Máster Universitario en Ingeniería Aeronáutica

The Space Environment

Macroscopic particle environment.

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Macroscopic objects in Earth orbit

Macroscopic particles refer to the contamination of *debris* derived from human space activities and and *micrometeoroids* (interplanetary dust particles) produced by different celestial sources (asteroids, comets, ...)

- Micrometeoroids:
  - Macroscopic sized particles of less than few millimeters in size moving in the interplanetary space of the solar system.
  - Those collected at the Earth's surface after survive the atmosphere impact (sized $10\ \mu\text{m} - 2\ \text{mm}$ are called *micrometeorites*. And can be collected on ground.
  - Due to the small size typical size of millimeters or below and encounters are random and are difficult to detect in orbit using ground-based radars.

- Space Debris:
  - In addition to normal space activity, it also results from the accidental or intentional destruction of spacecrafts and is usually categorized according to its size L as,

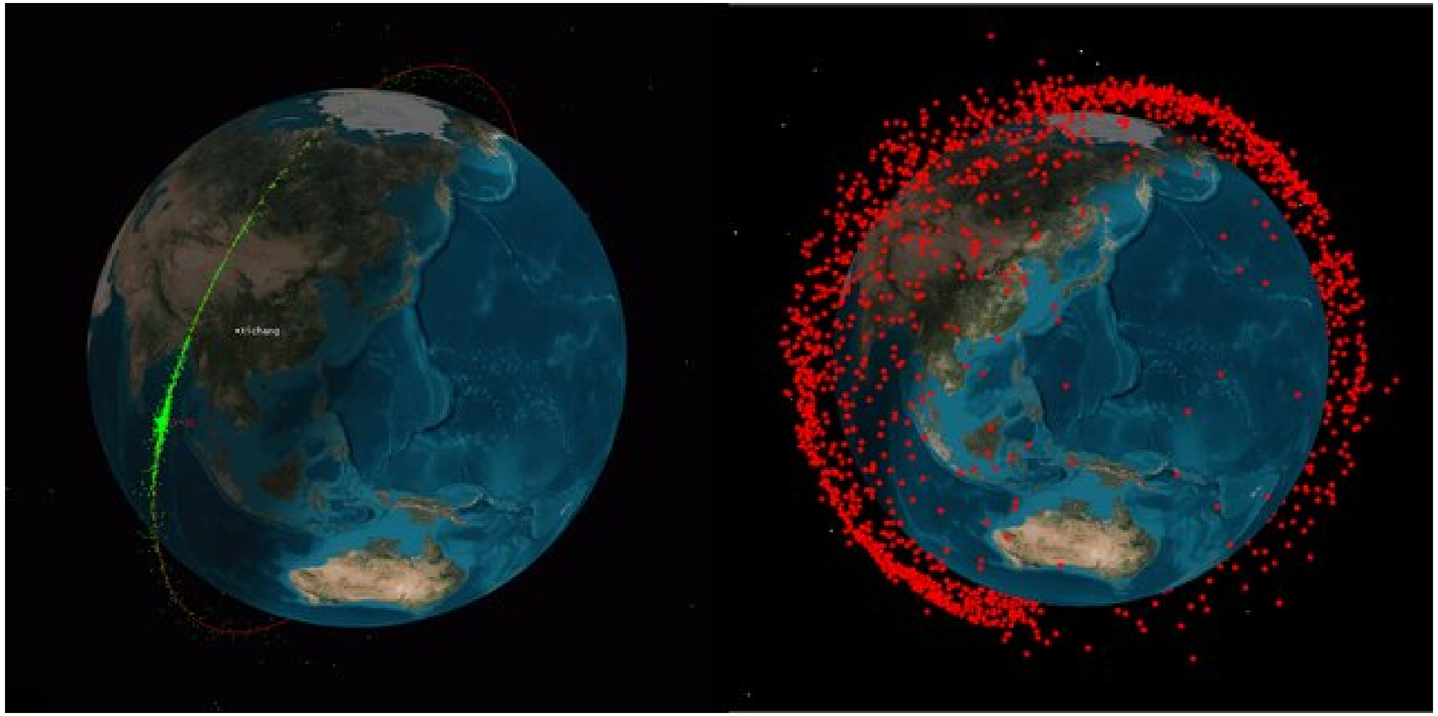
    Large $L > 10\ \text{cm}$
    Medium $10\ \text{cm} > L > 0.1\ \text{cm}$
    Small $L \leq 0.1\ \text{cm}$

  - Large fragments can be monitored from the ground using optical telescopes and radar stations. Space agencies track space debris and their orbits.
  - Medium and small fragments initially travel around the original orbit and inclination, but subsequent trajectories are randomized.

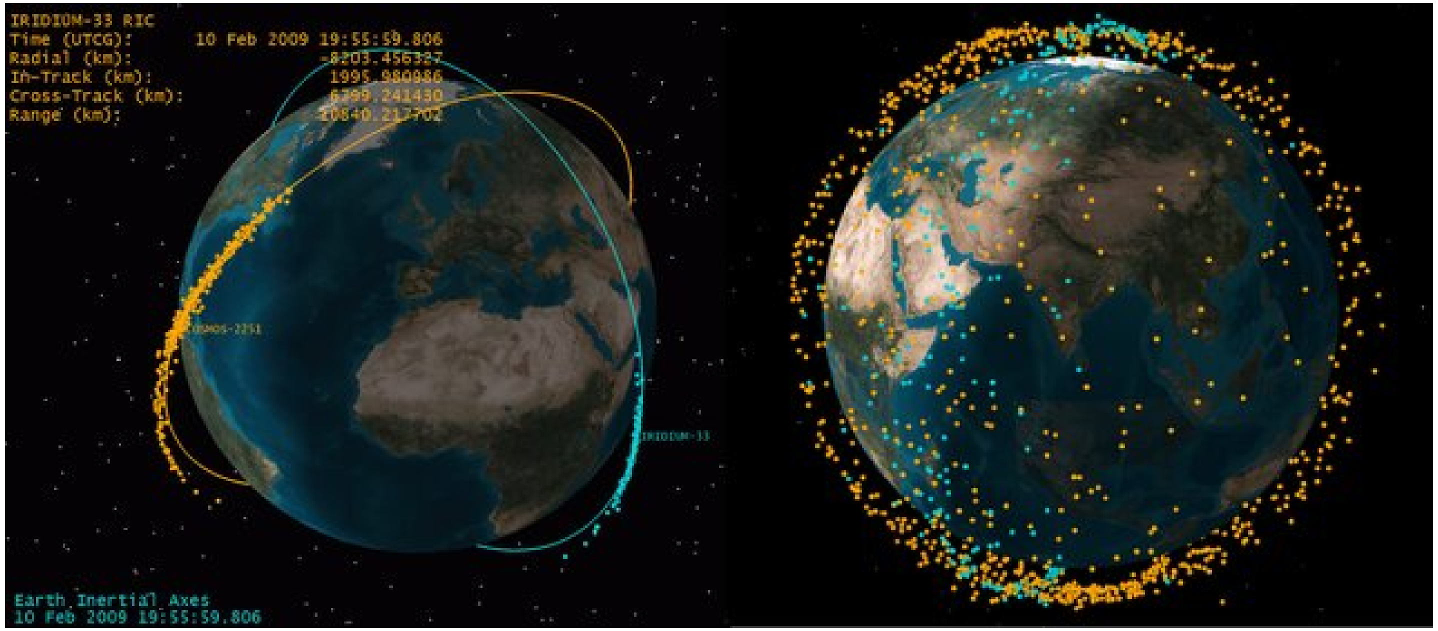
Space debris on Earth orbit

- Kessler syndrome (1978): Scenario in which the density of objects in LEO due to space pollution is high enough to cause a cascading process in which each collision produces new debris, increasing the probability of future collisions.
- US Space Surveillance Network (SSN http://www.space-track.org) tracks 23,000 orbiting objects larger than 10 cm (22,000 officially cataloged in 2021) with a sensitivity of approximate 5 cm at 400 km in LEO and over 20 cm GEO.
- ESA activities in space debris tracking.
  - The ESA Meteoroid and Space Debris Terrestrial Environment (MASTER) catalog gives $80\% \geq 10$ cm and $90\% - 99\% \geq 20$ cm for objects in LEO orbits.
  - Space debris web site https://sdup.esoc.esa.int
  - Space environment statistics https://sdup.esoc.esa.int/discosweb/statistics/
- Since the 2008-2009 fragmentation events the evolution can be considered of normal space operations.

Significant fragmentation events				
Year	Satellite	Orbit / Altitude	Event	Objects
2007	Fengyun 1C	PEO 865 km	Destruction	3,400
2008	Cosmos 2421	LEO 400 km	Explosion	500
2009	Cosmos 2251 Iridium 33	LEO 765 km	Collision	2,300



- Fragments of the FengYun 1C one year later its intentional destruction.

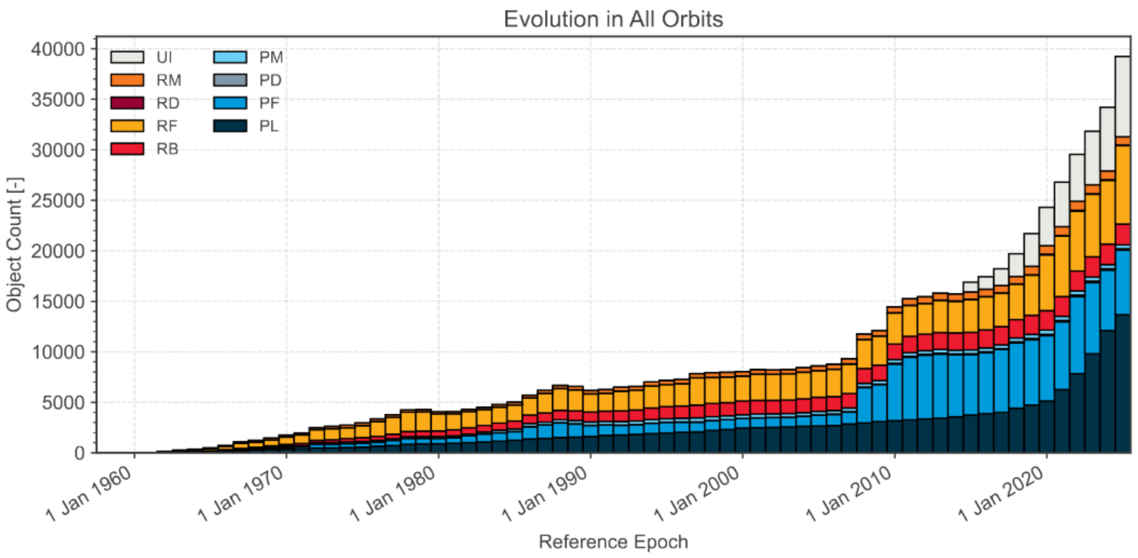


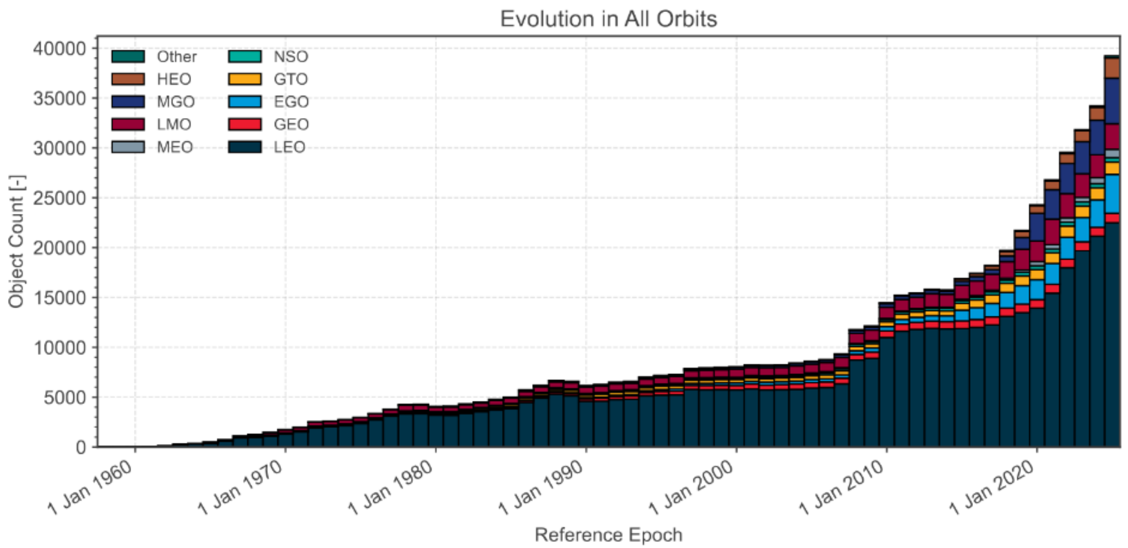
- The Iridium/Cosmos collision debris after 3 hours after the collision.

Figures from B.J. Sease. *Data reduction for diverse optical observers through fundamental dynamic and geometric analysis*. PhD Dissertation. Virginia Polytechnic Institute. (2016)

Macroscopic objects in Earth orbits

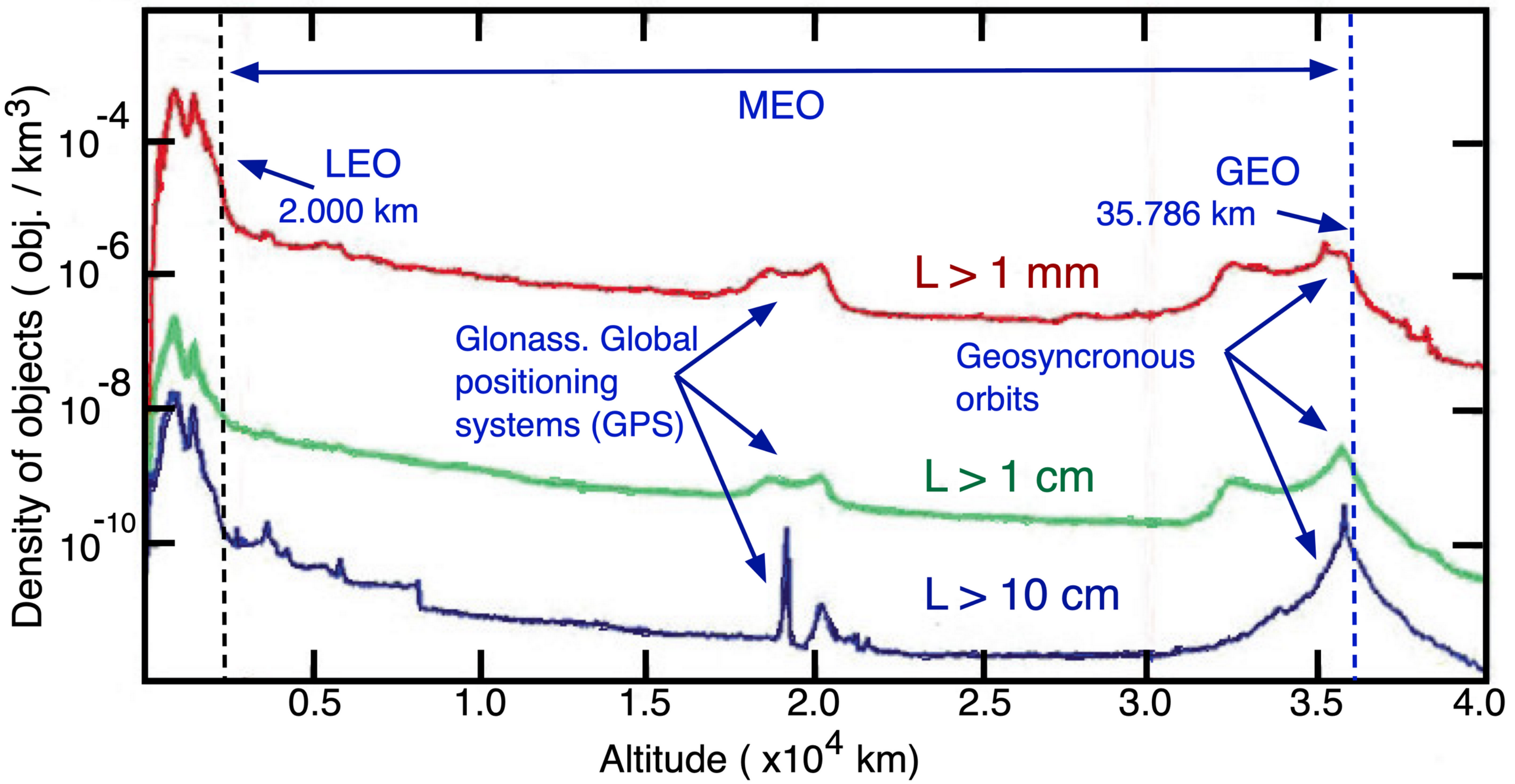
- Figures shows the increment of cataloged objects in orbit from different origins (left) and the steady increment in the mass according to the obits (right).
- Figures from ESA: https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025



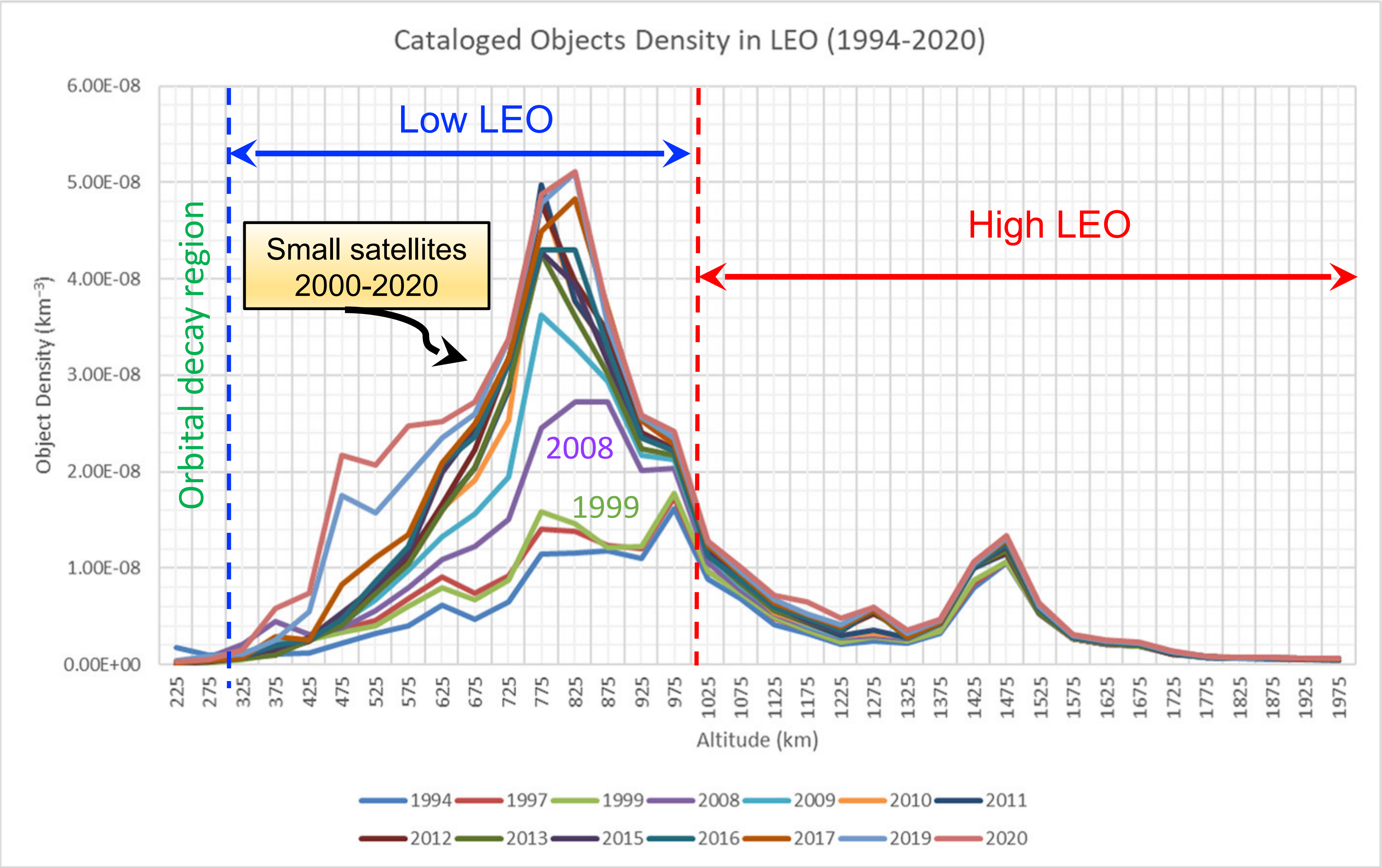


Type	Description
PL	Payload
PF	Payload Fragmentation Debris
PD	Payload Debris
PM	Payload Mission Related Object
RB	Rocket Body
RF	Rocket Fragmentation Debris
RD	Rocket Debris
RM	Rocket Mission Related Object
UI	Unidentified

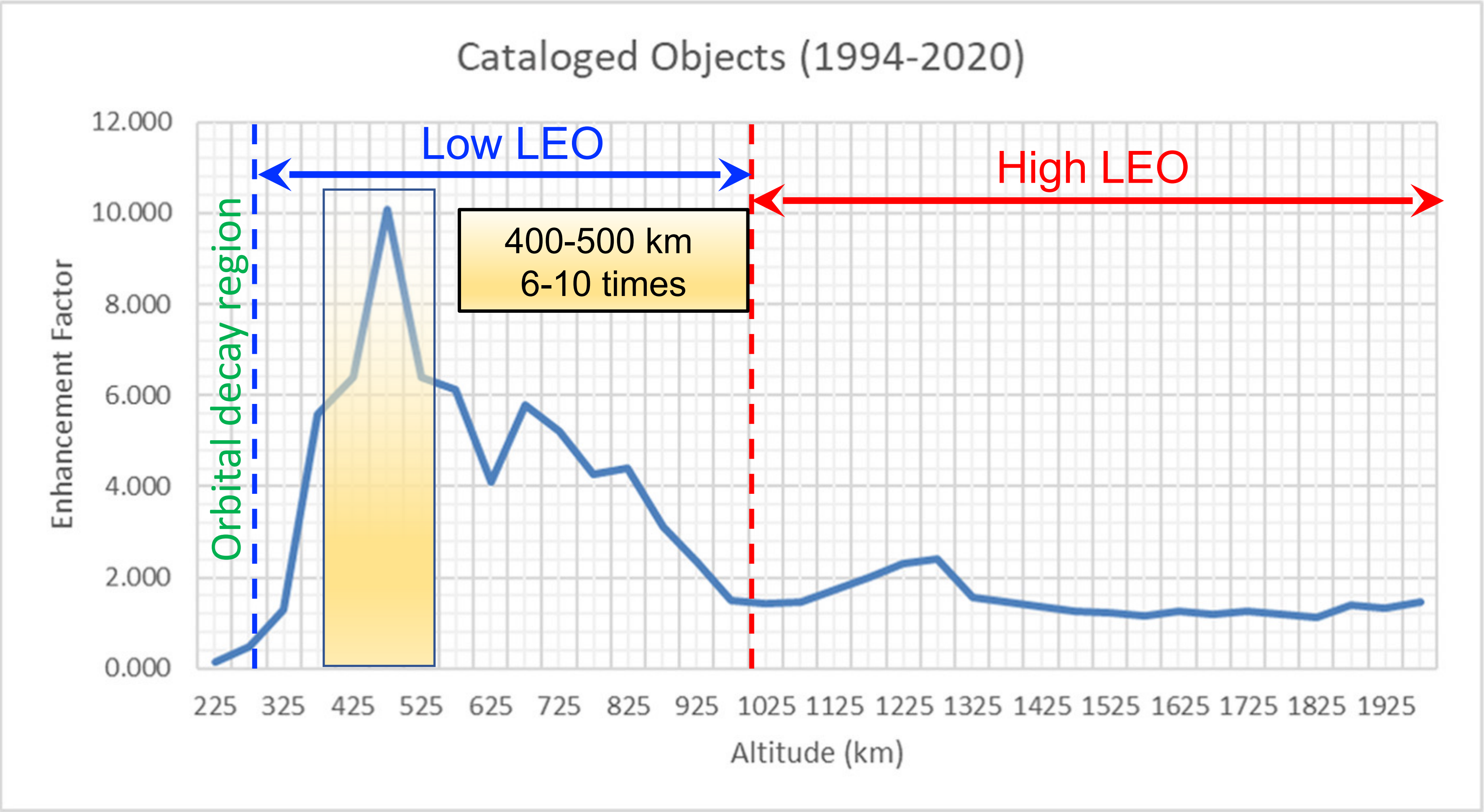
Orbit	Description	Orbit	Description
GEO	Geostationary Orbit	LEO	Low Earth Orbit
IGO	Inclined Geosynchronous Orbit	HAO	High Altitude Earth Orbit
EGO	Extended Geostationary Orbit	MGO	MEO-GEO Crossing Orbits
NSO	Navigation Satellites Orbit	HEO	Highly Eccentric Earth Orbit
GTO	GEO Transfer Orbit	LMO	LEO-MEO Crossing Orbits
MEO	Medium Earth Orbit	UFO	Undefined Orbit
GHO	GEO-superGEO Crossing Orbits	ESO	Escape Orbits



Original figure from: A. Rossi. *Population models of space debris*.
Proceedings of Dynamics of Planetary Systems. IAU Colloquium **127** (2005).



Evolution of densities of cataloged objects averaged over 50 km altitude boxes from the mean equatorial Earth's radius. From C. Pardini and L. Anselmo. *Evaluating the impact of space activities in LEO*. Acta Astronautica **184**, pp. 11-22, (2021).



Increment rate of cataloged objects averaged over 50 km altitude boxes from the mean equatorial Earth's radius. From C. Pardini and L. Anselmo. *Evaluating the impact of space activities in LEO*. Acta Astronautica **184**, pp. 11-22, (2021).

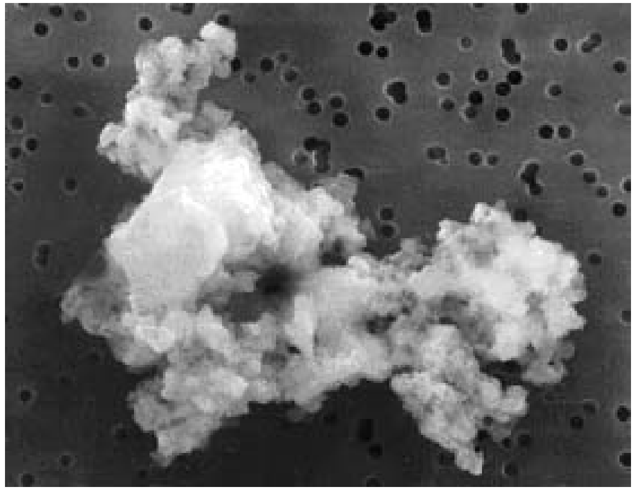
Micrometeoroids

Previous concepts:

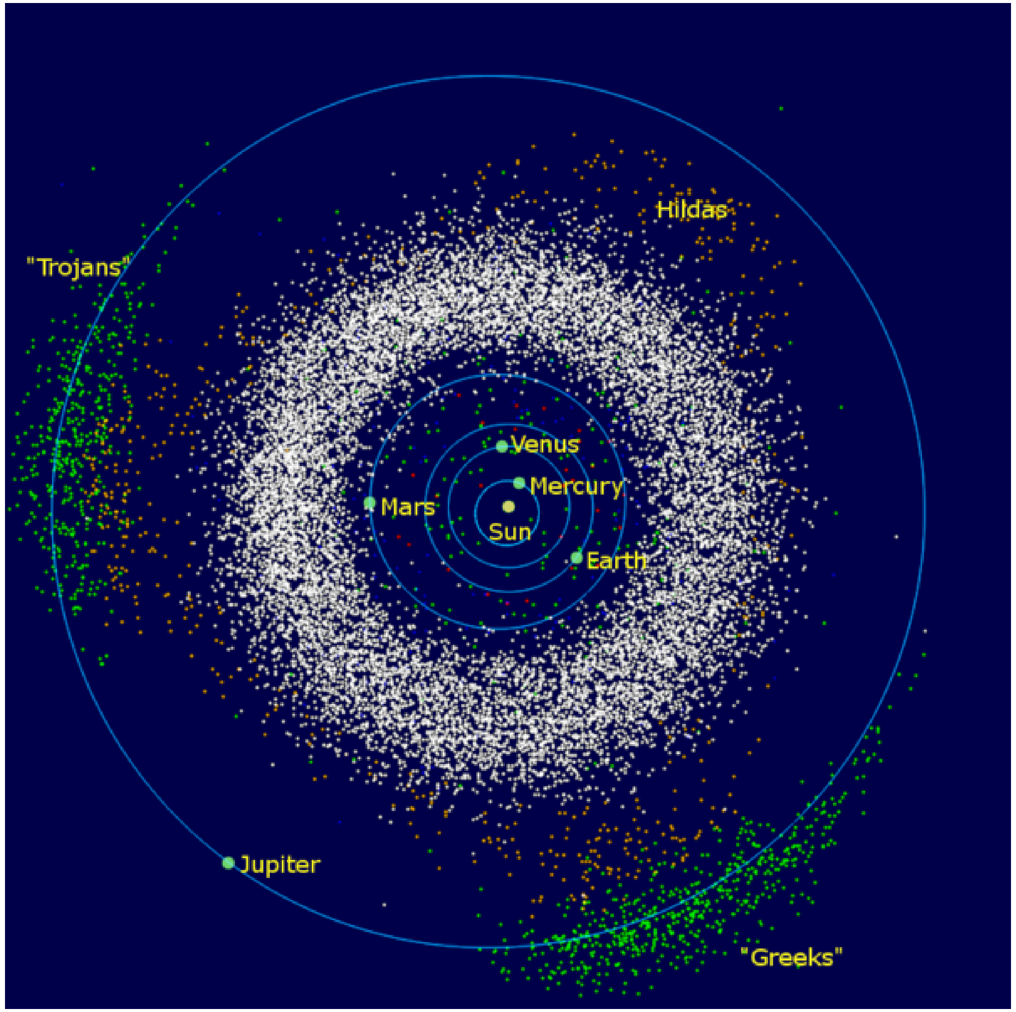
- Zodiacal light: Diffuse glow caused by the scatter of light by interplanetary dust.
- Interplanetary dust cloud (zodiacal cloud): Submillimetre sized dust particles extended along the ecliptic plane of the Solar System reaching the orbit of Jupiter. Their orbital evolution is controlled by gravity and the radiation pressure.
- Interplanetary dust particles (IDP) are collected at the stratosphere weighting $10^{-12} - 10^{-2}$ gr with have $L < 10\ \mu m$ sizes (long duration exposure facility)
- Micrometeoroids: Macroscopic sized particles of less than few millimeters in size moving in the interplanetary space of the solar system. Those collected at the Earth's surface after survive the atmosphere impact (sized $10\ \mu m - 2\ mm$ are called *micrometeorites*.

Zodiacal light, source Wikipedia.

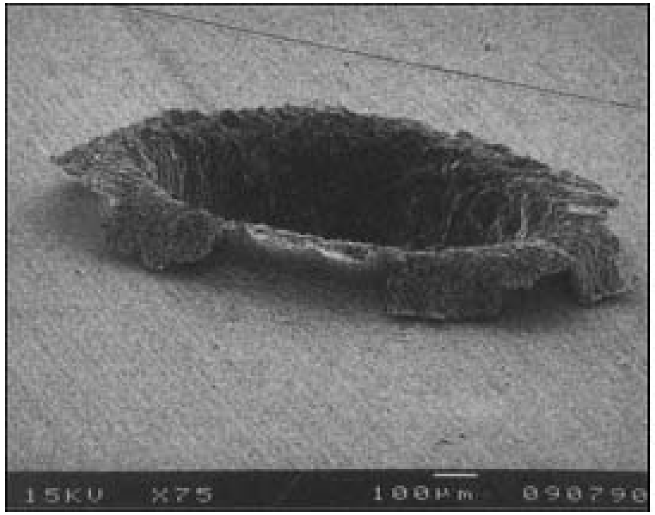
Micrometeoroid impact on window #7 of ISS Zvezda service module, source NASA.

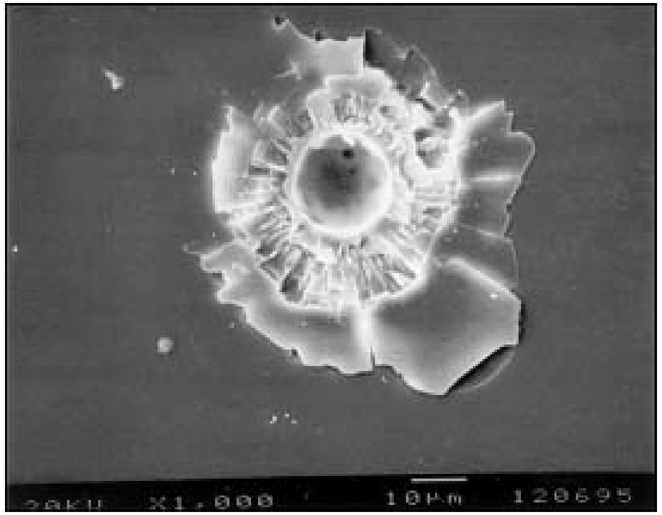


Meteoric particle collected at the earth's atmosphere of $100\ x\ 40\ \mu m$ of size, source ESA.



- Typical sizes of meteoroids are between 0.01 cm ($100\ \mu m$)
- Velocities of micrometeoroids are $v \sim 20\ km/s$
- Can be modelled (Grün, Devine) using a combination satellite data and observations.
- ESA Web site for micrometeoroid & space debris: https://space-env.esa.int/madweb/index.php





Impacts in on a ductile aluminum plate (left) and a fragile material (right). Source ESA, cited hyperlink.

F. Grün, H.A. Zook, H. Fechtig and R.H. Giese. *Collisional balance of the meteoric complex*. Icarus **62**, 244-272 (1985)

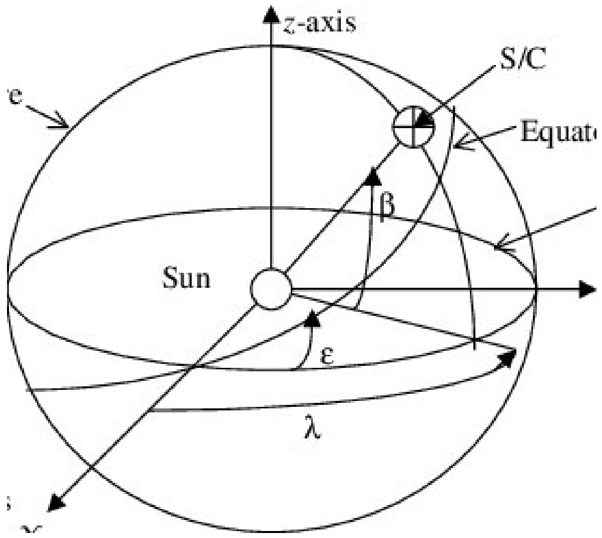
N. Divine. *Five populations of interplanetary meteoroids*. J. Geophys. Res. **98** (9) 17,029-17,048 (1993).

- Different approaches for:
  - Single particle dynamics: Tracking individual particles $[\boldsymbol{r}(t), \boldsymbol{v}(t)]$ can be practical for asteroids and/or large space fragments.
  - Organized streams: Such as meteor streams or new fragments, later randomized at the original orbital inclination around the original orbit.
  - Background environment: Statistical models for sporadic meteors, zodiacal and interplanetary dust, etc.

- For the micrometeoroids in the Earth's orbit in heliocentric coordinate we can write,

$$dN = [h_m \, dm] \times [g(\boldsymbol{r}, \boldsymbol{v}) \, d^3r \, d^3v]$$

where dN is the number of particles with,



- Mass between $(m, m + dm)$ given by $h_m dm$ and independent of time.
- Position and velocities within (d^3r, d^3v) located at point $(\boldsymbol{r}, \boldsymbol{v})$ of phase space.
- Stationary density $g(\boldsymbol{r}, \boldsymbol{v})$ of points in the phase space independent of (m, t) and tis probability is a function of the constant of motion and can be approximated by,

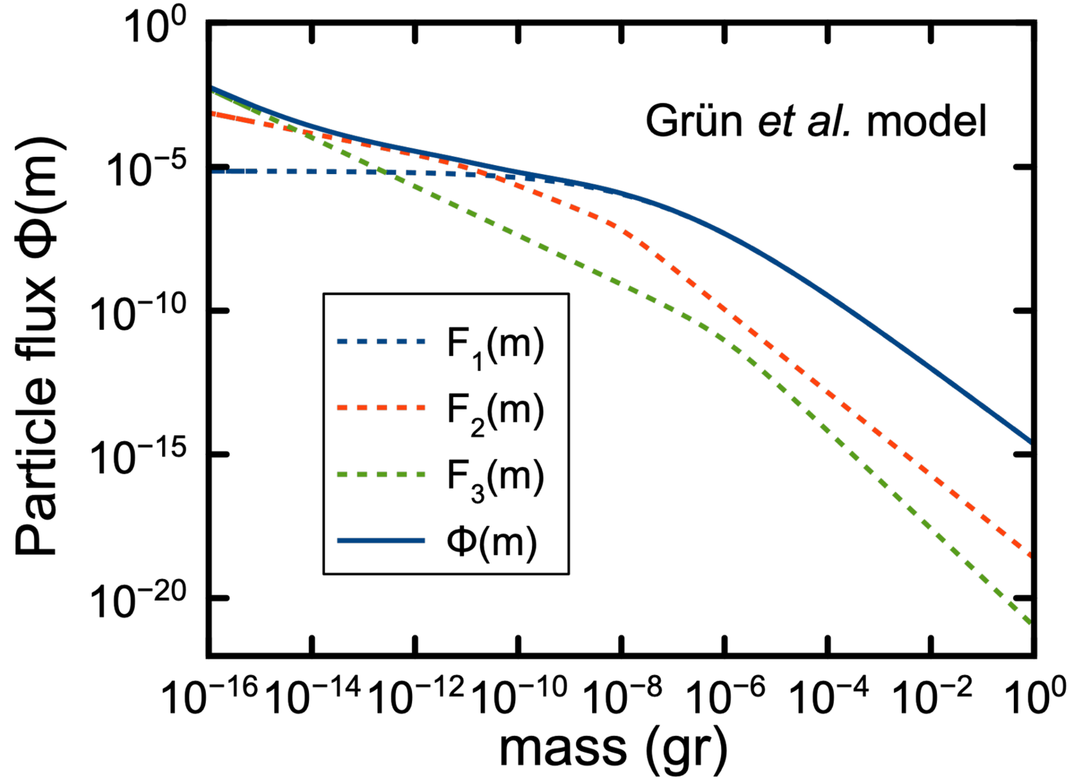
$$g(r_1, e, i) = \frac{1}{2\pi\, e} \left(\frac{r_1}{GM_o} \right)^{3/2} N_1(r_1) \, p_i(i) \, p_e(e)$$

where e is the eccentricity, i the inclination and r_1 the perihelium distance and (p_e, p_i, N_1) functions.

- Models assume a form for $g(r_1, e, i)$ and the cumulative mass distribution,

$$H_M = \int_m^{\infty} h_m \, dm$$

Micrometeoroids in the inner solar system



$$\Phi(m) = [F_1(m) + F_2(m) + F_3(m)]$$

$$\rho_m\ (\text{gr cm}^{-3}) = \begin{cases} 2.0 & \text{m} < 10^{-6}\text{gr.} \\ 1.0 & 10^{-6} \le \text{m} \le 10^{-2}\ \text{gr.} \\ 0.5 & \text{m} > 10^{-2}\text{gr.} \end{cases}$$

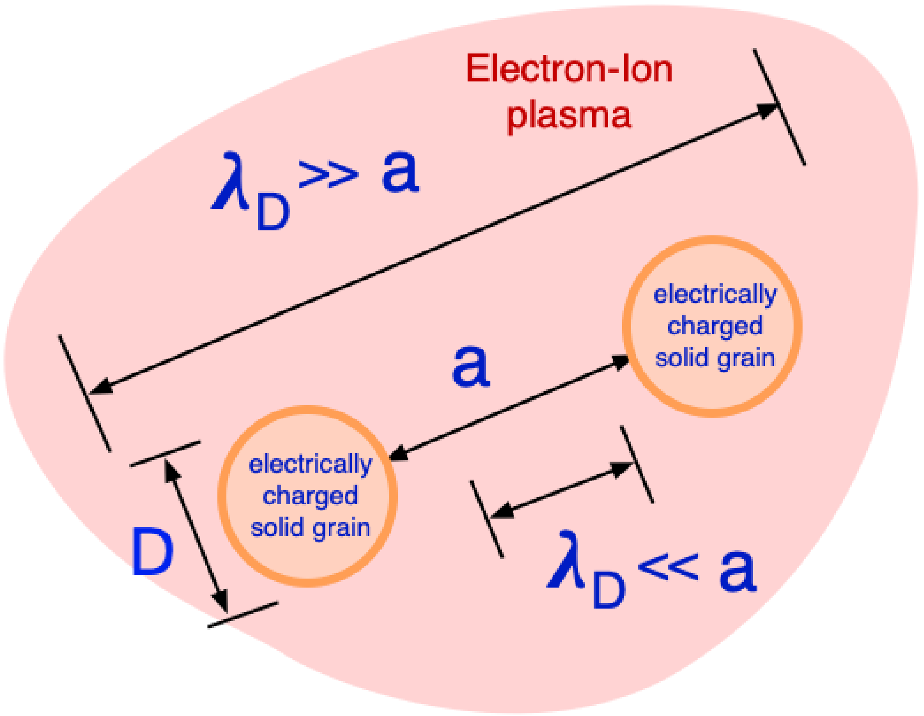
- Grün *et al.* interplanetary dust model(*)
  - The flux $\Phi(m)$ represents the total number of particles with mass greater than m grams impacting the unit area from a single hemisphere (2π rads.) per second.
  - Valid at $1\ \text{AU}$ (approximately the orbit of the Earth).

The model considers three different solid particle groups

$$\begin{cases} F_1(m) = (15.0 + 2.2 \cdot 10^3\ m^{0.306})^{-4.38} & \text{m} > 10^{-9}\text{gr.} \\ F_2(m) = 1.3 \cdot 10^{-9}\ (m + 10^{11}{\times}m^2 + 10^{27}{\times}m^4)^{-0.36} & 10^{-14} \le \text{m} \le 10^{-9}\ \text{gr} \\ F_3(m) = 1.3 \cdot 10^{-16}(m + 10^6{\times}m^2)^{-0.85} & m < 10^{-14}\text{gr.} \end{cases}$$

Dusty plasmas in the Solar System

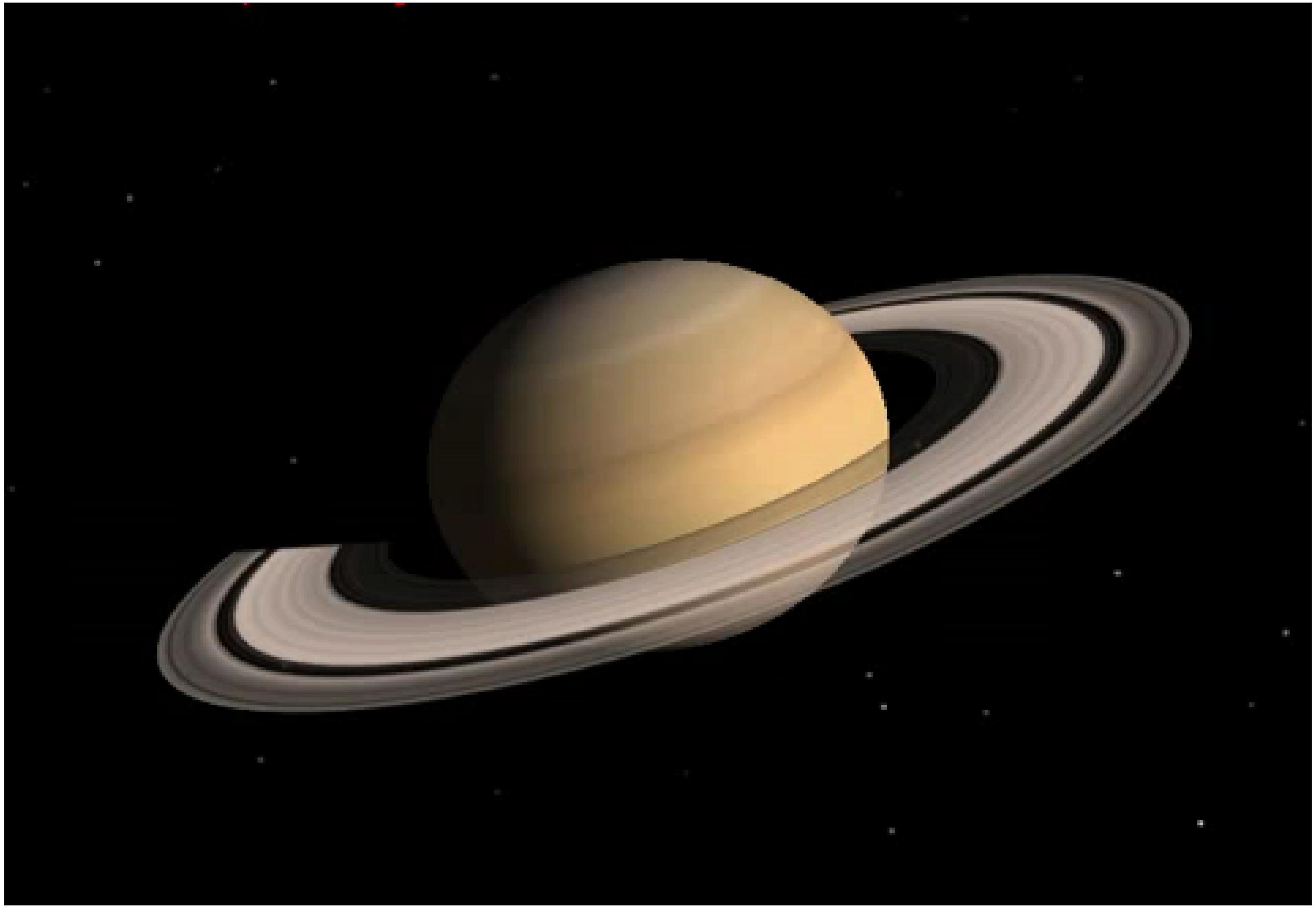
- $r_d \ll \lambda_D < a$: Dust grains are very separated from each other, constituting a collection of isolated bodies, immersed in the plasma and electrically shielded. They are independent particles interacting with the plasma that surrounds them.
- $r_d \ll a < \lambda_D$: Since the Debye length is the dominant longitude, the electrically charged dust particles participate in the collective plasma response and strictly speaking constitute a plasma of dust grains, electrons and ions, we call this system *dusty plasma*.



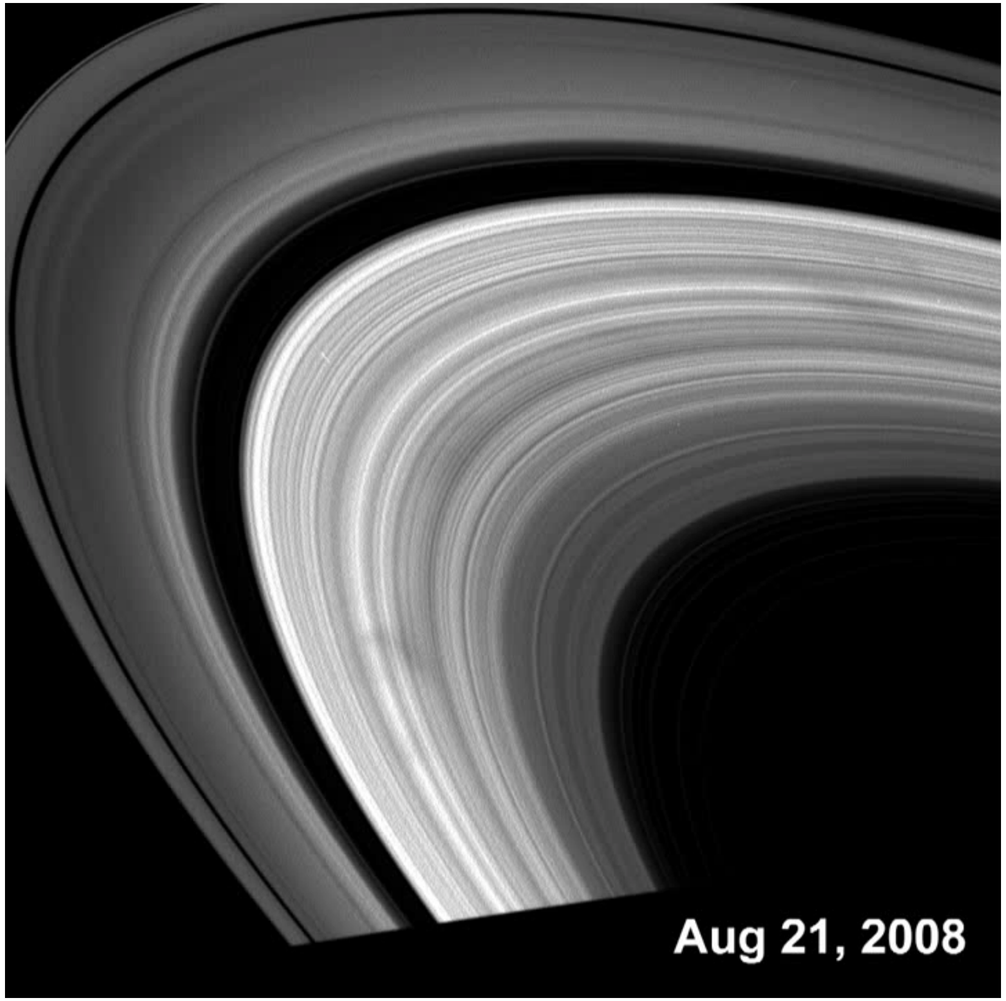
Property	Classical plasma	Dusty plasma
Electric charges	$-e,\ q_i = Z_i e$	$-e,\ q_i = Z_i e,\ q_d = Z_d\, e$
Quasineutrality	$Zn_i - n_e = 0$	$Z_i n_i - n_e \pm Z_d n_d = 0$
Particle masses	$m_e \ll m_i$	$m_e \ll m_i \ll m_d$
Frequencies	$\omega_{pi} \ll \omega_{pe}$	$\omega_d \ll \omega_{pi} \ll \omega_{pe}$

Parameters for various dusty plasmas					
	n_e (cm^{-3})	T_e (eV)	n_d (cm^{-3})	D (μm)	λ_D (cm)
Noctilucent clouds	10^3	0.01	10	0.1	$2.4\ 10^3$
Saturn F ring	10	$10 - 100$	10	1	$7.4\ 10^5 - 2.5\ 10^5$
Moon	$500 - 10^3$	$0.1 - 5$	$5\ 10^3$	$0.3 - 0.7$	$1.1\ 10^4 - 5.3\ 10^4$
Flame	10^{12}	0.2	10^{11}	$0.001 - 1$	0.33
Rocket exhaust	10^{13}	0.3	10^8	$0.5 - 1$	0.13

- R. Merlino. *Dusty plasmas: from Saturn's rings to semiconductor processing devices*. Adv. Phys. **6**, (1) 1873859-1,69 (2021).

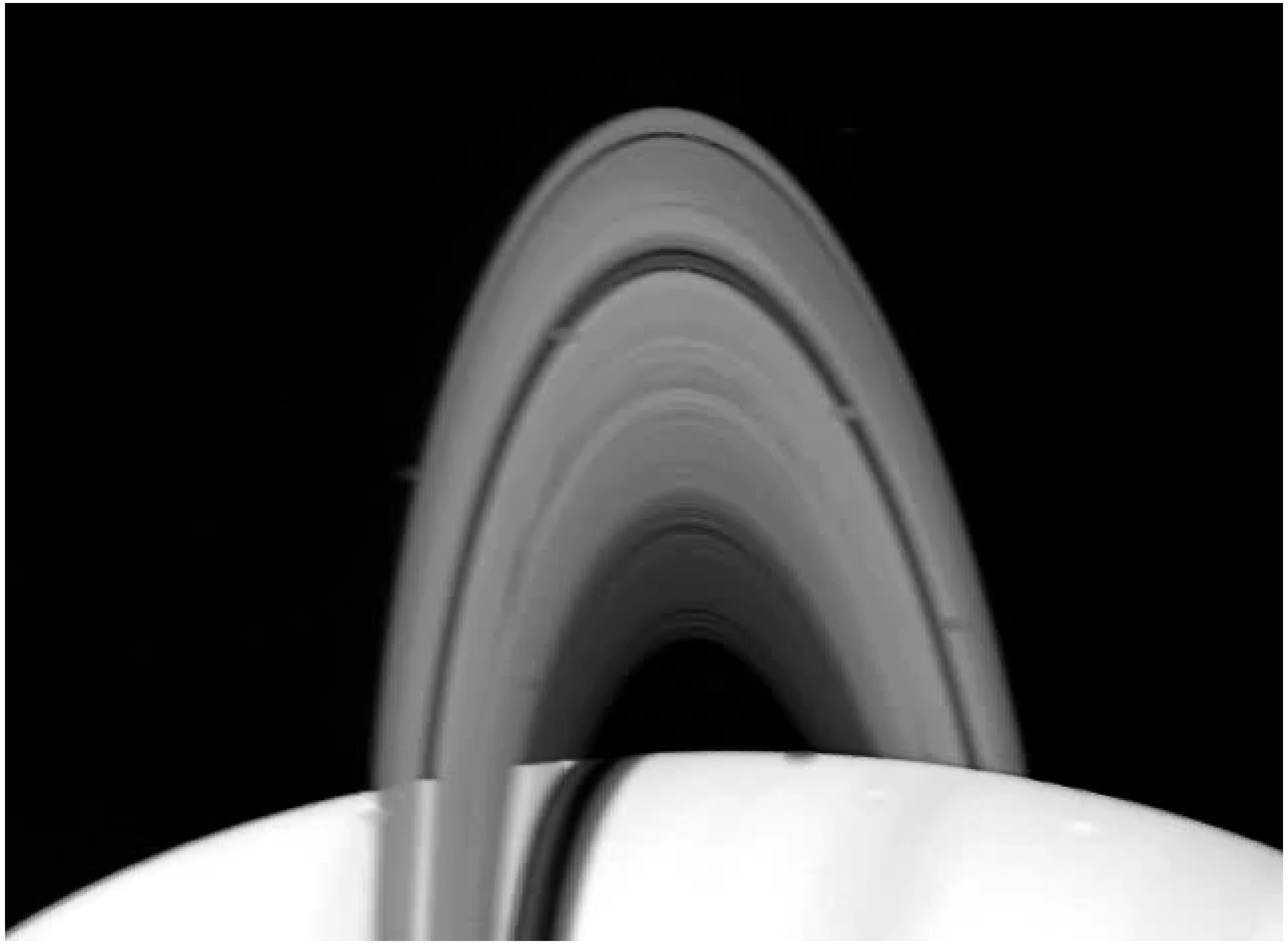


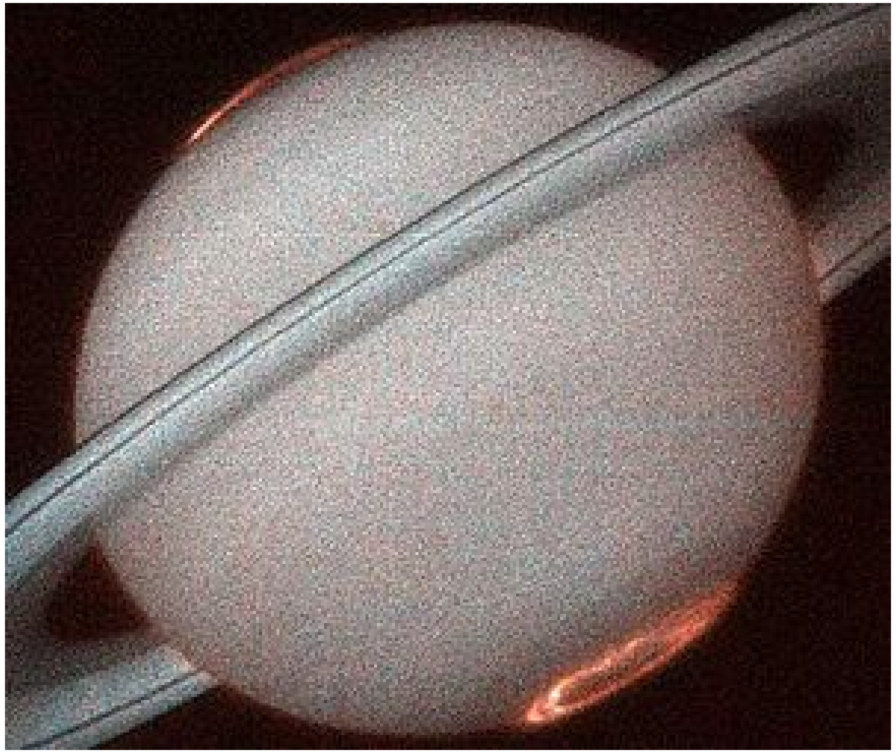
Graphic materials from Cassini-Huygens missions, source NASA/ESA
https://science.nasa.gov/mission/cassini/

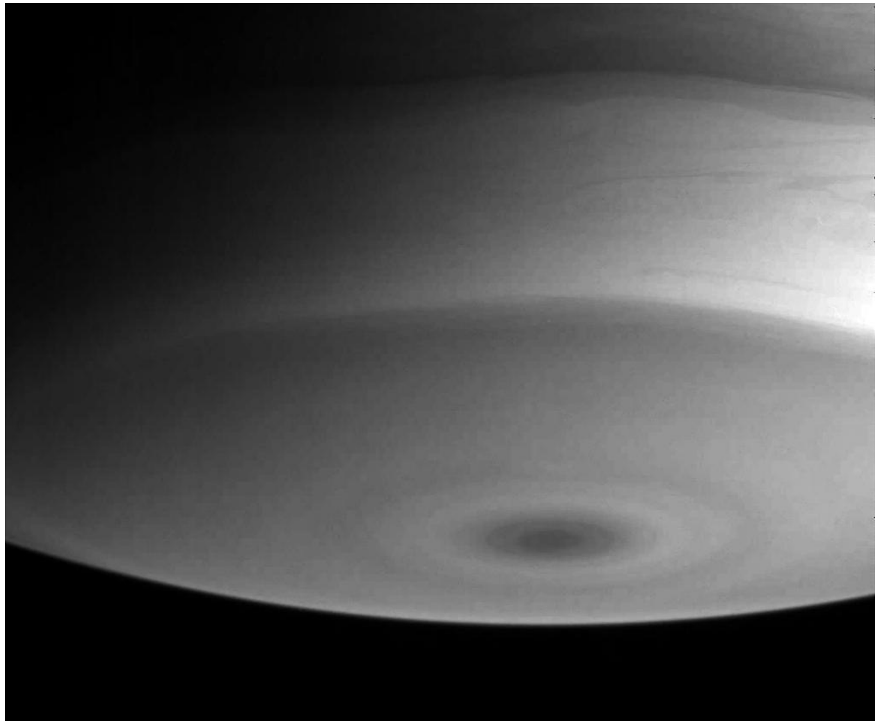


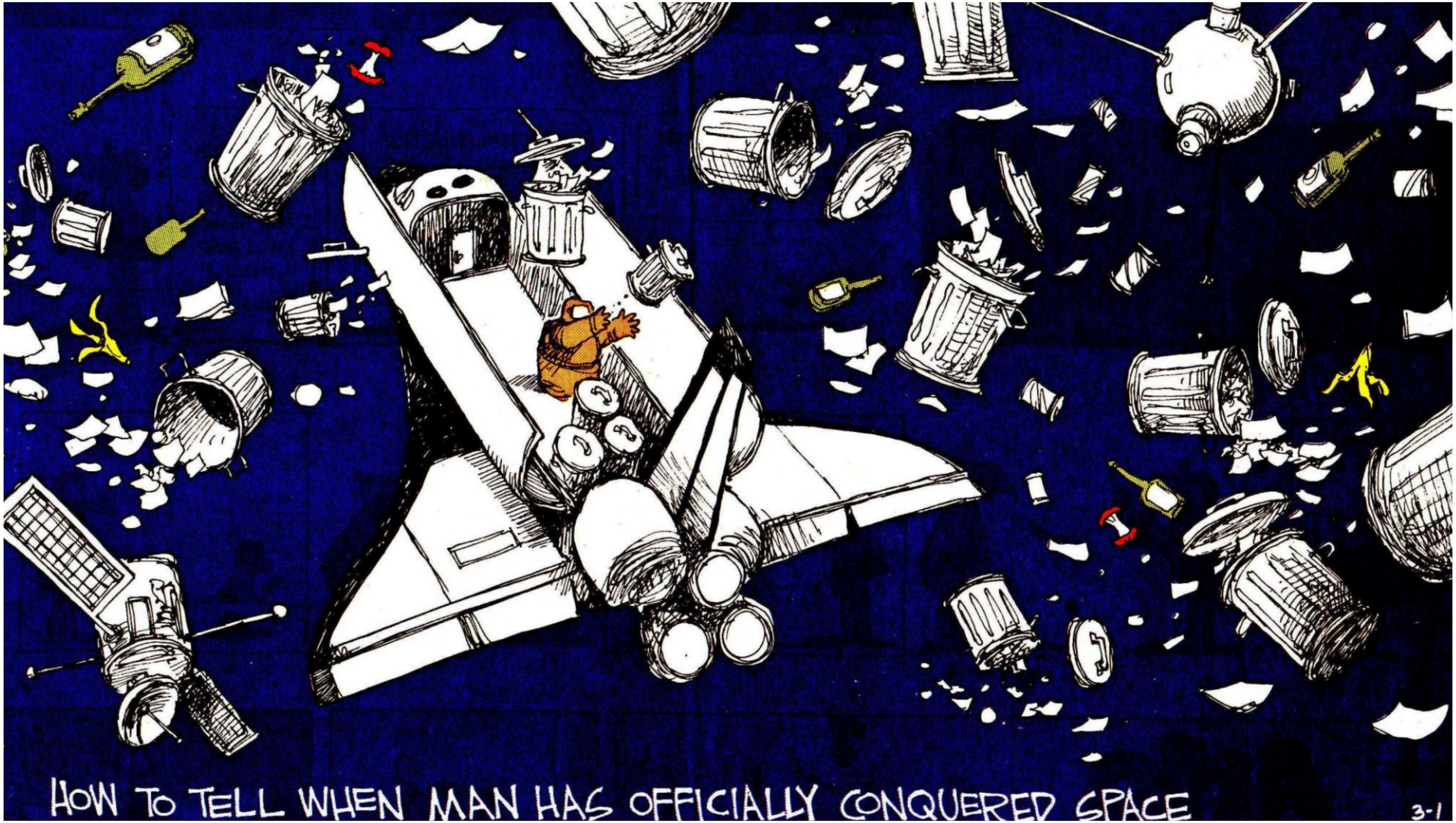
- These waves called spokes are *waves in the dusty plasma* of the Saturn rings.
- We observed the fluctuations of the dust grain density n_d that produce the dispersion of light.

- M. Horányi, T.W. Hartquist, O. Havnes, D.A. Mendis and E. Morfill. *Dusty plasma effects in Saturn´s magnetosphere*. Rev. Geophys. **42**, (4) 2004RG00151-1,20 (2004).
- J.-E-. Wahlund et al. *Detection of dusty plasma near E-ring of Saturn*. Planet. Space Sci. **57** pp. 1795-1806 (2009).








HOW TO TELL WHEN MAN HAS OFFICIALLY CONQUERED SPACE
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