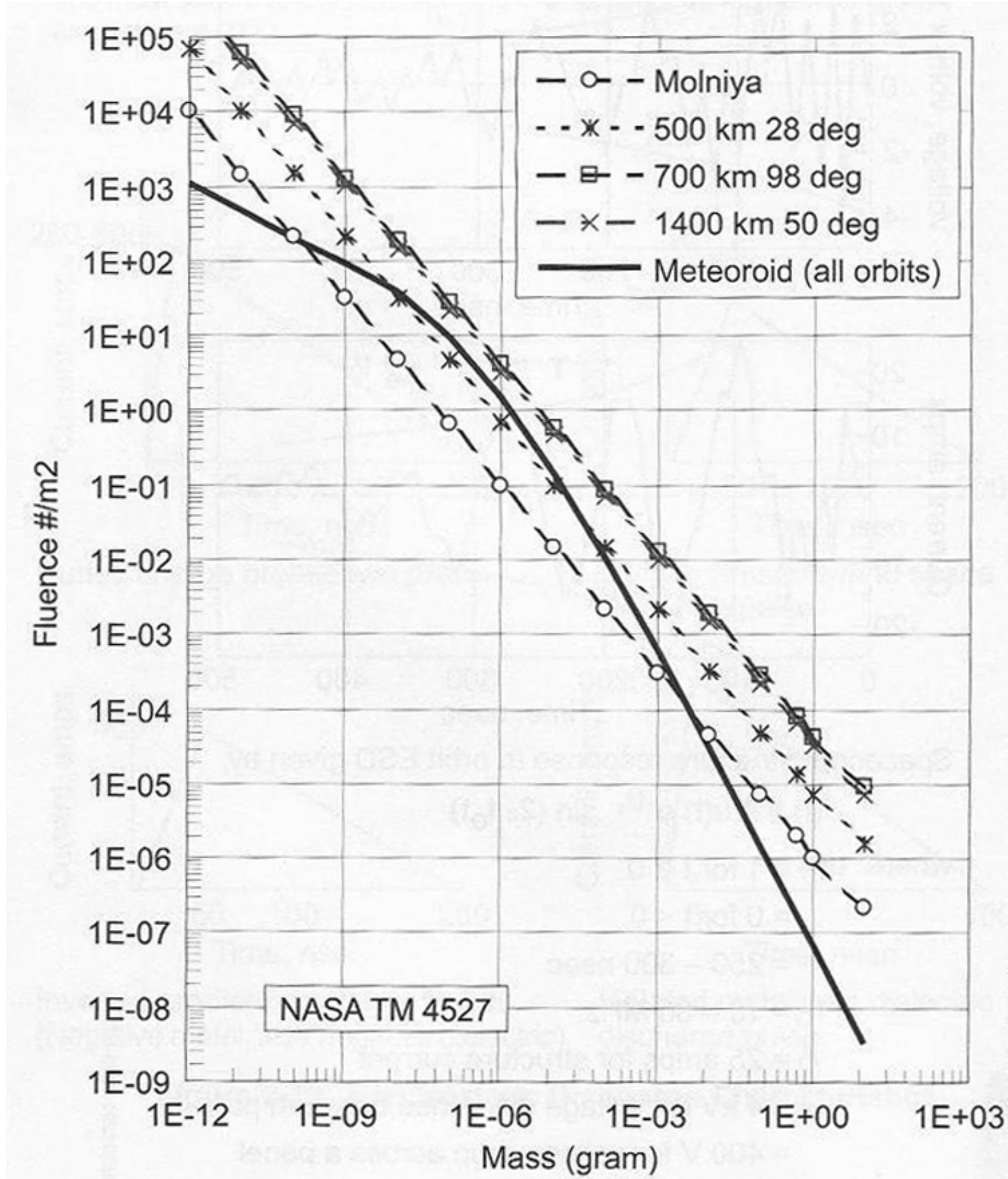
Credit: Ketsdever

MMOD flux in GEO



Credit: Ketsdever

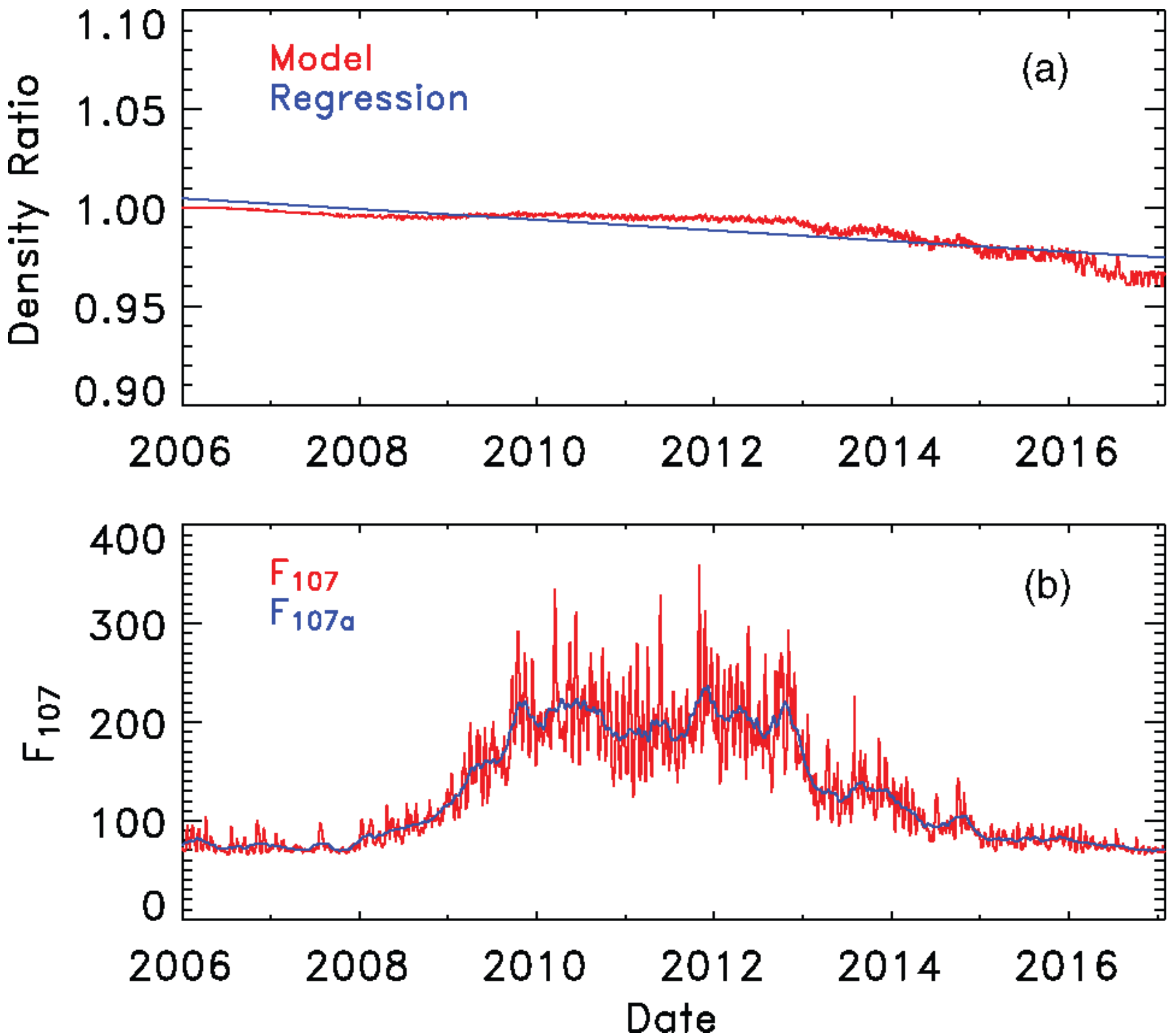
Micrometeoroid and debris yearly fluences vs. mass (grams) for a variety of orbits



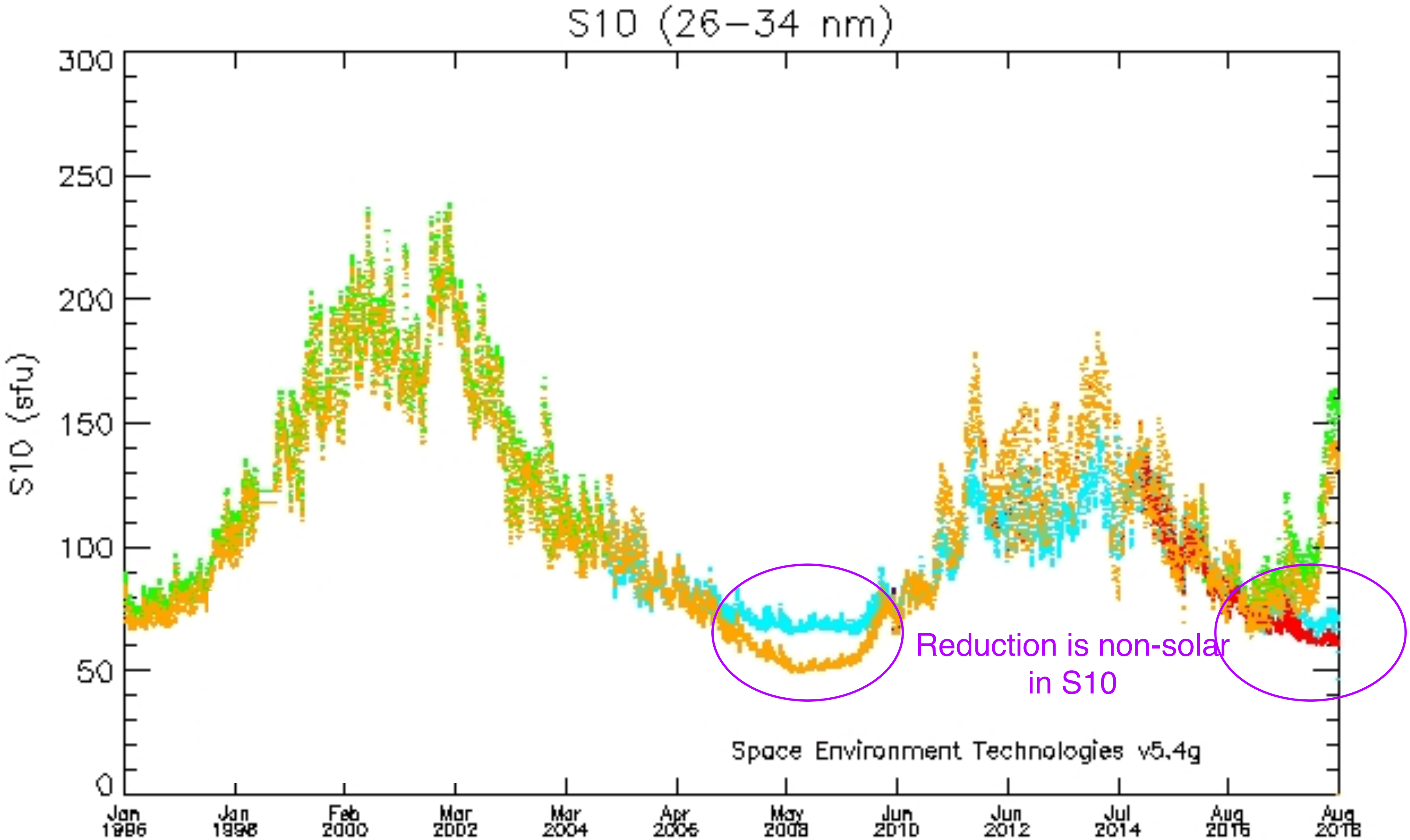
Debris perturbations

- Orbital Debris is affected by several forces once it is created
- For all orbit altitudes, gravitational attraction is the primary force that determines orbital characteristics
- For LEO orbits, especially below 800 km, atmospheric drag is an important force as the thermospheric densities are modulated by solar cycle, active region evolution, solar rotation, and flare event irradiance variability
- Solar radiation pressure, plasma drag, and electrodynamics, as secondary forces, can also affect debris orbits
- Thermospheric cooling from CO_2 added to lower thermosphere due to lower atmosphere anthropogenic sources leads to longer debris lifetimes

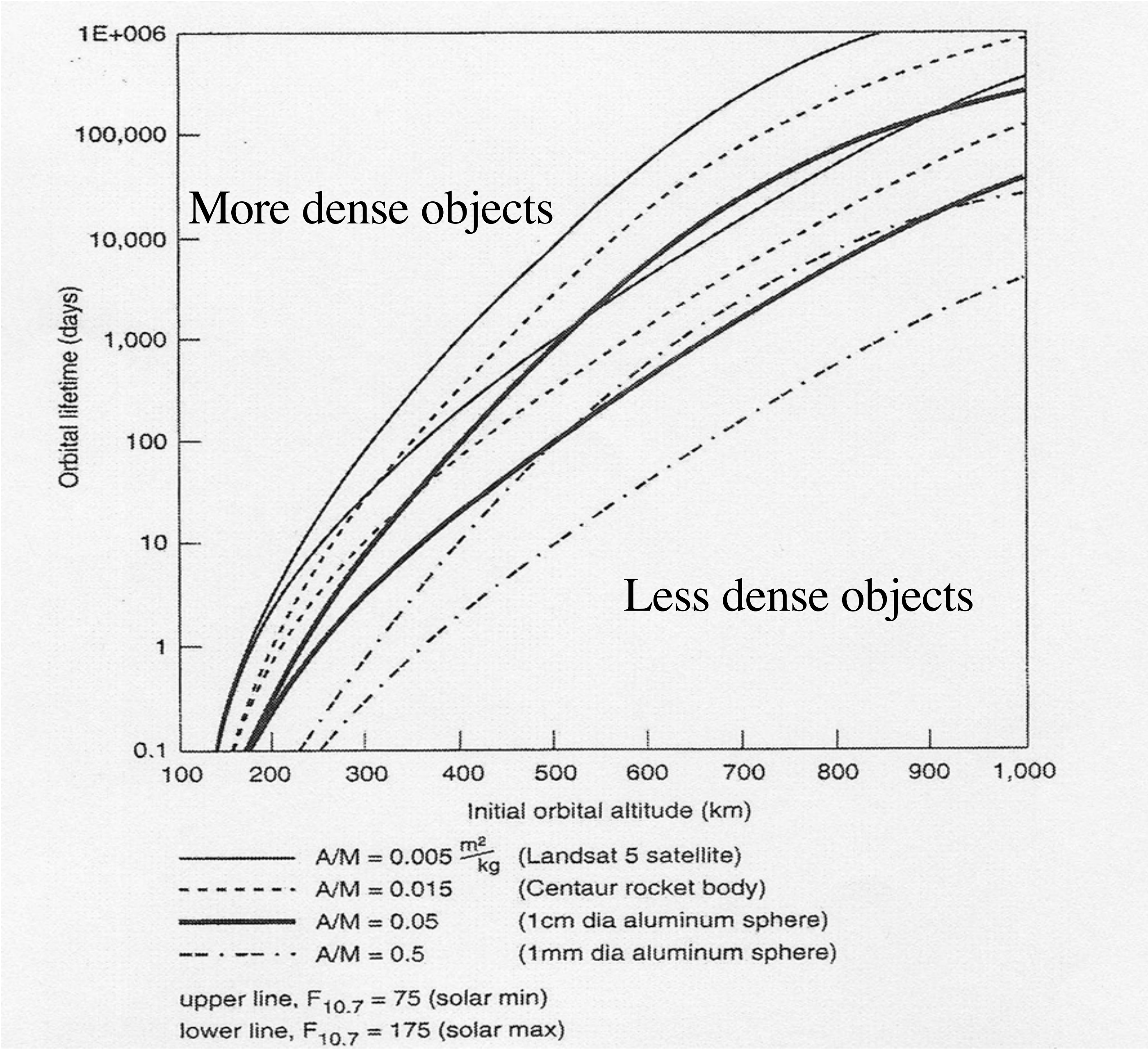
Global Mean Model Forecast of the Effect of Increasing CO_2



Indirect evidence of increasing CO_2



OD LEO lifetime



Credit: Ketsdever

OD LEO lifetime

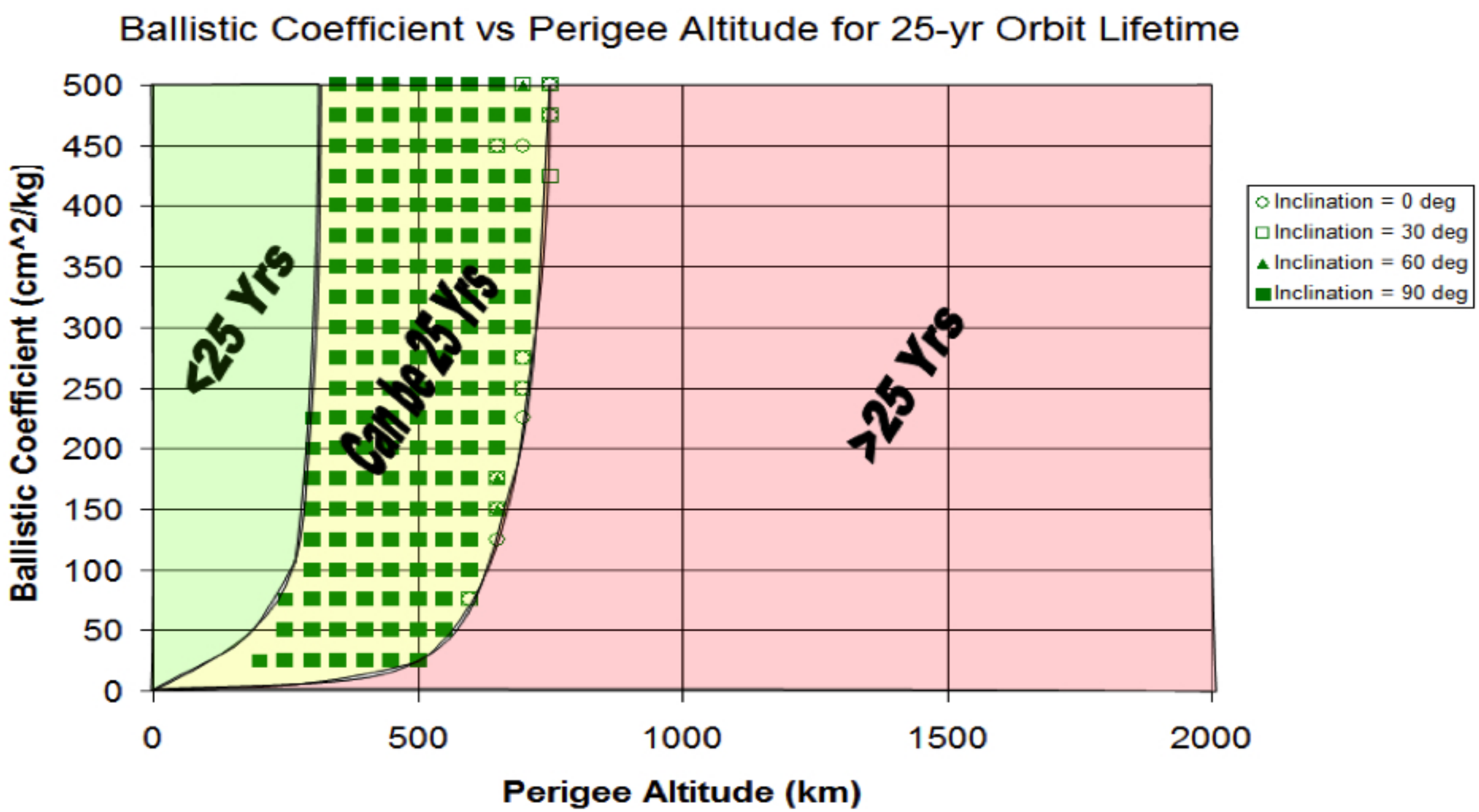


Figure 19: Ballistic coefficient versus initial perigee altitude for all cases exhibiting 25-year orbit lifetime (apogee assumed < 10,000 km)

Effects

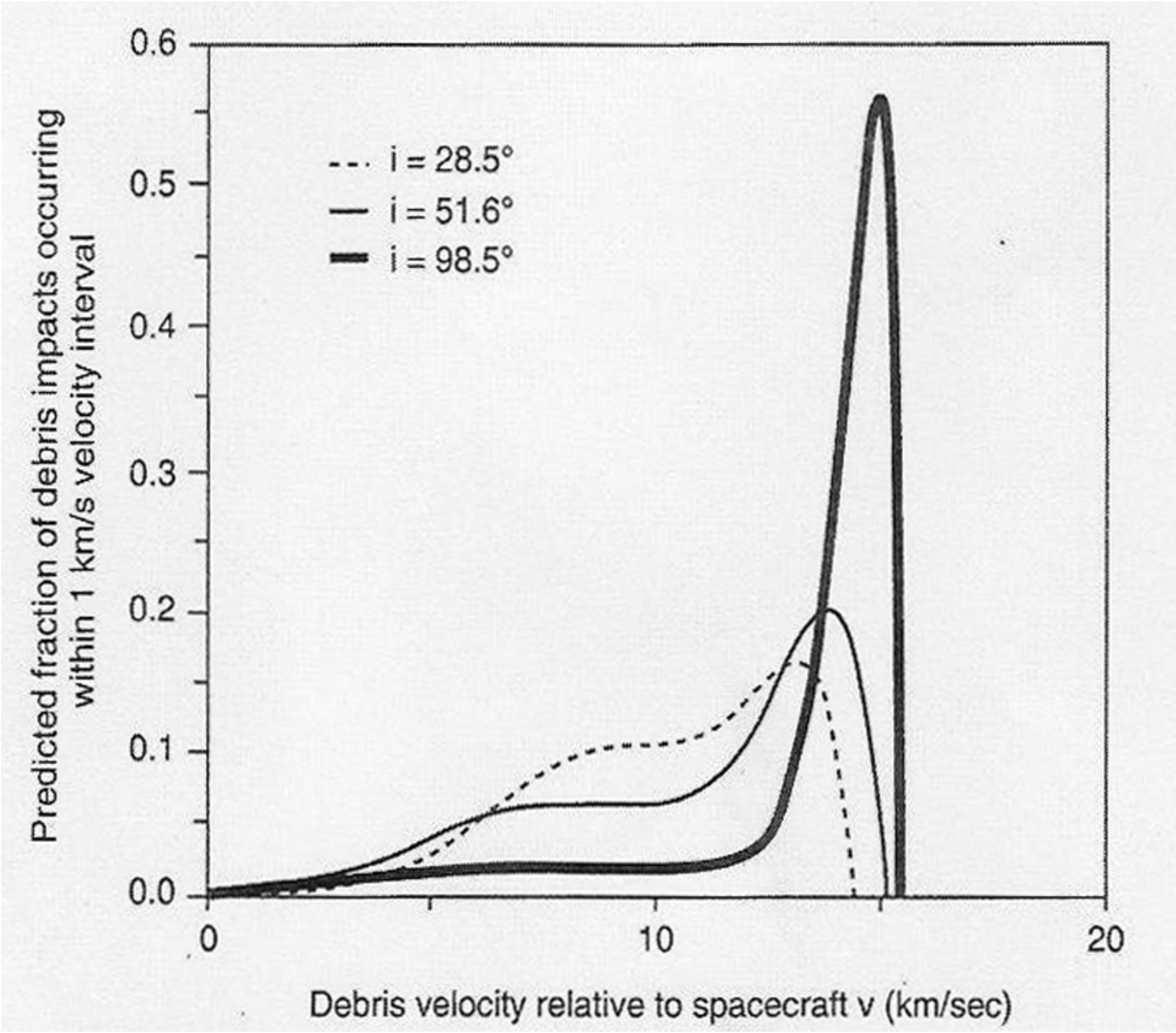
Hypervelocity impact

Hypervelocity impacts

- Hypervelocity impacts are the **primary effect** of micrometeoroids and space debris
- First step is to estimate debris flux for a spacecraft's orbital regime
- Then combine with hypervelocity impact damage model estimates to predict the likelihood that debris will cause damage to the spacecraft during its functional lifetime
- The probability for a collision depends primarily upon the spacecraft size, the debris flux in an orbital environment, and the amount of time spent exposed to the environment
- Damage in a collision is a function of kinetic energy, T, of impact which is the debris velocity relative to the spacecraft
- For example, an object in LEO moving at 13 km s^{-1} relative to a spacecraft will have a roughly equivalent energy released by the the explosion of 40 times its mass of TNT
- A 1 cm diameter aluminum sphere (like a ball bearing) has a mass of ~1.4 grams and T ~ 56 g TNT or 0.24 MJ.

Credit: Ketsdever

LEO OD impact velocity



Credit: Ketsdever

Hypervelocity impacts

- Hypervelocity impacts can cause several modes of damage
  - Craters (have a diameter larger than point of impact)
  - Spallations (knocking out target particles)
  - Perforations (penetration through target material)
  - Petalled holes (penetration plus target material ripped open)
  - Cracks (stress fractures)
- The amount of damage depends on impacted material of spacecraft component and the physics of the collision (e.g., impact velocity, angle) (100-1000 times the mass of the incident particle can be ejected)
- Even if no penetration occurs of s/c skin, the reflection of the impact shock wave can cause small particles (μm – mm sizes) to spall from the back of the impacted wall

Credit: Ketsdever

Hypervelocity impacts

- Hypervelocity impact shocks can cause delamination and removal of surface coatings beyond the diameter of a crater
- The impact shock can initiate cracks in brittle material and create localized plasmas which cause discharges and upsets
- The thickness t (cm) of a material that can be completely penetrated by a debris particle is

$$t = K_1 m^{0.352} \rho^{1/6} v_\tau^{\ 0.875} \qquad \textbf{(12-20)}$$

where *m* is the mass of the impactor in grams, ρ is the density of target material in g cm^3, v_τ is the relative impact speed in km s^{-1} and K_1 is a material constant (using a derived LDEF value of 0.72)

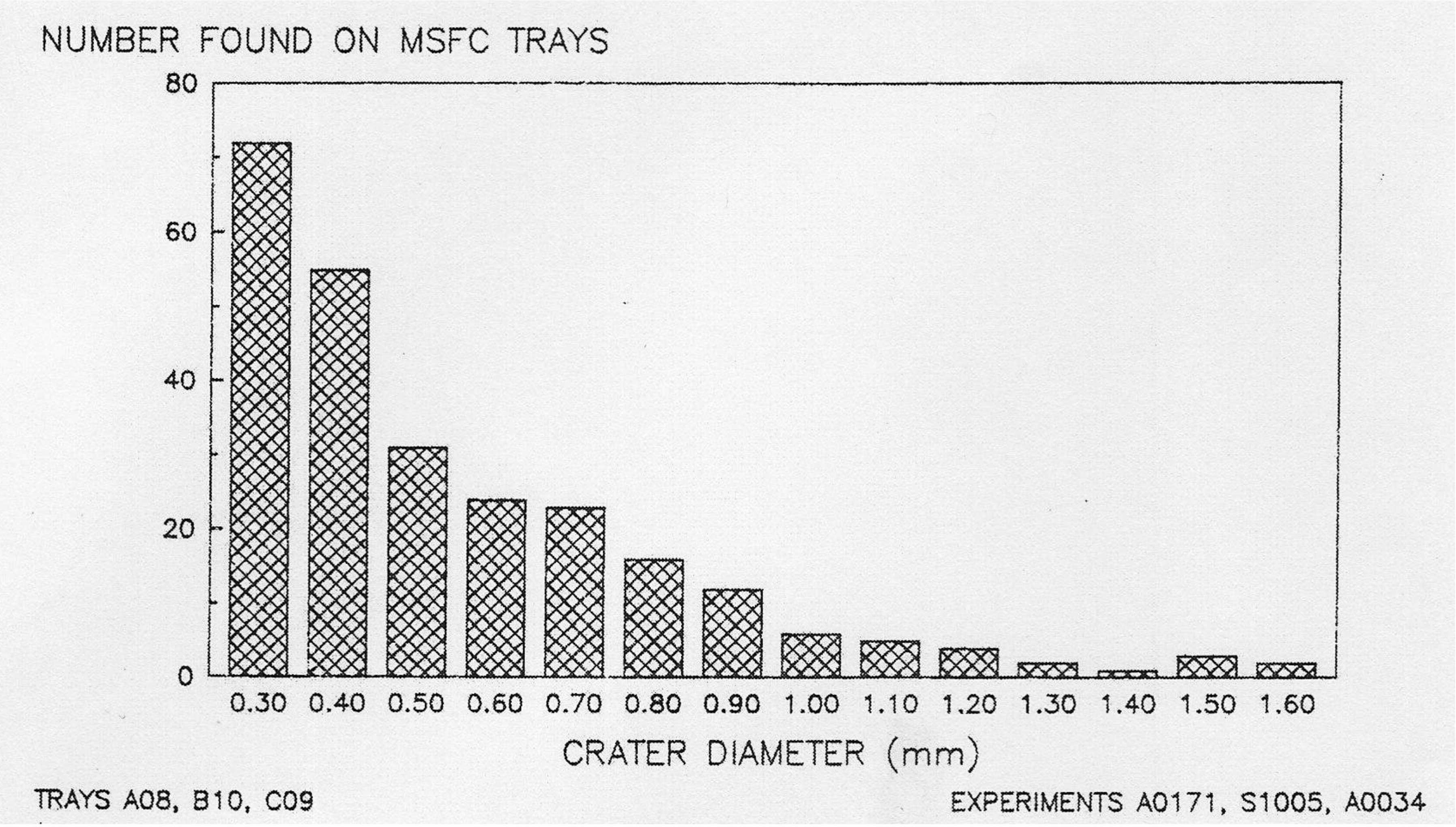
- The crater depth, *P*, produced by debris particles which do not completely penetrate the material is given by

$$P = 0.42 m^{0.352} \rho^{1/6} v_\tau^{\ 2/3} \qquad \textbf{(12-21)}$$

for an aluminum plate (in cm)

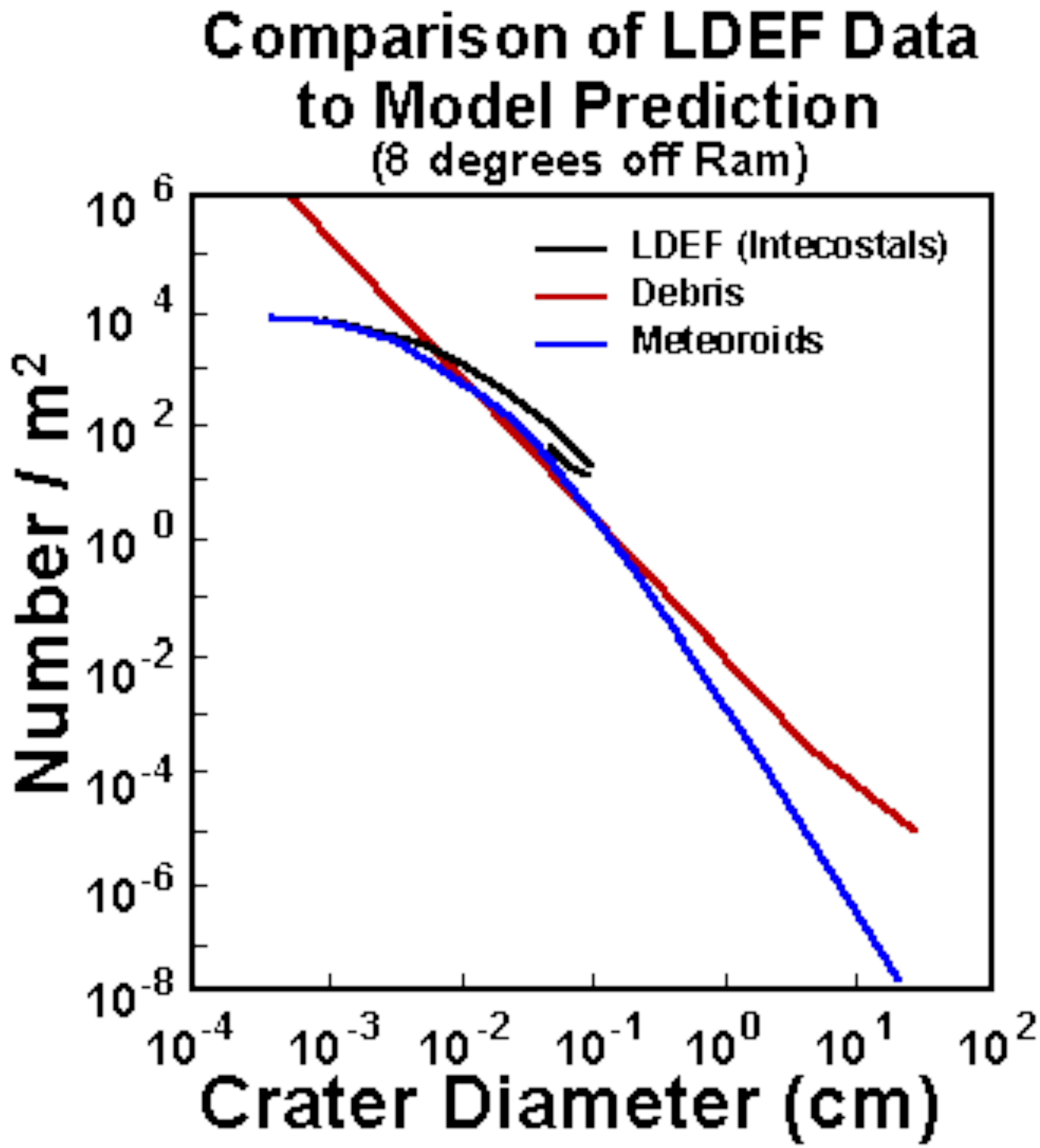
Credit: Ketsdever

LDEF impact craters



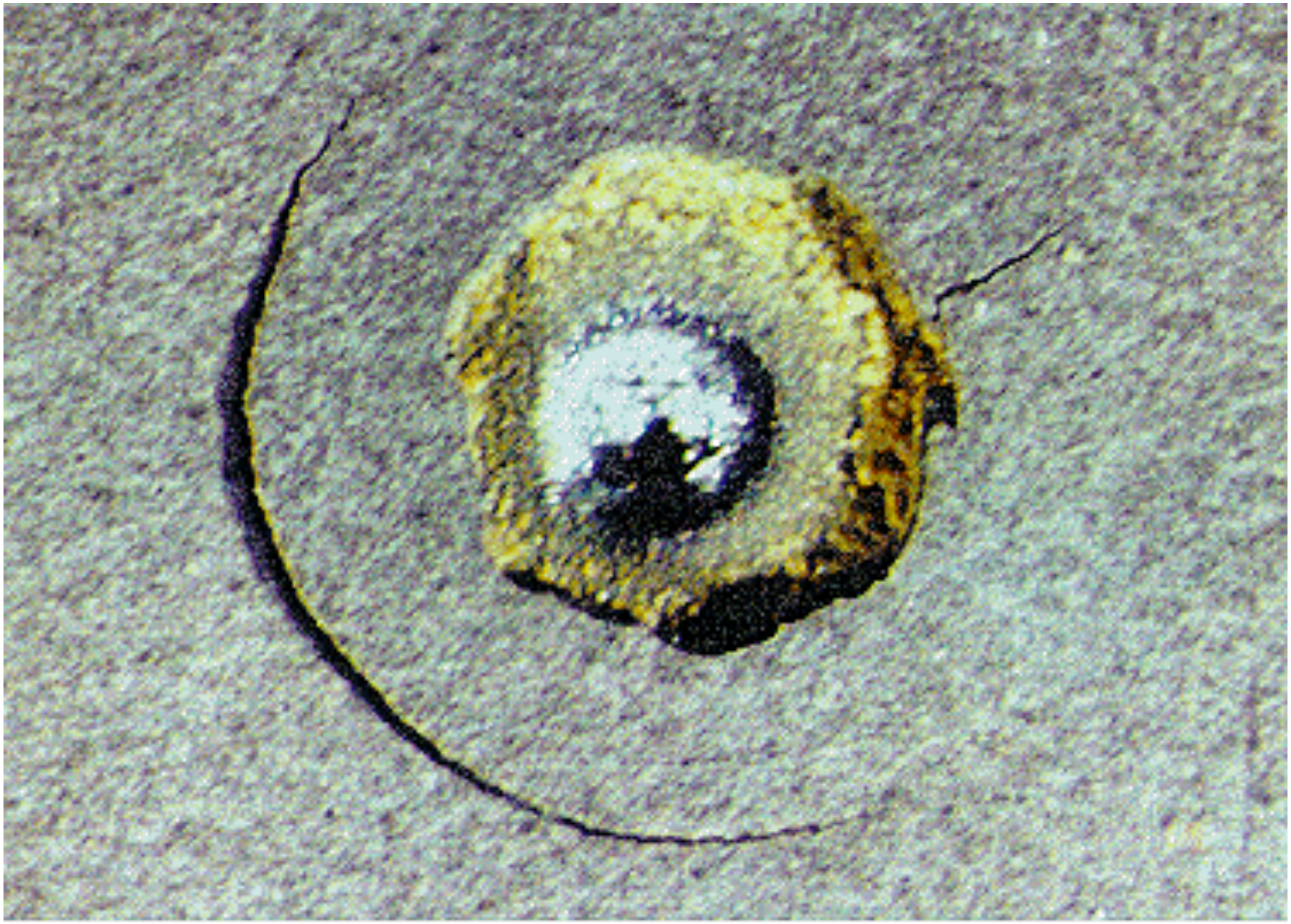
Credit: Ketsdever

LEO OD impact craters from LDEF



Credit: NASA

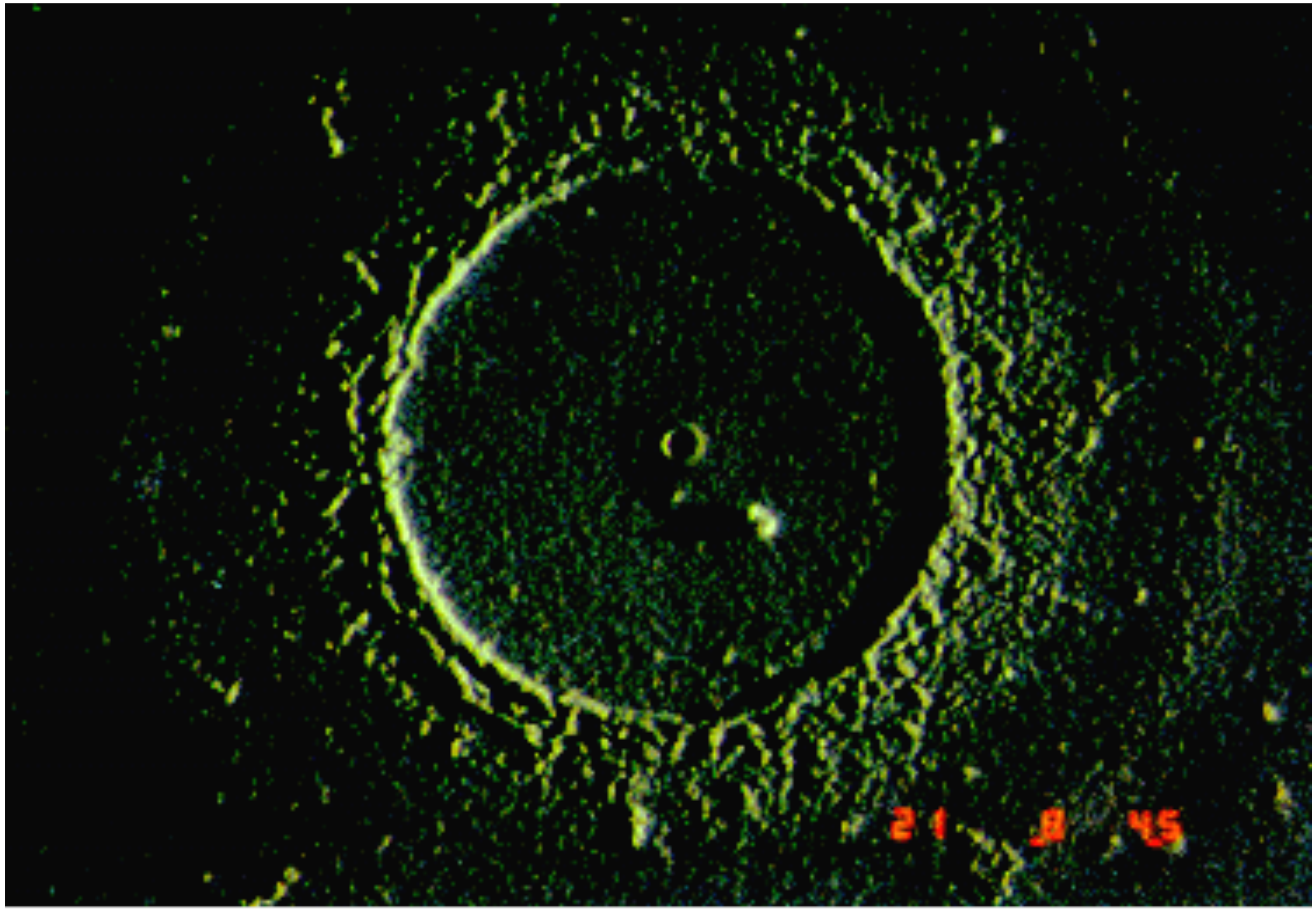
LEO OD impact: LDEF crater, spall, & stress crack



Central crater and partial spall of the paint layer on a painted aluminum surface

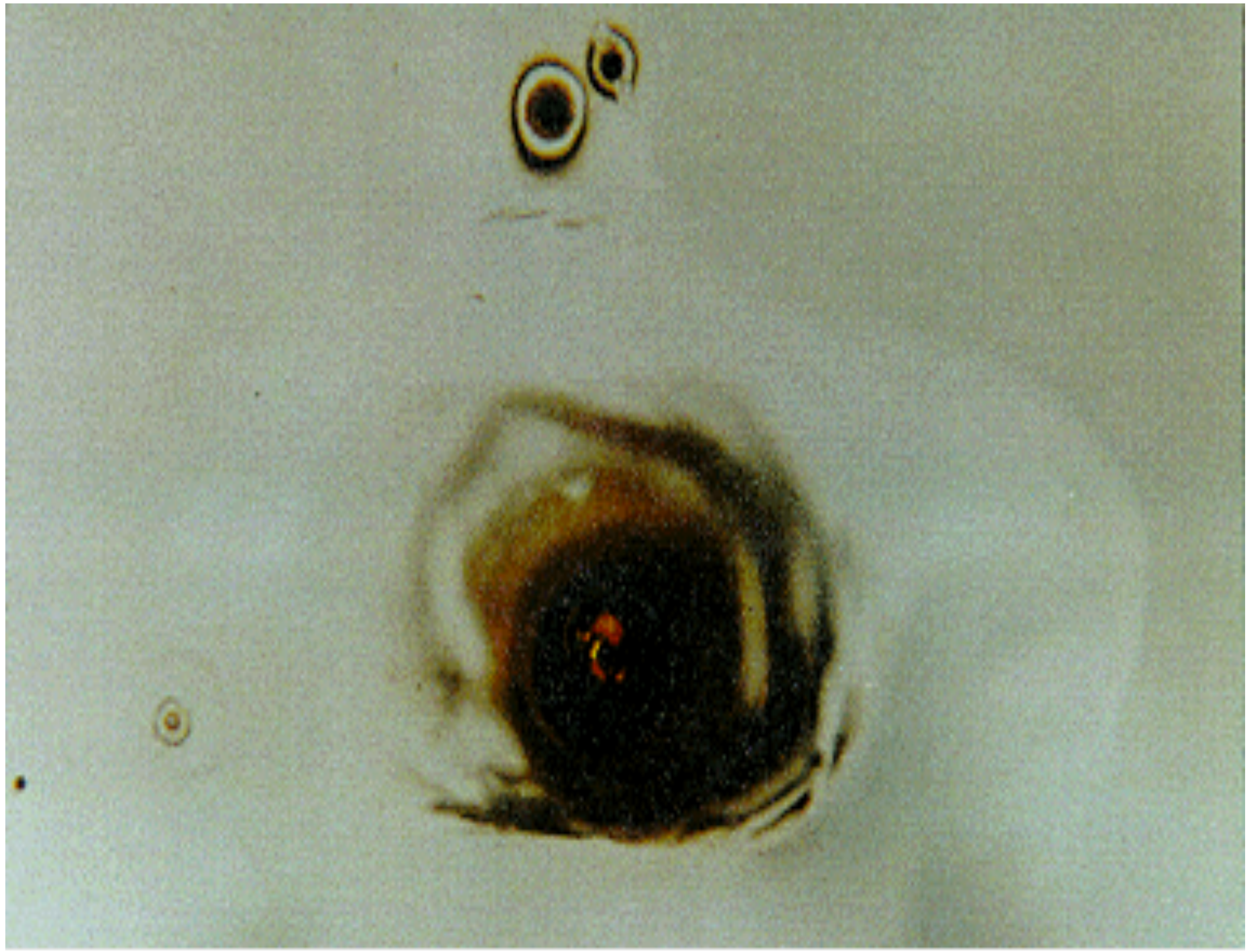
Credit: NASA

LEO OD impact: LDEF crater and spall



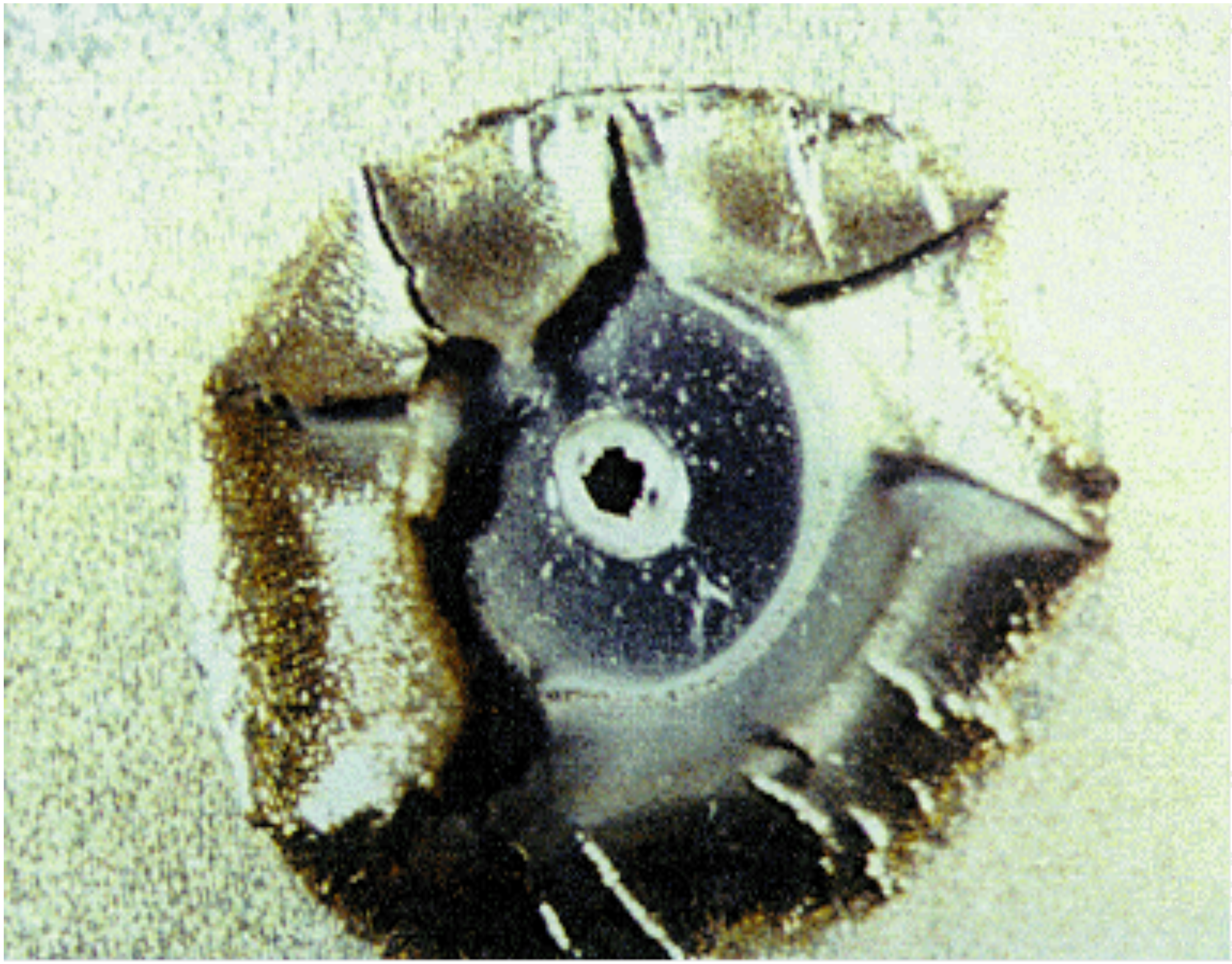
Low-angle light photograph of an impact into a painted aluminum surface highlighting the paint spall zone commonly assocaited with such impacts

LEO OD impact: LDEF penetration



Penetrations, and commonly assocaited ringed structure, in silver-Teflon thermal blanket

LEO OD impact: LDEF penetration and petalling

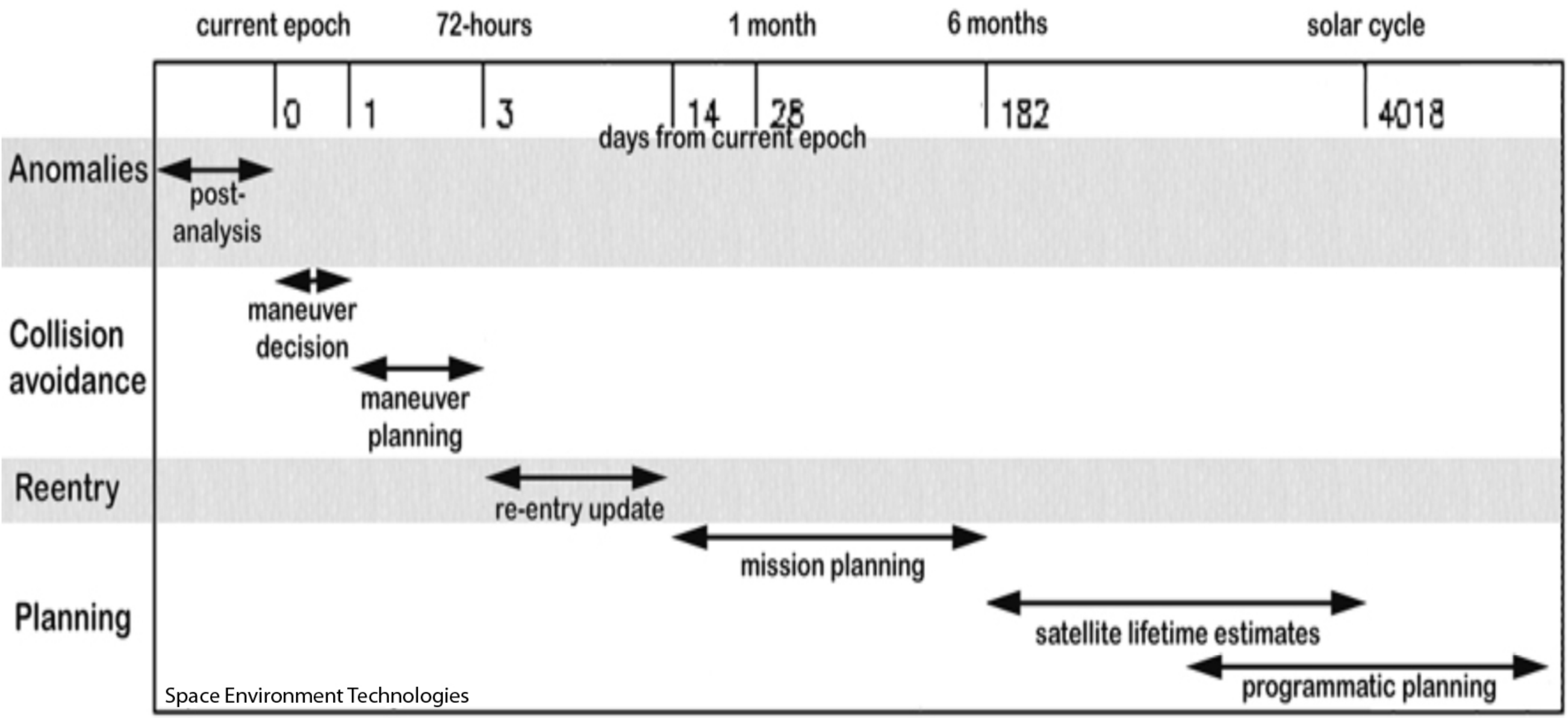


Penetration through an aluminized Mylar foil

Standards, guidelines, models

Mitigation paths for debris

Mitigation relevant time frames



Debris sources

- Debris is generated by a number of processes
  - **A. Vehicle-released objects**
    - hardware intentional release such as explosive bolt parts, spring release mechanisms, spin-up devices, camera covers
    - intentional waste products from MIR, Shuttle, and ISS
  - **B. Fragmentation**
    - explosions created by residual propellant in tanks
    - deterioration of materials
    - collisional impacts with other bodies
  - **C. Mission operations and maneuvers**
    - solid rocket motor operation where Al_2O_3 particles with velocities around 4 km s^{-1} and particle sizes not larger than 10 μm but up to 10^{20} particles created during one motor firing
    - unplanned or non-operational disposal of vehicle at EOL

Space Debris Mitigation International Standard (IS 24113)

Project management for debris mitigation

E

Tools and models for debris mitigation

Testing methods for debris mitigation

Standards cover full project lifecycle

A – **Limit debris generation by vehicle**
- Prevention of uncontrolled hardware release
- Waste
- Surface degradation
- Upper stages
- Propulsion
- Mech. devices
- Experiments

B – **Limit debris due to collisions**
- Post collision – loss of function
- Post-collision – creates debris
- Avoidance – tracked objects

C – **Disposal manoeuvre**
- Requirements definition and design
- Operational monitoring and predictions
- Disposal and verification

D – **Re-entry safety**
- Re-entry risk assessment
- Re-entry predictions
- Re-entry management and operations

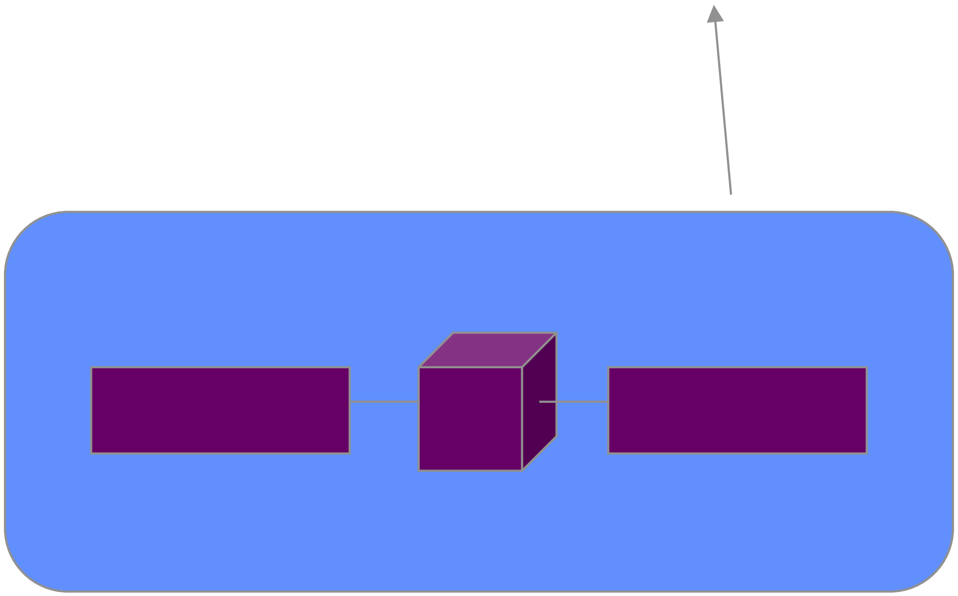
Stds developed by WG1, WG3 and WG6

"Spacecraft in a box"

Waste

Experiments

Prevention of uncontrolled hardware release (Explosion products)



Objective - keep all spacecraft elements in this blue "box"

Mechanical devices (parts)

Surface degradation (Material generated from spacecraft surfaces)

Upper stages

Propulsion (material)

A Limit Debris Due to Vehicle

Limit Debris Generated by Vehicle
- Limits on Debris
- General Requirements for Limiting Release
- Concept of limiting release
- Scope of Released Items
- Categories/Functions
- Definition

Waste
- Chemical
- Coolant
- Aerosols
- Vented Water/Waste

Upper Stages
(Big Items)

Experiments
- NASA Std

Propulsion
- Solid Motors
- Liquid Motors
- Detach Motors
- Upper Stages

Prevention of Uncontrolled Hardware Release
- Passivation
- Pressure
- Battery

A Limit Debris Due to Vehicle - con't.

Limit Debris Generated by Vehicle

Mechanical Devices including contained explosions, pyros etc

•Separation Devices
•Covers
•Deployment Mechanisms
•Shrouds
•Attachment Rings
•Robotic Tools
•Deployment Systems
•Bolt Cutters
•Tethers

Surface Degradation

•Surface Coatings
•Thermal Blankets/Surfaces
•Surfaces

A Limit Debris Due to Vehicle

- All Non-operational Ejections
- Method of reporting debris generation (from each group
  - Total assessment of debris released
  - Requirements (Life/mass/hazard)
  - Dispersement limits - density of clouds
- Hazard identification (Report definition) -Chemical, Radiological, Kinetic, Other
- Risk Assessment -
  - Specify/define statistical debris release - limits
  - Individual elements not allowed unless life is very short
- Must consider risk to existing assets for any release of non-operational item (from Upper stage - To - small)
- Define Surface Degradation
  - <u>Not</u> collision damage in avoiding debris due to collision

B Limit Debris Due to Collision

Limit Debris due to Collisions
- •Categories/Functions
- •Definitions
- •Scope

Post Collision - Creates Debris
- •Materials and coatings ‘Best Practice’
- •Materials selection
- •Experimental data test and reporting
- •Limit debris generation by material selection (following impact reduce (by design) generation of debris)

Avoidance – Tracked Objects
- •Not mature enough for standards
- •But Standard format for orbital information (tracked and operational)
- •Objective is common framework for exchange orbit and manoeuvre info

Post Collision - Loss of Function [Disposal Manoeuvres]
- •Design to avoid loss of function leading to disposal problems
- •Methodology for calculating reliability (Disposal, Non-functionality)
- •(Outcomes – OK; Correction – shielding etc; No solution → Case-by-case basis)

Credit: ISO

B Limit Debris Due to Collision

- The scope of these “supporting technical standards” may include:
- Post-collision – creates debris
  - Reporting format for collisions
- Avoidance – tracked objects
  - Technical Report on best practice for collision avoidance (includes launch control)
  - Orbit Propagation Data Standards - Tool Standard Accuracy
  - Initial Hazard Analysis for satellite → Format for communicating Intentions
  - Short-term Collision Avoidance
  - Launch Control to Track

C Disposal Manoeuvres

Requirements Definition and Design Phase (Mission and Hardware) - Definitions and Requirements

- Missions, Consumables, Hardware, Communications
- Tools and methods (models and calculations)
- Method for calculating EOL parameters
- Establish threshold values for through life monitoring
- Reporting format for EOL manoeuvre required
- Redundancy/Reliability

Disposal Manoeuvres

- Reporting requirements
- Definitions, Scope
- Verification

Disposal and Verification

- Disposal decision and planning
- Reporting format for disposal plan
- Reporting format for verification of EOL manoeuvre

Operational Monitoring and Predictions Phase

- Requirements for monitoring the space system
- Measurement of parameters for through life monitoring
- Measurement of consumables and resources
- Reporting format for through life test

D Re-entry Safety

Re-entry Safety
- EOL Manoeuvre
- Controlled/Uncontrolled - Definition
- Flow Diagram
- Requirements

Re-entry Risk Assessment
- Re-entry hazard prediction

Re-entry Predictions (Time and trajectory)
- Carry out lifetime assessment
- Evaluate orbit trajectories
- Measurement of consumables and resources

Re-entry Management and Operations
- Post Re-entry Verification and Reporting

Requirements Definition and Design Phase

Operational monitoring and predictions

Re-entry and verification

E Tools and Models

- For each of the four implementation standards, tools and models are required
- To carry out many of the calculations, standard models are required in each of these five categories
  - Solar irradiance models (ISO 21348)
  - Solar/geomagnetic models (ISO 21348, 16698)
  - Atmospheric models (ISO 14222, 11225)
  - Ionosphere models (ISO 16457)
  - Debris and Meteoroid models (ISO 14200)
  - Tracked object catalogue/Operational spacecraft catalogue (Celestrak)

E Micrometeoroid & debris models

Examples of MMOD environment models

- SPDA 2000 (Russia)
- MASTER 2005 (ESA)
- ORDEM 2000 (USA)

- SSP-30425 (NASA for ISS)
- Bumper-II

Process-based Implementation standard (guideline for utilization).

Space Debris Model Specifications

Item		ORDEM2000	MASTER2001	MASTER2005	DAMAGE	SPDA	LEGEND	IDES
Bibliography		[1]	[2]	[3]	[4]	[5-7]	[8, 9]	[10-15]
Source		NASA	ESA		Southampton University	RSA	NASA	DERA
Modeling approach		mesurement data	semi-deterministic analysis		statistical and near-deterministic methods	stochastic semi-analysis	mesurement data	semideterministic analysis
Applicable regime	Minimum size	> 10 μm	> 1 μm		0.1mm	> 1mm	> 1mm	> 10 μm
	Orbital regime	200 – 2000 km	186 – 36786 km		2000 – 37786 km	400 – 2000, 35300 – 36200 km	200 – 40000 km	
	Evolutionary period	1991 – 2030	1958 – 2050	1957 – 2055	long term	medium and long term	short and long term	short and long term
Input parameter		Apo/Peri Altitude Semi-major axis Eccentricity Inclination Argument of perigee	･Target Orbit Scenario Semi-major axis, Eccentricity, Inclination, Right asc. of asc. node, Argument of perigee ･Inertial Volume Scenario Geocentric distance, Right ascension, Declination ･Spatial Density Scenario Lower/Upper alt. limit, Lowe/Upper decl. limit					
Output data		Flux vs. Size, Orbit position, Altitude, Latitude	･Flux vs. Size, Mass, Semi-major axis, Eccentricity, Inclination, Altitude, Latitude, Impact velocity, Impact declination, Time, etc. ･Spatial density vs. Size, Mass, Altitude, Declination, Time					
Debris source terms	TLE background	all soutces together	yes			all sources together	yes	
	Fragments		yes				yes	
	SRM dust/slag		yes				yes	
	NaK droplets		yes				yes	
	Paint flakes		yes				none	
	West ford needles		yes				yes	
Meteoroid	Background	none	Divine-Staubach		none	none	none	none
	Streams		Jenniskens-McBride, Cour-Palais					
Primary data source / Validation		SSN catalog, LDEF, Haystack radar, HST-SA, STS window and radiator, HAX radar, Goldstone radar	LDEF, HST (SM1), EuReCa, *PROOF2001*	LDEF, CME, HST (SM1, SM3B), EuReCa, *PROOF2005*	mesurement data, IDES, MASTER			
Model features			Flux to spheres, Oriented surf., GUI, Time browser		GTO, mitigation strategies, GUI			
Engineering model available for intentional use		yes	yes	yes				no
Release data		2002	2002	2006		2001		1996

E Standardizing Tools and Models

- Different approaches can be used
  - Report model parameters in a standard
  - Define a process-based model so that range of models (current and future) can be used
  - Example "Space environment (natural and artificial) — Process for determining solar irradiances" (**ISO 21348**)

E Standardizing Tools and Models

Implementation standard	Calculation task requiring tools and models	Model: Atmosphere	Solar/geomagnetic	Meteoroids	Debris	Catalogue (+ tracking data
Limit debris due to vehicle	Generation of material from s/c surface	X	X	X	X	
	Propagation of objects generated (lifetime, dispersion)	X	X			
	Risk to catalogued objects	X	X			X
Limit debris due to collision	Calculate collision probability (total, case -by case)	X	X	X	X	X
	Generation of debris following collision					
	Loss of function following collision			X	X	
Disposal manoeuvre	Lifetime, evolution of object (passive) in orbit	X	X			
	Orbit maintenance and manoeuvre (lifecycle management)	X	X			
Re-entry safety	Re-entry prediction (lifetime, orbit propagator)	X	X			X
	Re-entry risk to population					X
	Fragmentation prediction	X				

Published, In process, To be initiated	Terrestrial and Lunar Space Environment LEO	PEO	MEO	GEO	>GEO
	Space Systems and Operations Orbital Domains				
Testing/Analysis/ Framework	15856, 17851, 21980, 22295, AUL	15856, 17851, 21980, 22295, AUL	15856, 17851, 22295, AUL	15856, 17851, 22295, AUL	15856, 17851, AUL
Cosmic Rays	15390, 17520, (space weather)	15390, 17520, (space weather)	15390, 17520, (space weather)	15390, 17520, (space weather)	15390, 17520, (space weather)
Solar photons	21348, (space weather)	21348, (space weather)	21348, (space weather)	21348, (space weather)	21348, (space weather)
Solar particles	16698, 17520, 18147, (solar wind) , (space weather)	16698, 17520, 18147, (solar wind) , (space weather)	16698, 17520, 18147, (solar wind) , (space weather)	12208, 16698, 17520, 18147, (solar wind) , (space weather)	16698, 17520, 18147, (solar wind) , (space weather)
Solar fields	16698 (solar wind), (space weather)	16698 (solar wind), (space weather)	16698 (solar wind), (space weather)	16698 (solar wind), (space weather)	16698 (solar wind), (space weather)
Main magnetic field	16695, 16698, (space weather)	16695, 16698, (space weather)	16695, 16698, (space weather)	16695, 16698, (space weather)	16695, 16698, (space weather)
Magnetosphere	16695, 16698, 19923, 20584, (space weather, PC-index)	16695, 16698, 19923, 20584, (space weather)	16695, 16698, 22009, 19923, 20584, (space weather)	12208, 16695, 16698, 22009, 19923, 20584, (space weather)	16695, 16698, 22009, 19923, 20584, (space weather)
Radiation Belts	17761, 20584, 17520, 21979, (IRENE, internal chrg), (space weather)	17761, 20584, 17520, 21979, (IRENE, internal chrg), (space weather)	20584, 17520, 21979, (IRENE, internal chrg), (space weather)	20584, 17520, 21979, (IRENE, internal chrg), (space weather)	20584, 17520, 21979, (IRENE, internal chrg), (space weather)
Plasmasphere	16457, 20584, (space weather)	16457, 19923, 20584, (space weather)	16457, 19923, 20584, (space weather)	16457, 19923, 20584, (space weather)	16457, 19923, 20584, (space weather)
Ionosphere	16457, 16698, 20584, (space weather)	16457, 16698, 20584, (space weather)			
Neutral atmosphere	14222, 11225, 16698, (AO, sat drag), (space weather)	14222, 11225, 16698, (AO, sat drag), (space weather)		June 12, 2018	
Micrometeoroids	14200	14200	14200	14200	14200
Debris	14200, (rad debris)	14200, (rad debris)	14200	14200	14200
Lunar					10788

Space Environment Domains

Resources

- **AIAA SP-069-1994** *Contemporary Models of the Orbital Environment*
- **MASTER** orbit debris program
- **NASA Technical Standard 8719.14** Process for Limiting Orbital Debris (Aug 2007)
- **ISO 24113** Space Debris Mitigation Requirements
- **ISO 14200** Guide to process- based implementation of meteoroid and debris environmental models (orbital altitudes below GEO + 2 000 km)

Summary

- **Micrometeroid and orbital debris environment**
  - Micrometeroid (MM) environment
    - Sources, terrestrial effects, fluences, directionality
  - Orbital Debris (OD) environment
    - Population/sources, types, detectability, fluences, perturbations/lifetime
  - Effects
    - Hypervelocity impacts (cratering, spallation, penetration, perforations, cracks), thickness of materials
  - Mitigation paths for debris
    - ISO TC20/SC14 ODCWG
  - Standards, guidelines, models