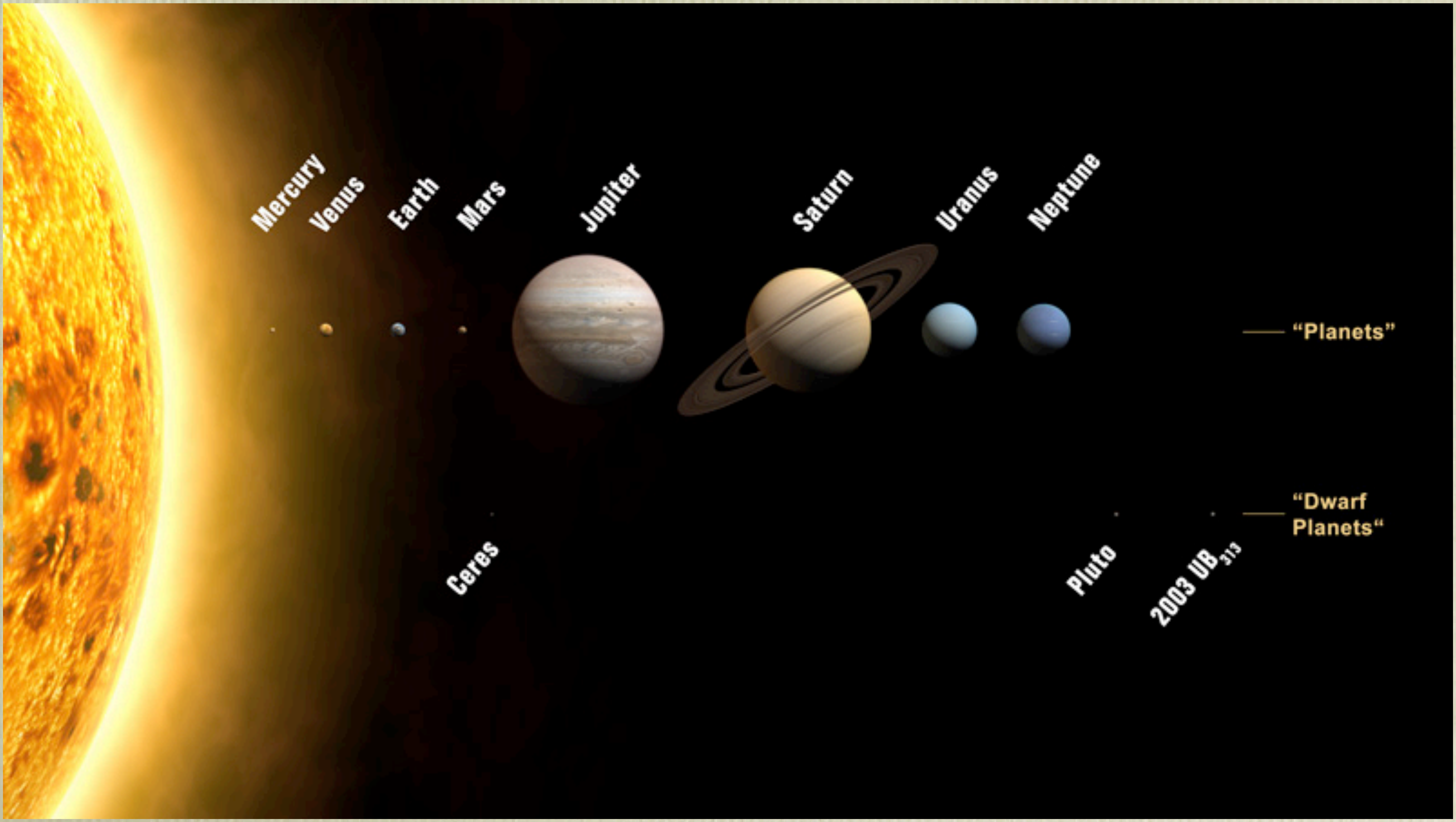
Small Bodies in the Solar System

Objects of the Solar System

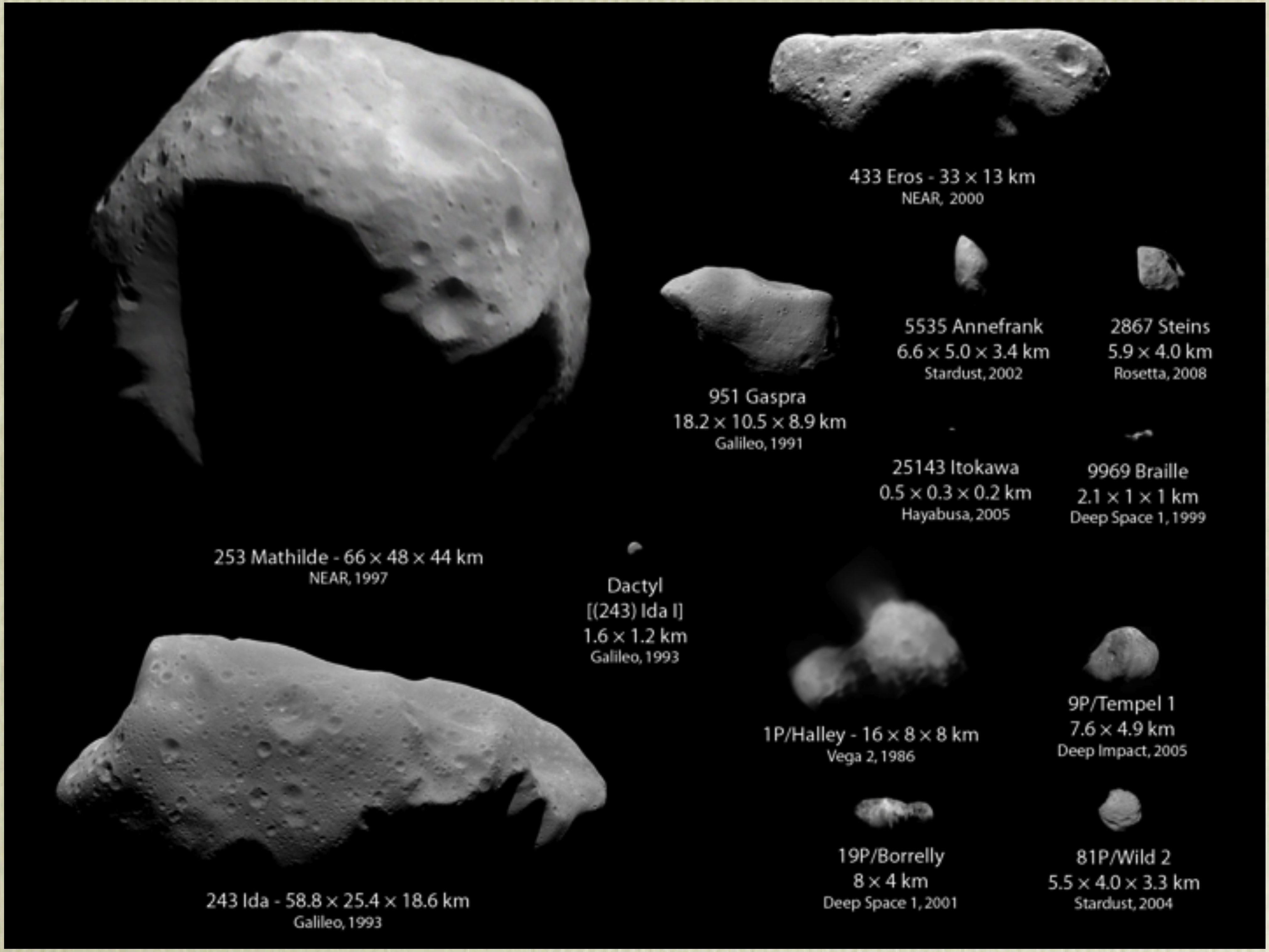


Small Bodies in the Solar System

- Comets
- Asteroids (Main Belt, NEAs)
- Trans-Neptunian Objects (Kuiper Belt, Centaurs)
- Meteorites
- Dust
- Dwarf Planets
- Moons

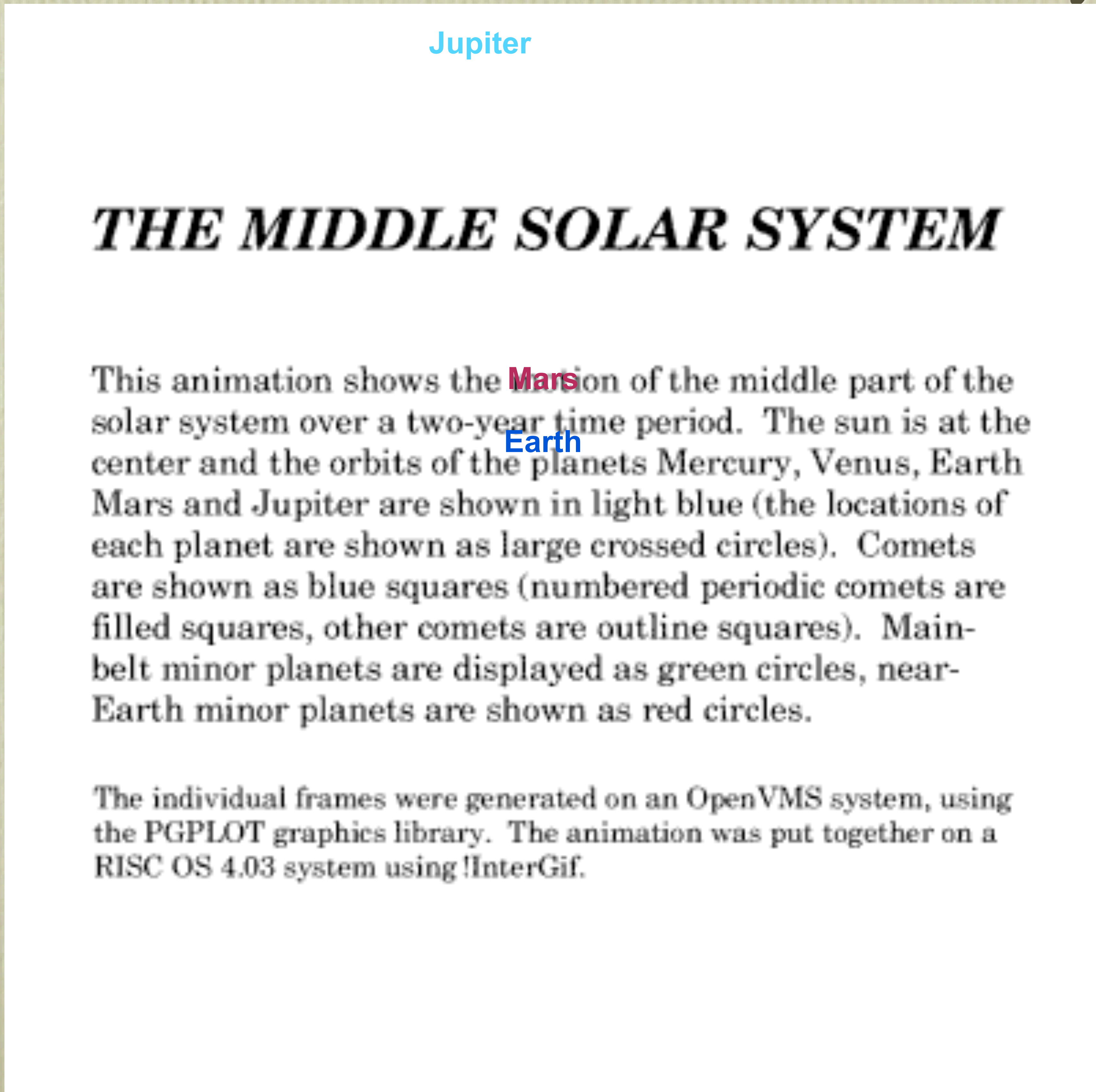
How Do Small Bodies Look Like?

Images of all asteroids and comets visited by spacecraft.



Where do we find them?

The Inner Solar System



THE MIDDLE SOLAR SYSTEM

This animation shows the motion of the middle part of the solar system over a two-year time period. The sun is at the center and the orbits of the planets Mercury, Venus, Earth Mars and Jupiter are shown in light blue (the locations of each planet are shown as large crossed circles). Comets are shown as blue squares (numbered periodic comets are filled squares, other comets are outline squares). Main-belt minor planets are displayed as green circles, near-Earth minor planets are shown as red circles.

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.

Green: Main Asteroid Belt

Red: Near-Earth Asteroids

Blue dots: Trojans

Blue squares: comets

The Outer Solar System

THE OUTER SOLAR SYSTEM

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

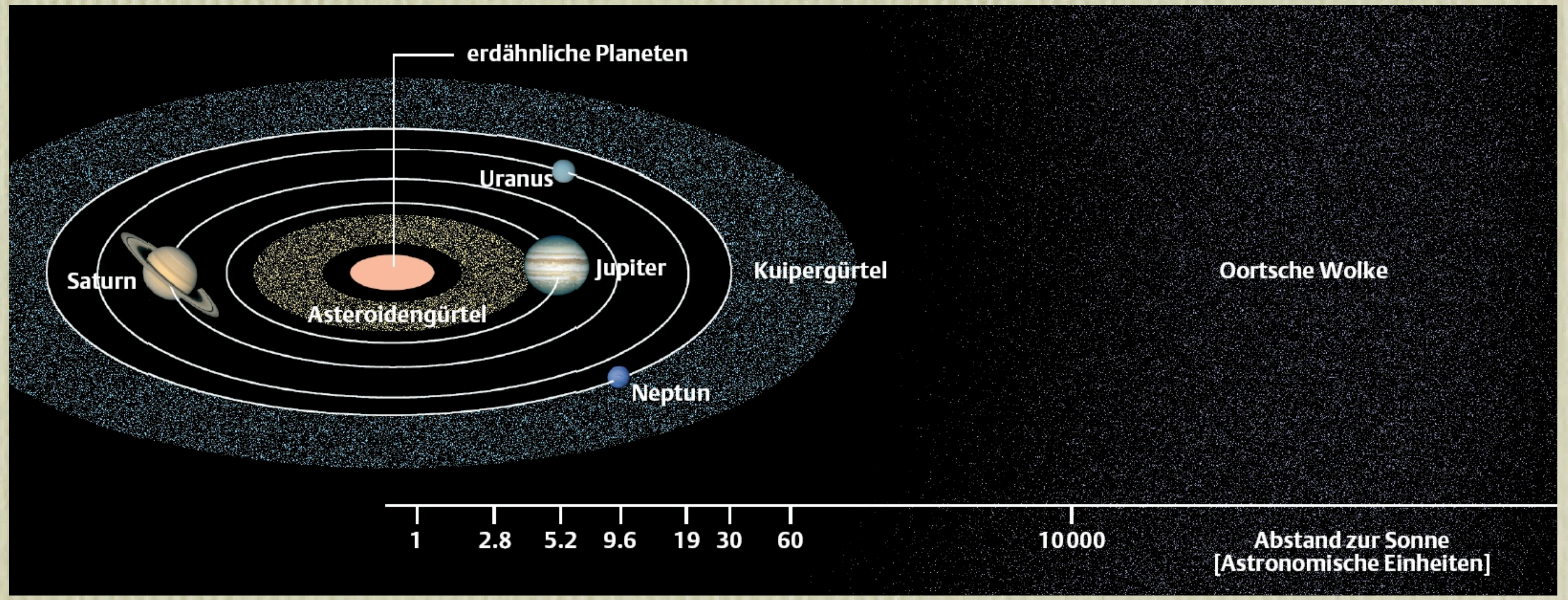
The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.

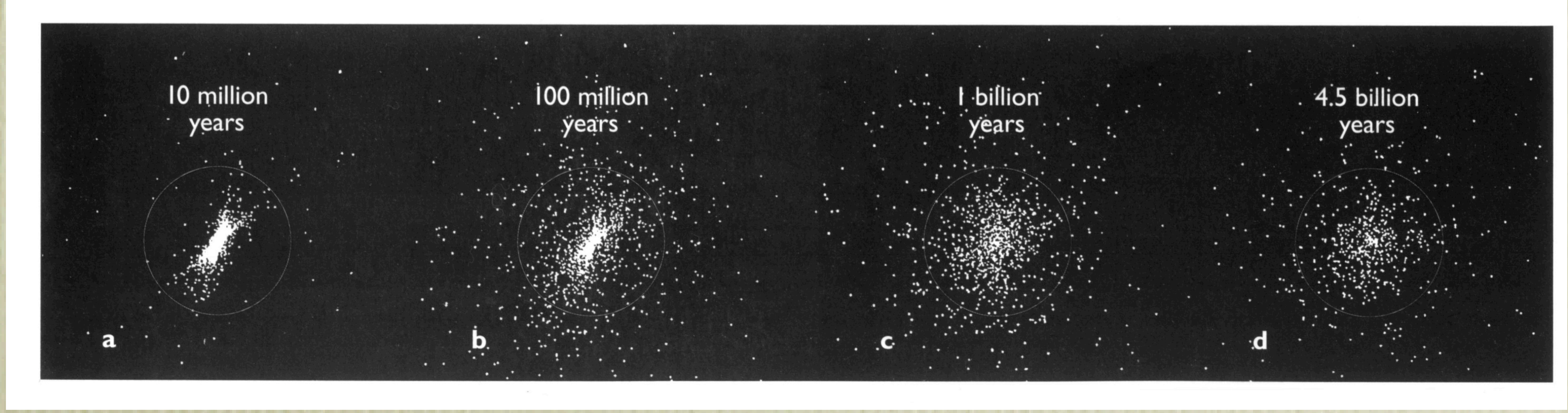
<u>Red:</u> Kuiper Belt

<u>White:</u> Plutinos (2:3 resonance with Neptune)

<u>Blue squares:</u> Comets

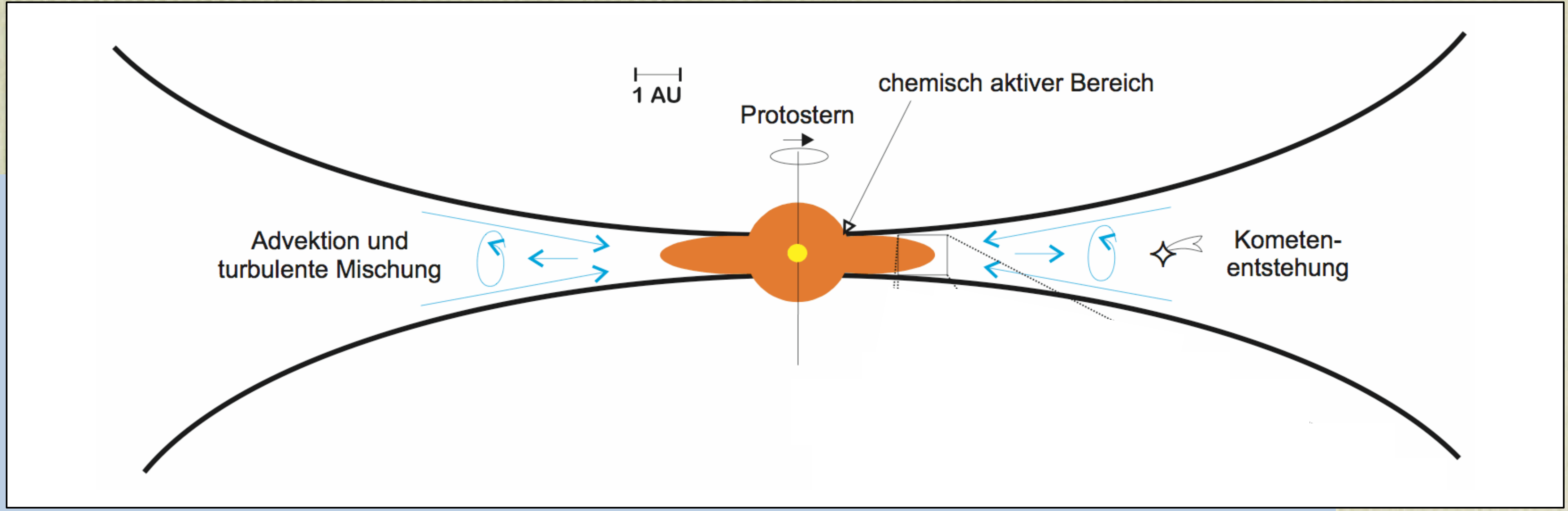
The Oort Cloud

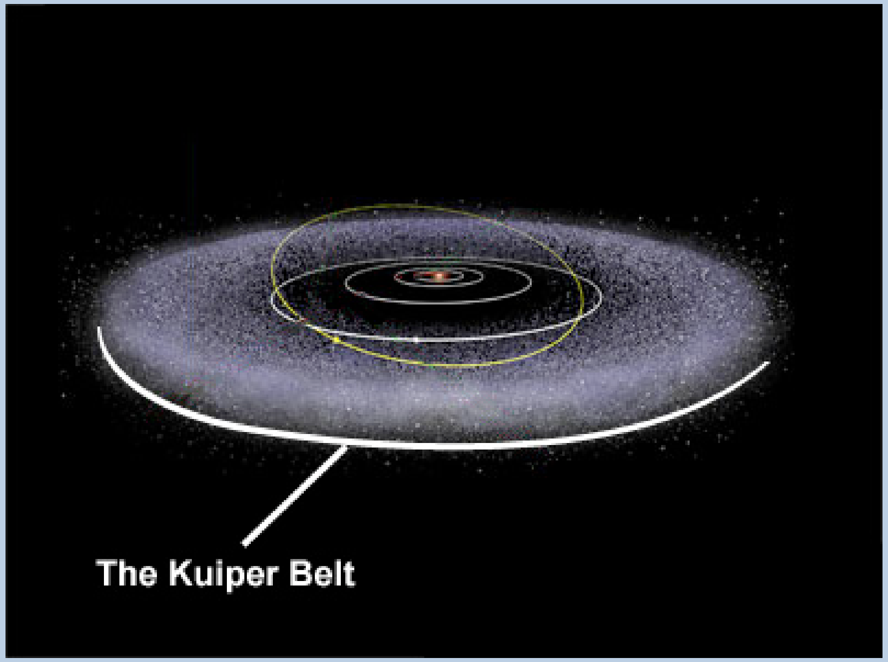


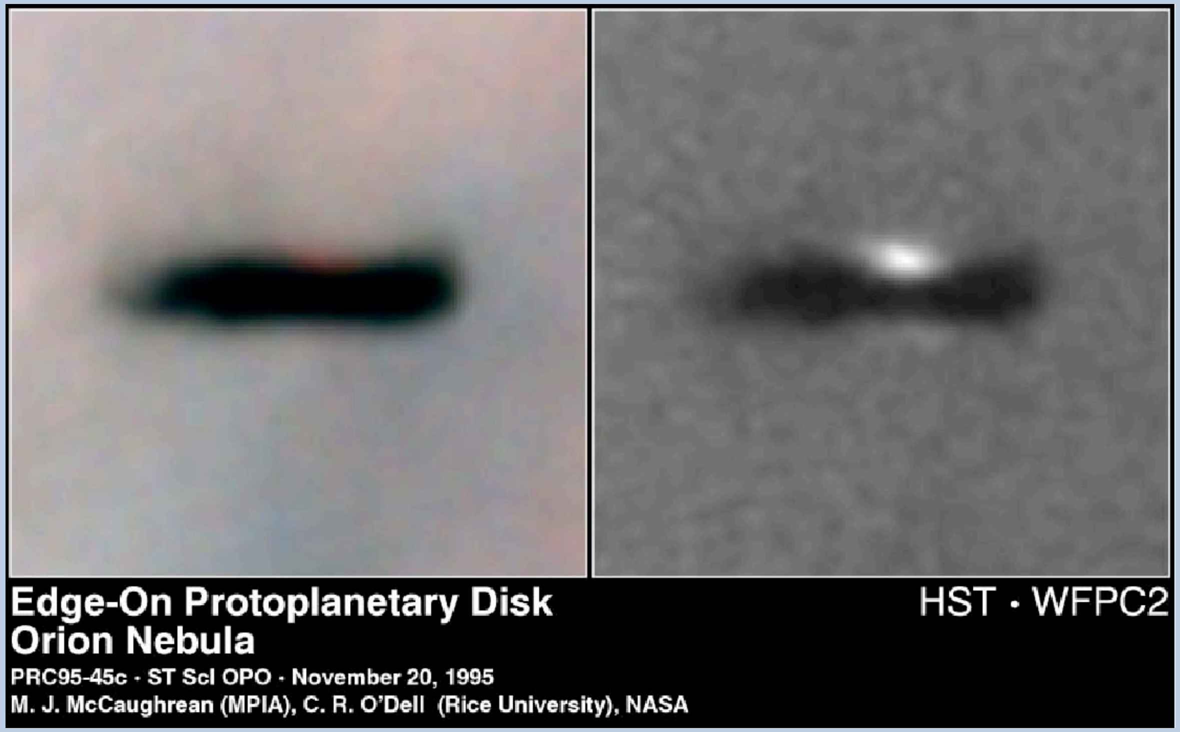


- Formed by encounters and gravitational scattering of planetesimals between Jupiter and Neptune.
- Reservoir for 'fresh' comets.
- Scattering with galactic neighbourhood leads to 'loss' into inner solar system.

The Young Solar System (very simplistic)







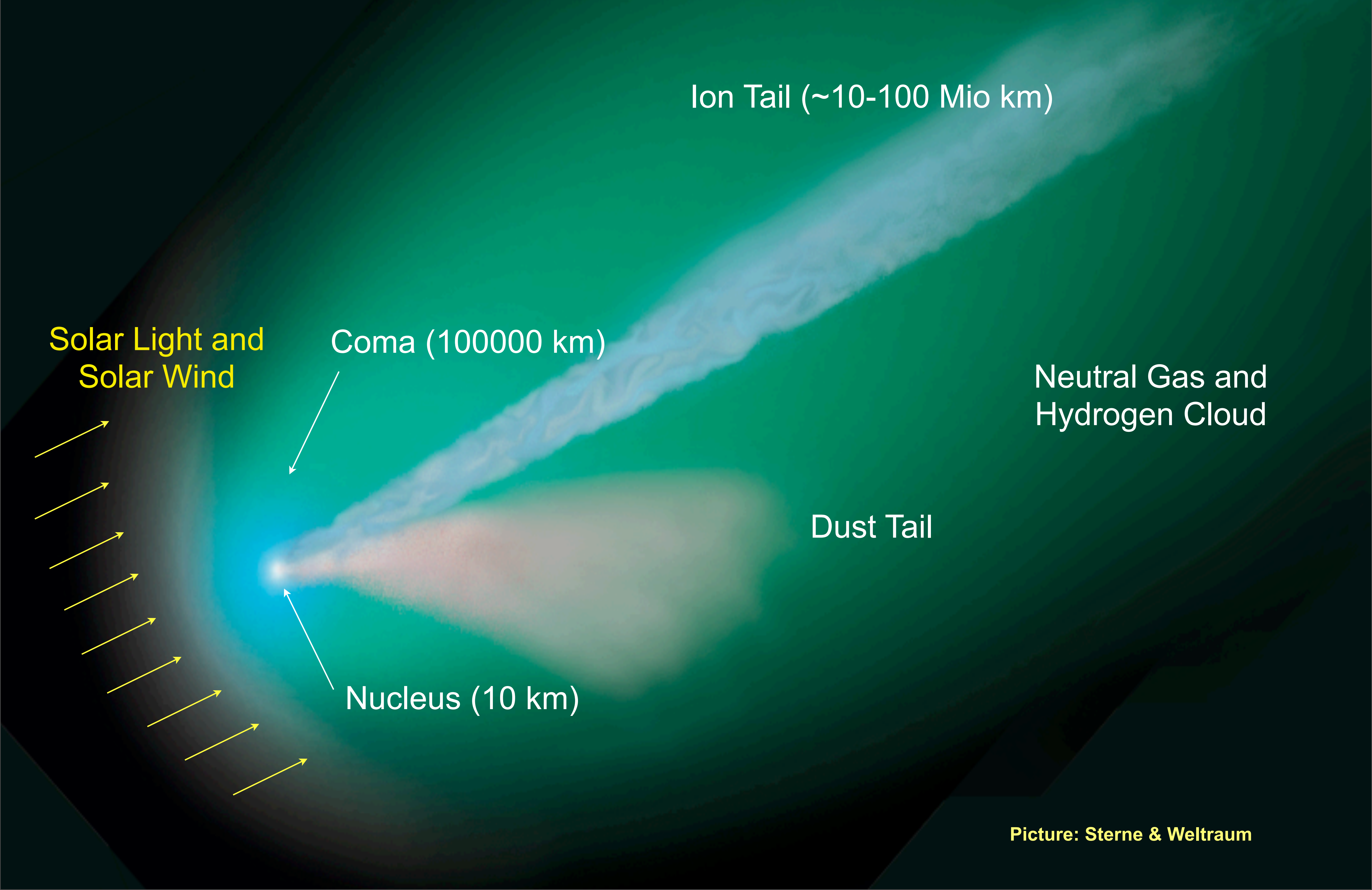
Comets were formed in the cold outer regions of the solar system.

Why Do We Study Small Bodies?

- Leftovers from the formation phase of the solar system
- Comets are most primitive objects in the solar system
- Study processes and forces which have a significant effect only on small bodies (e.g. radiation pressure)

Comets

Comets: Overview



Comets: Overview

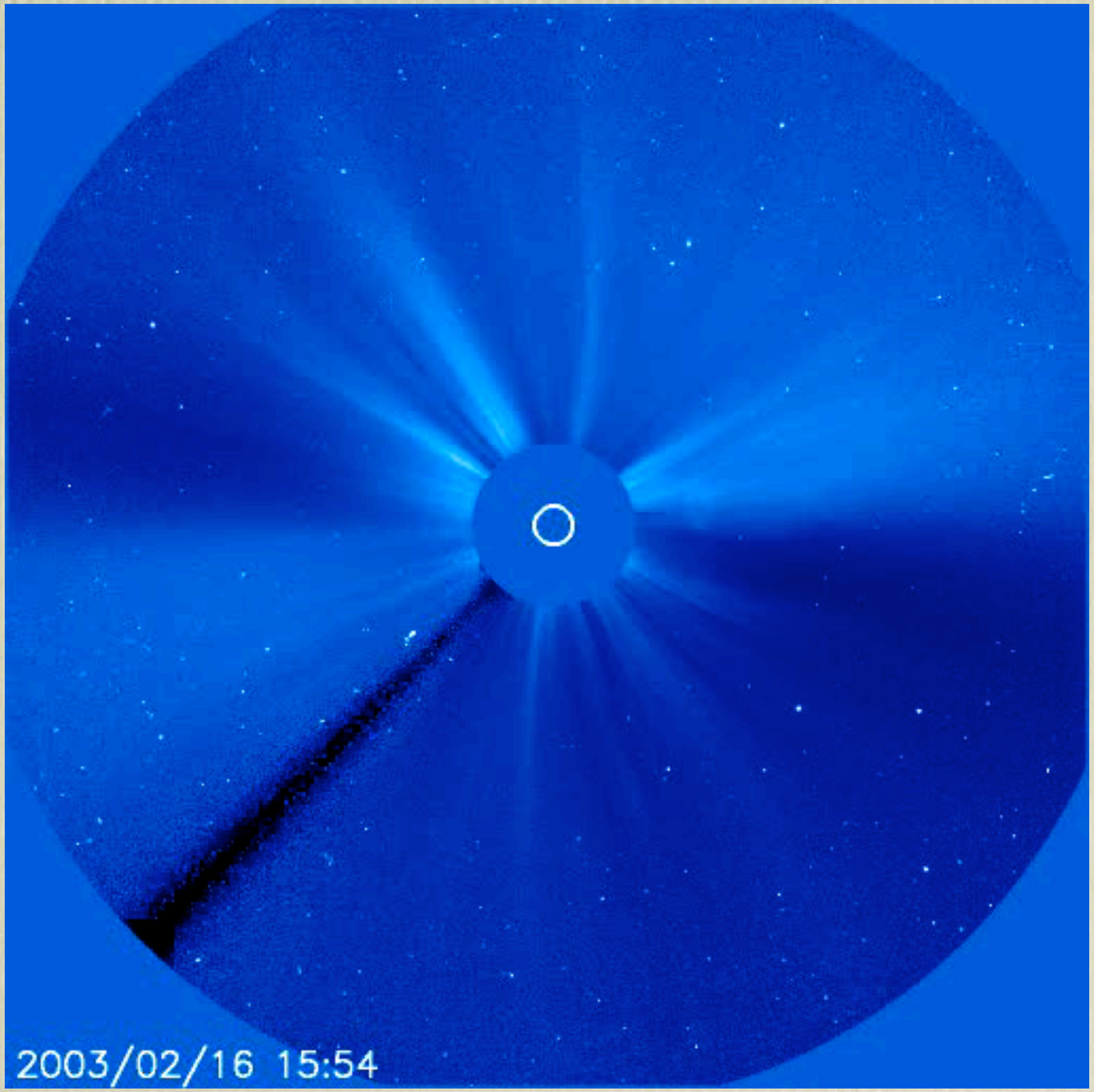
Comet Hale-Bopp

Movie: ESA/NASA/SOHO

Comet NEAT

Comets: Overview

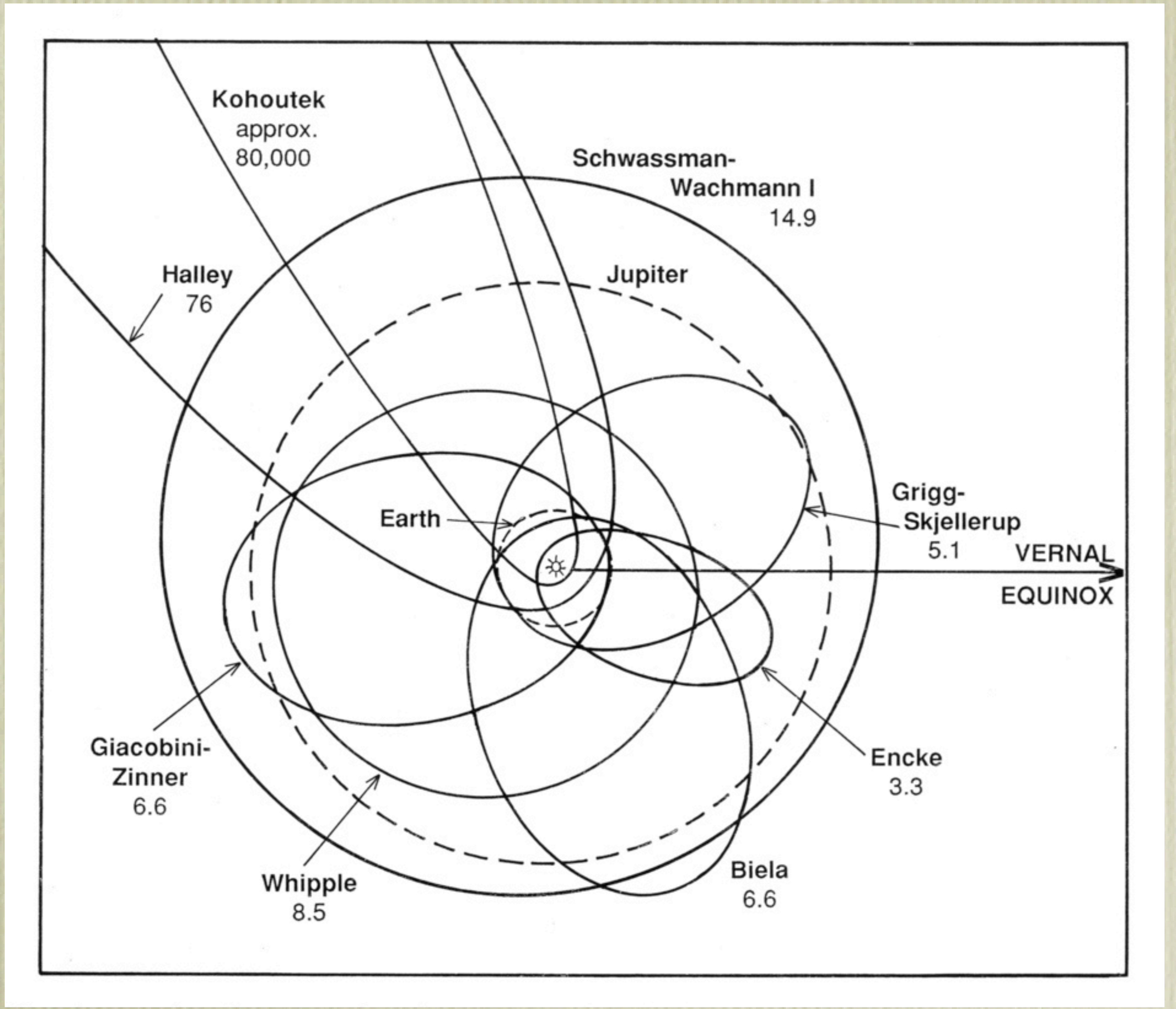
Comet Hale-Bopp



Movie: ESA/NASA/SOHO

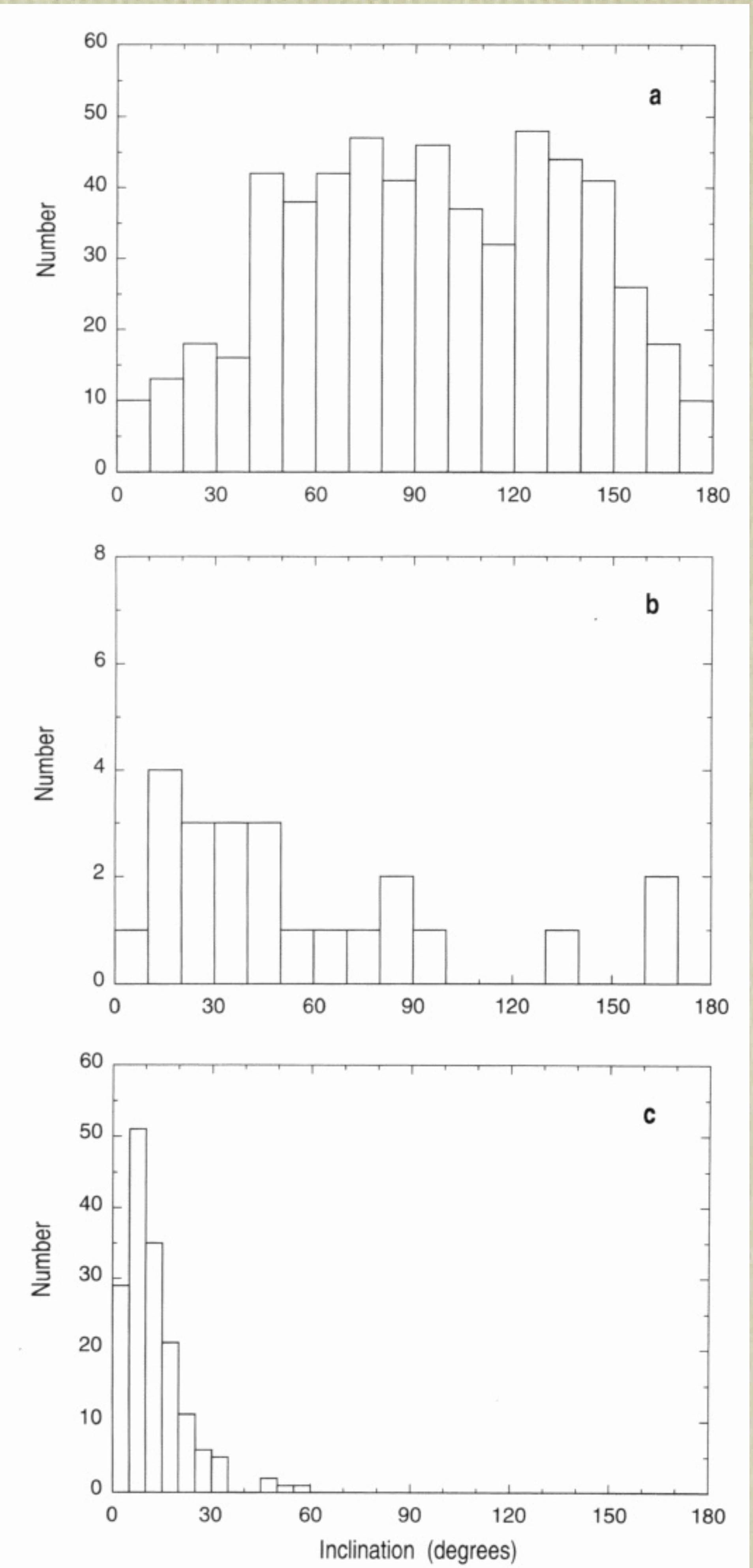
Comet NEAT

Cometary Orbits



Orbits elliptical or hyperbolic (no extreme hyperbola observed, all comets belong to the solar system).

Graphics from: L. McFadden et al., Encyclopedia of the Solar System



Cometary Orbits: Inclinations

<u>Dynamical classes:</u>

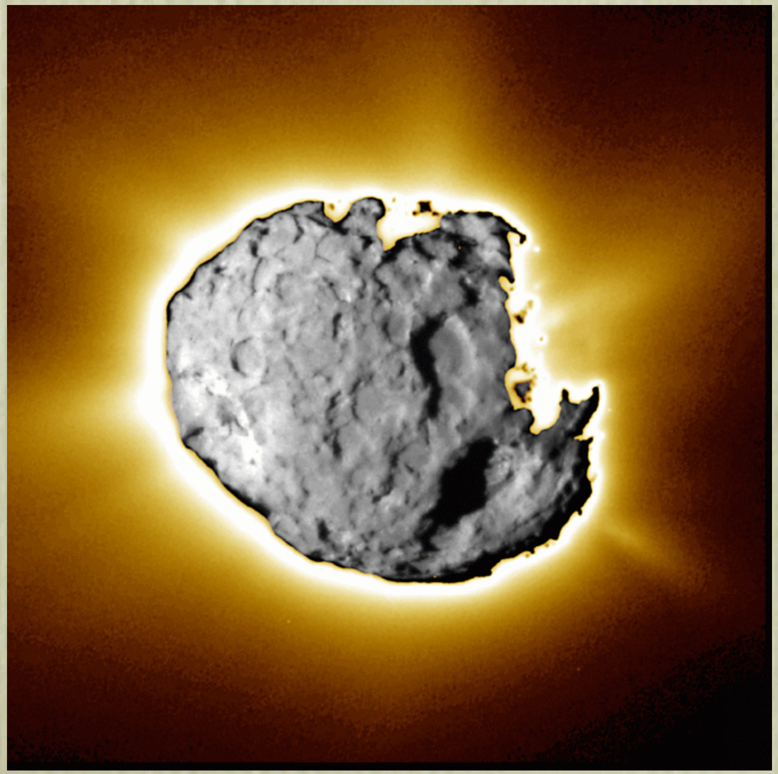
- **a**: long-period comets (P > 200 yr), isotropic distribution, large inclinations, inverse semimajor axis peaks at zero ⇒ originate from Oort cloud (fresh comets), 10^{12} objects in Oort cloud.
- **b**: intermediate period comets (20 yr < P < 200 yr)
- **c**: short-period comets (P < 20 yr), low inclinations, captured and dominated by Jupiter, 'evolved' objects, originate from Kuiper Belt.

Graphics from: L. McFadden et al., Encyclopedia of the Solar System

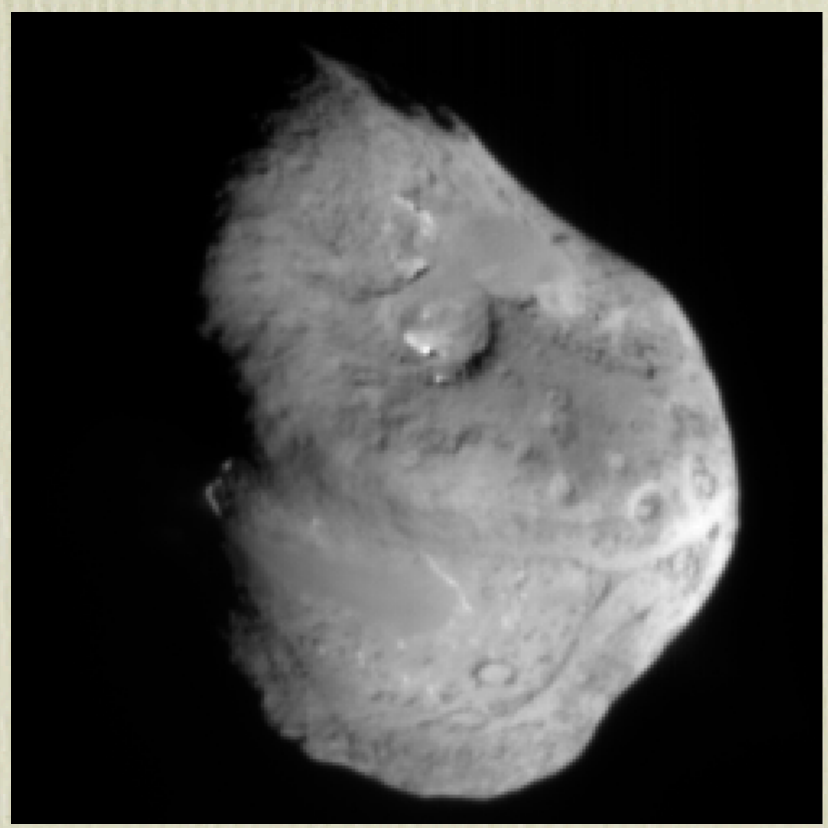
Cometary Nuclei

Halley (Giotto)

Borelli (Deep Space 1)



Wild 2 (Stardust)

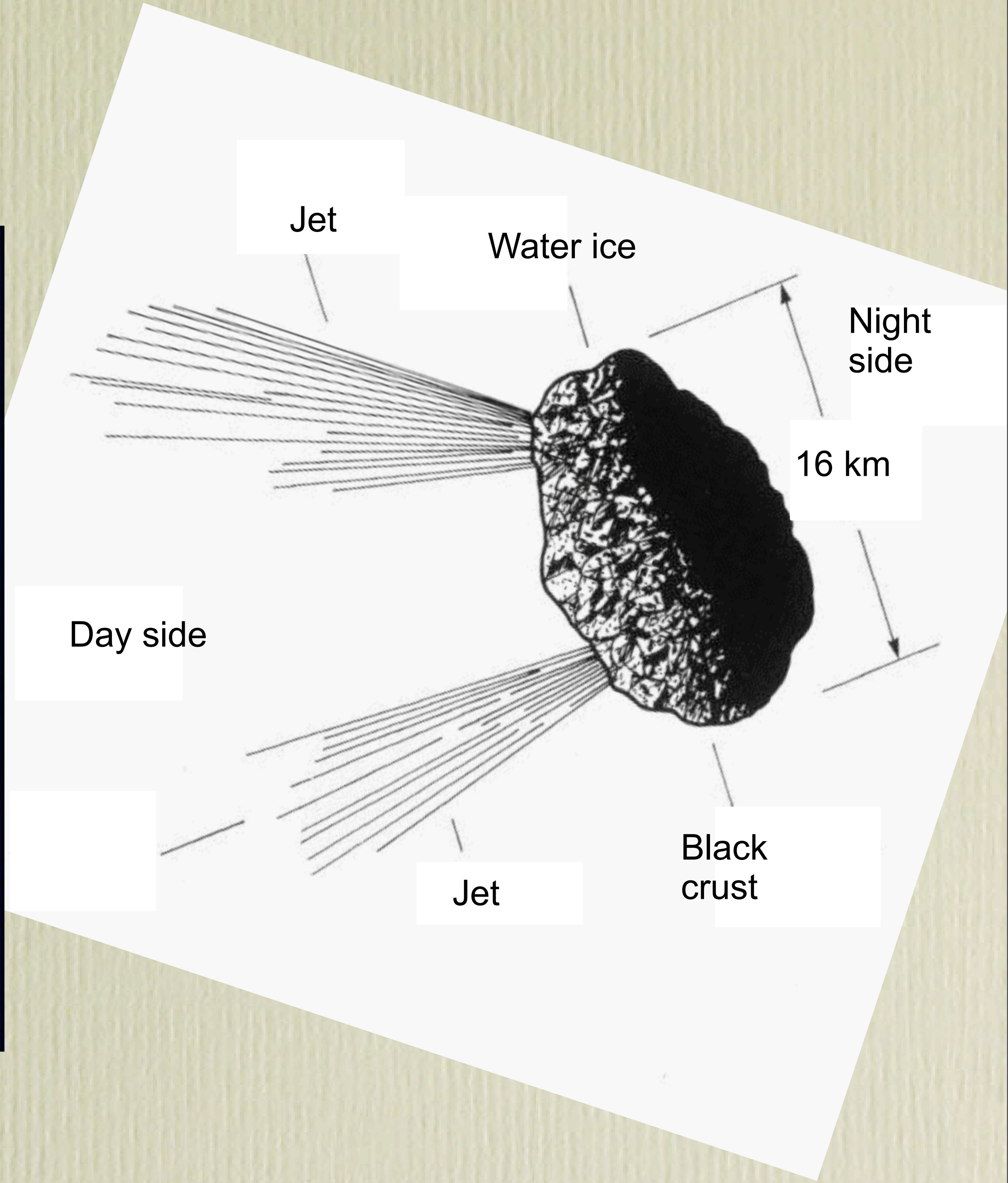


Tempel 1 (Deep Impact)

Nucleus Structure

Comet Halley

Movie: ESA/MPS



Properties of Comets (1)

- Material evaporates from surface when nucleus is heated close to the Sun. Frozen ice sublimates and forms gas. Coma diameter ~ 10^5 to 10^6 km.
- Activity inside ~ 5 AU from the Sun mostly water-driven. Sublimation of CO and CO_2 leads to activity out to 10 AU. Maximum gas production several 100 tons per second. Activity frequently localized in jets.
- Embedded dust is accelerated by the evaporating gas. Gas/Dust ratio ~ 0.1 to 10 (by mass).
- Activity probably produced in upper few centimeters for meters of the nucleus crust.
- Mass loss per revolution about the Sun: ~ 1%, ⇒ comet survives ≈ 1000 revolutions. Continuous supply of new comets required!
- Nuclei show irregular structure; sizes ~ 600 km (Wirtanen) to 30 km (Halo-Bopp).

Properties of Comets (2)

- Extremely dark surface (albedo 1-5%). Comets are the darkest objects in solar system.
- Very porous and low density ($\rho < 1000$ kg/m^3).
- Nucleus composition: "Dirty snowball" (85% water ice, 4% CO, 3% CO_2, 1% N_2, rest organic compounds).
- Three types of dust particles found in Halley's dust: silicates, metallic and organic (elements C, H, O, N).
- Element abundances very similar to CI condrites and solar photosphere (measured for Halley only) ⇒ comets are remainders from early solar system.
- Crust formation: dust remains or falls back to surface.

Nucleus Structure and Composition

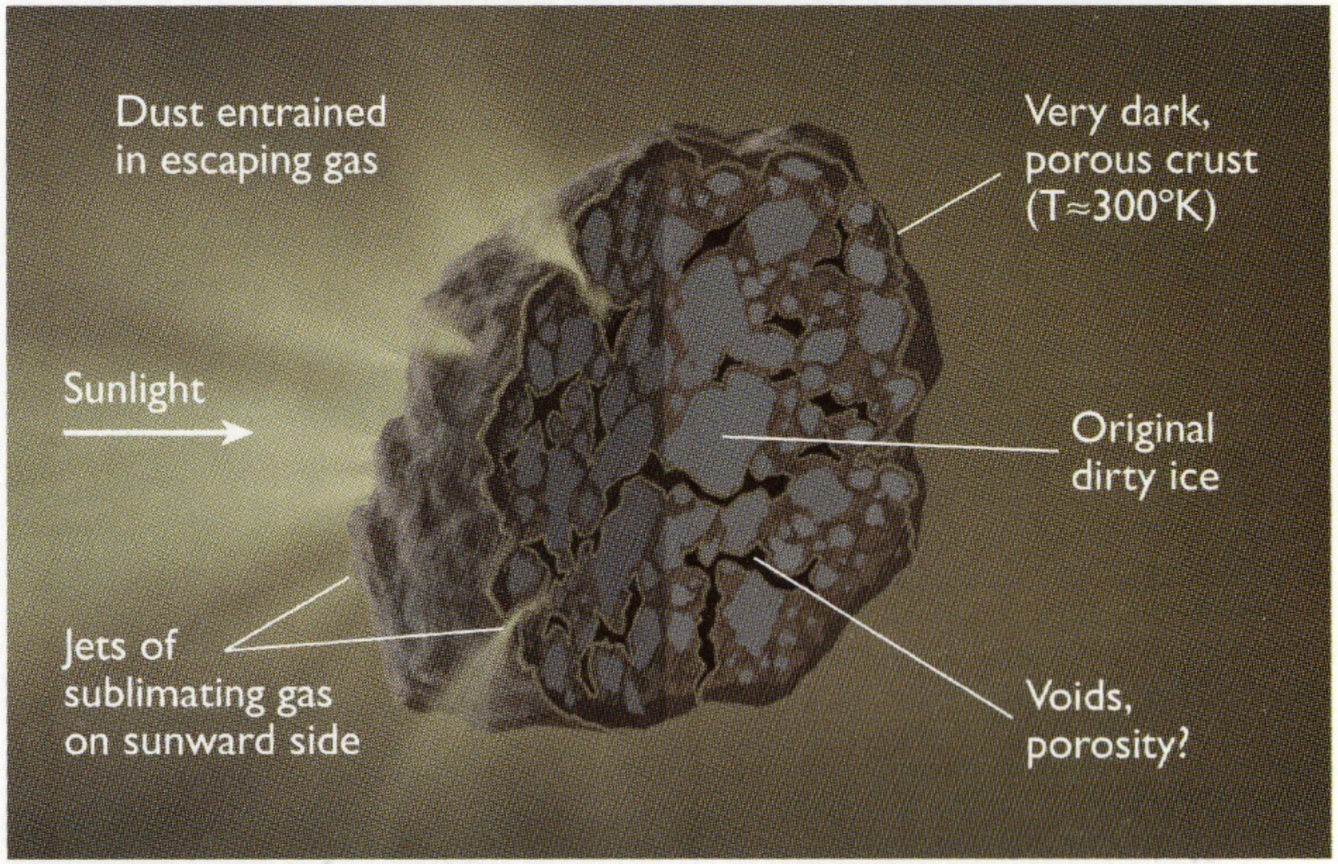
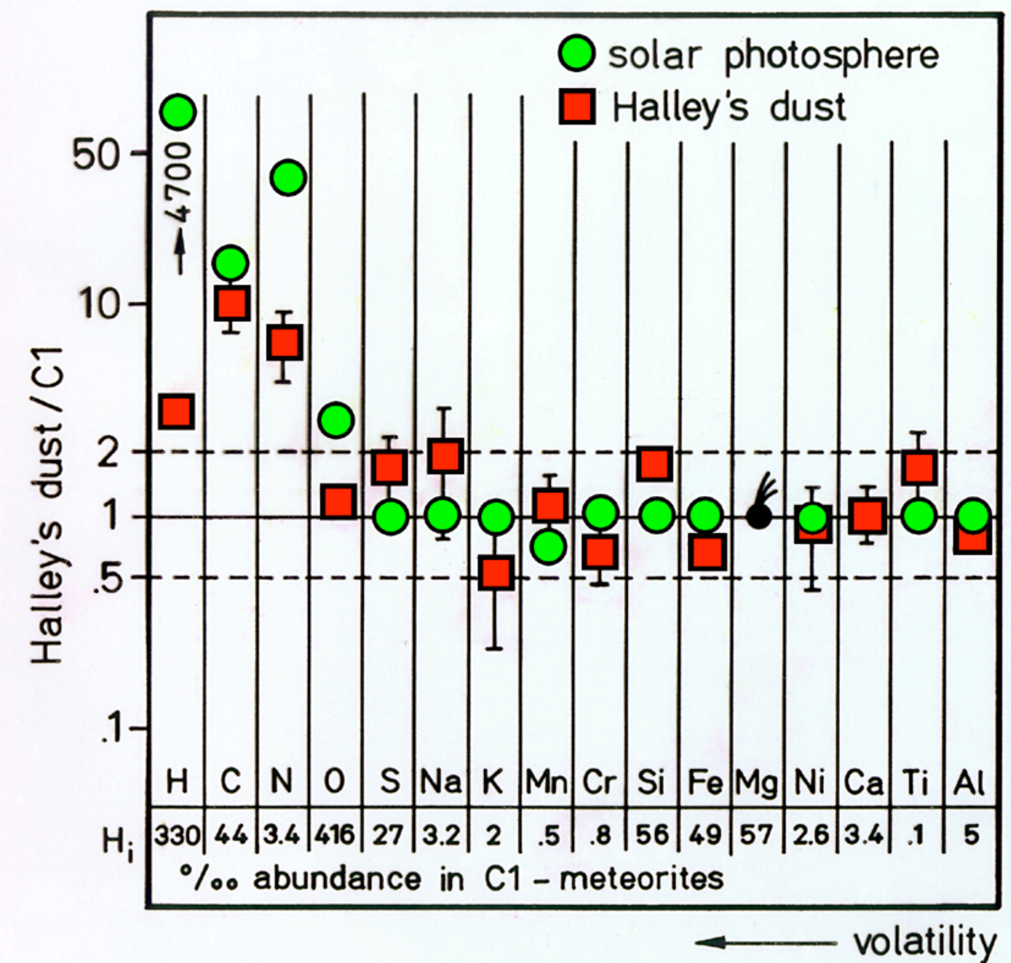


Figure 16. Fred Whipple's "icy conglomerate" model, as extended by Armand Delsemme, and spacecraft observations of Halley's nucleus are the basis for this idealized rendering of a cometary nucleus.

Graphics from: J. Kelly Beatty, The New Solar System



Graphics from: E. Jessberger/MPIK; Univ. of Münster

Composition of cometary dust grains very similar to CI chondrites and solar photosphere. This implies that all three bodies were formed from the same primordial nebula.

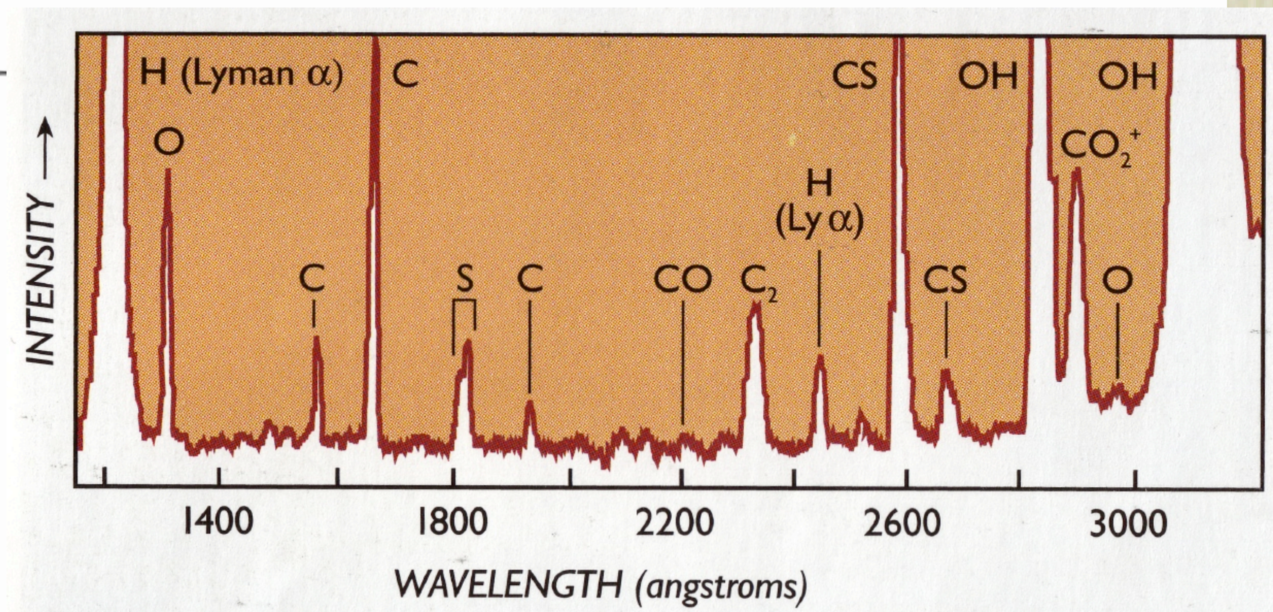
Chemical Species Identified in Comets

Identification by radio, microwave, IR, visual, and UV spectra

H	C	O	S	CO_2	HDO	CHO	DCN	HNC	CO	CS	NH	OH
C_2	$^{12}C^{13}C$	CH	$H_4C_2O_2$	^{13}CN	$H^{13}CN$	$HC^{15}N$	OCS	SO_2	S_2	SO		
C_3	NH_2	H_2O	HCOOH	C_2H_2	H_2S	H_2CS	HNCO	CH_4	HCO	CN	HC_3N	Na
NH_3	H_2CO	HCN	CH_3OH	CH_3CN	HC_3N	NH_2CHO	C_2H_6					
C^+	CO^+	CH^+	CN^+	HCO^+	CO_2^+	H_2O^+	H_2S^+	N_2^+	H_3O^+			

Identification by mass spectra

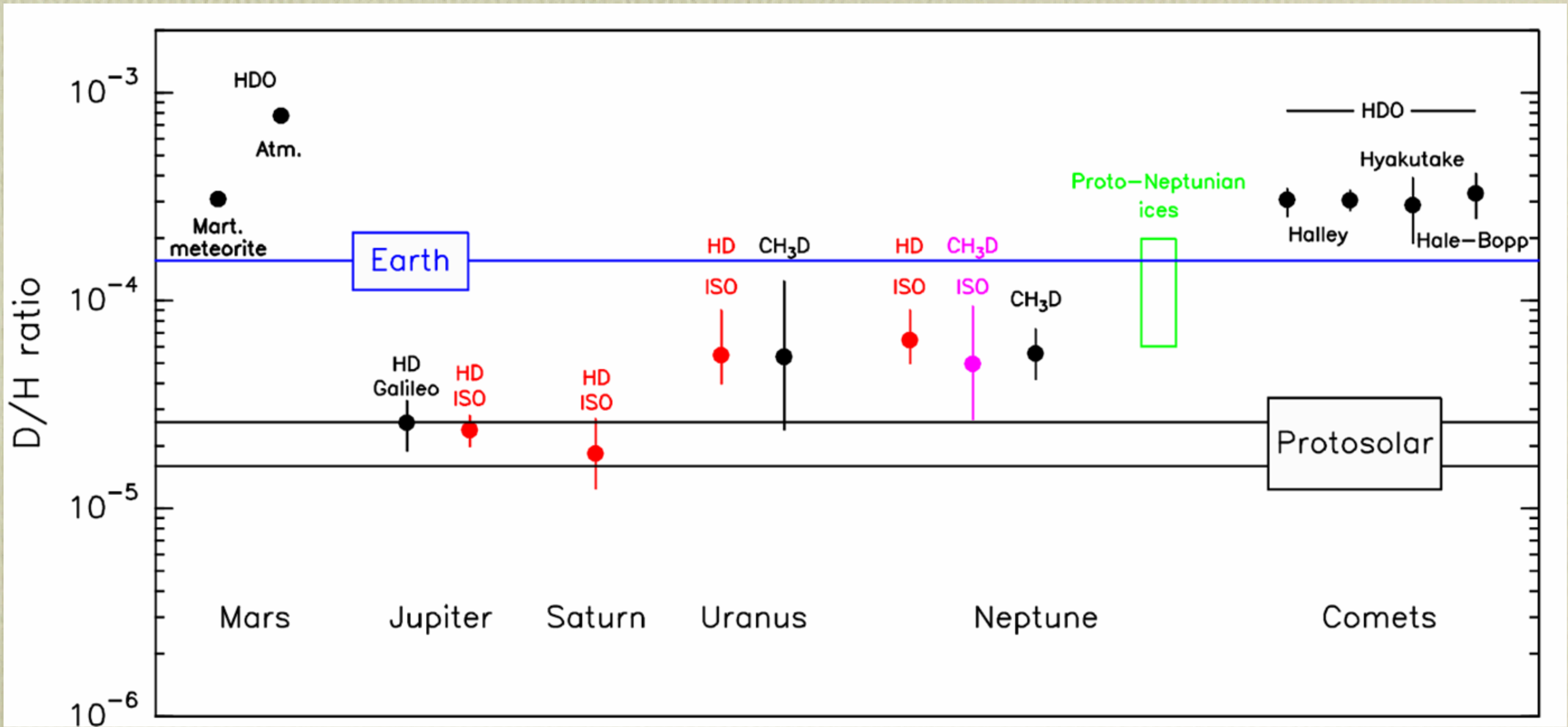
Mass	Ions			Neutrals		
1	H^+					
12	C^+					
13	CH^+					
14	CH_2^+	N^+				
15	CH_3^+	NH^+				
16	O^+	CH_4^+	NH_2^+			
17	OH^+	NH_3^+	CH_5^+			
18	H_2O^+	NH_4^+		H_2O		
19	H_3O^+					
23	Na^+					
28				CO	N_2?	C_2H_4?
30				H_2CO		
31	H_3CO^+					
35	H_3S^+					
36	C_3^+					
37	C_3H^+					
39	$C_3H_3^+$					
44				CO_2		



UV Spectrum of Comet Bradfield

Table from: L. McFadden et al., Encyclopedia of the Solar System   Graphics from: J. Kelly Beatty, The New Solar System

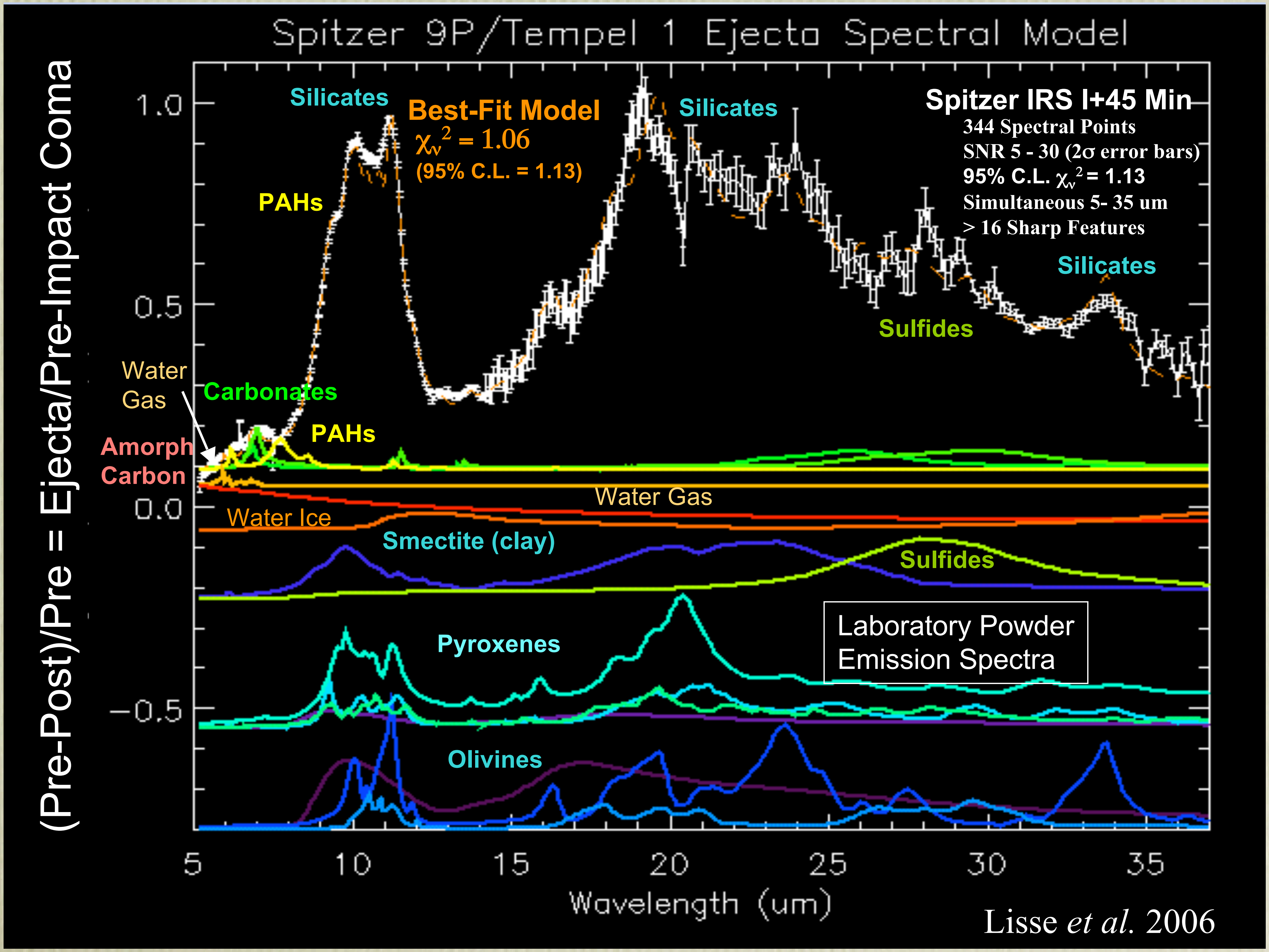
Comets: D/H Ratio



Graphics from: Michael Küppers/ESA

- Deuterium/Hydrogen in comets enriched over values of giant planets.
- Comets candidates for terrestrial oceans, but they cannot be the only source for terrestrial water. Oceans must be diluted with less deterium enriched water from other source (perhaps hydrated silicates in meteorites)

Cometary Spectra



Lisse *et al.* 2006

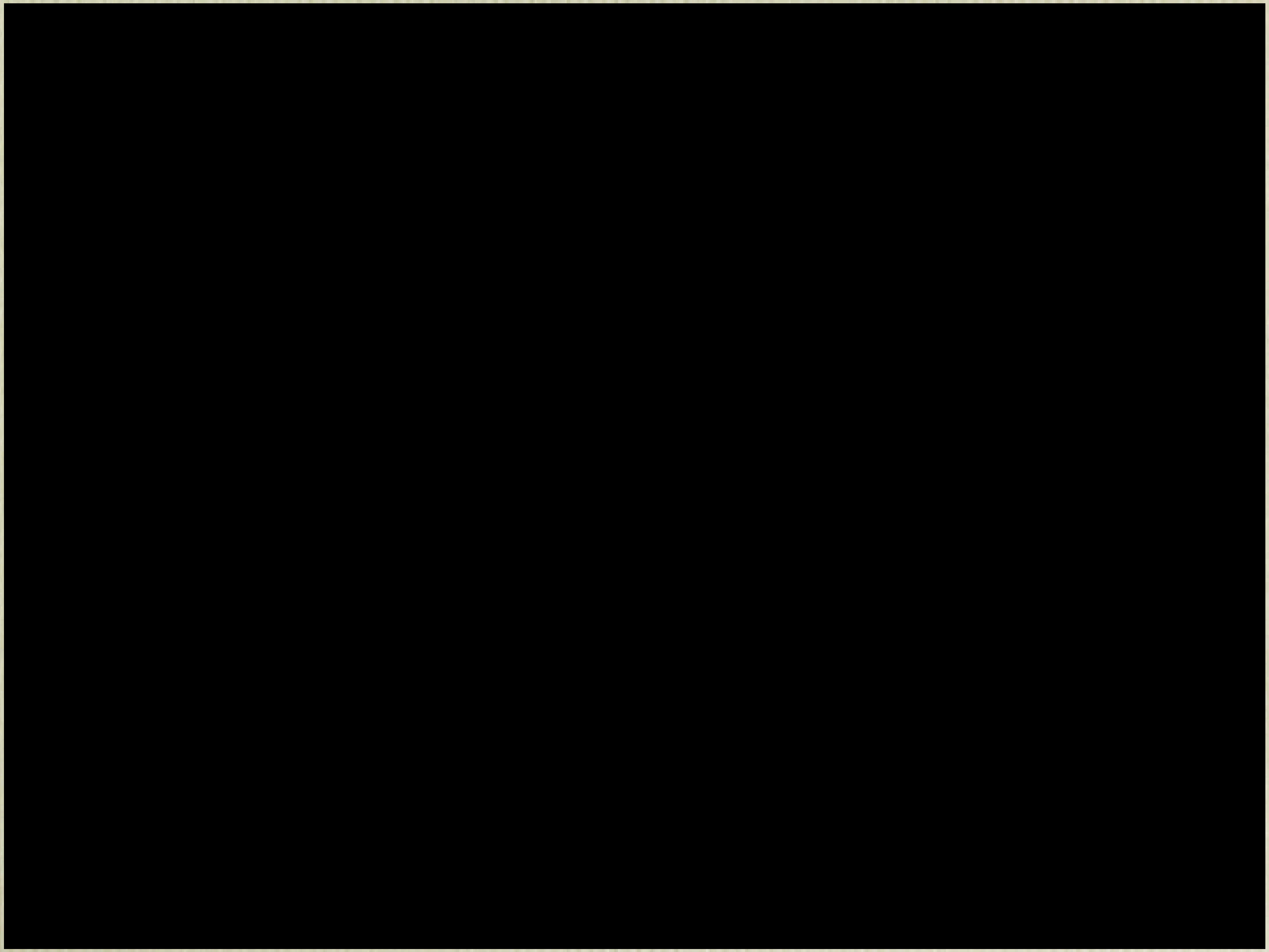
Deep Impact

- 370 kg projectile fired onto nucleus of comet Tempel 1.
- Impact speed 10.3 km/sec.
- Impact crater: ~ 100m ∅ (estimated).
- 10^4 - 10^5 tons.
- Water ejected: ~ 7000 tons.
- Effective nucleus radius: 3 km.
- Rotation period: 41.85 hours.
- Density: ~ 350 kg/m^3.
- Large dust content.

Image: NASA/Deep Impact

Deep Impact

Impact onto Tempel 1 as seen from projectile.



Movie: NASA/Deep Impact

Nucleus Structure of Tempel 1

- Layered structure.
- Crater-like surface features. Impact craters? If yes, than very slow surface erosion.
- Flat areas (a, b). Water molten and re-frozen?
- Scarp, 20m high (4 little arrows).

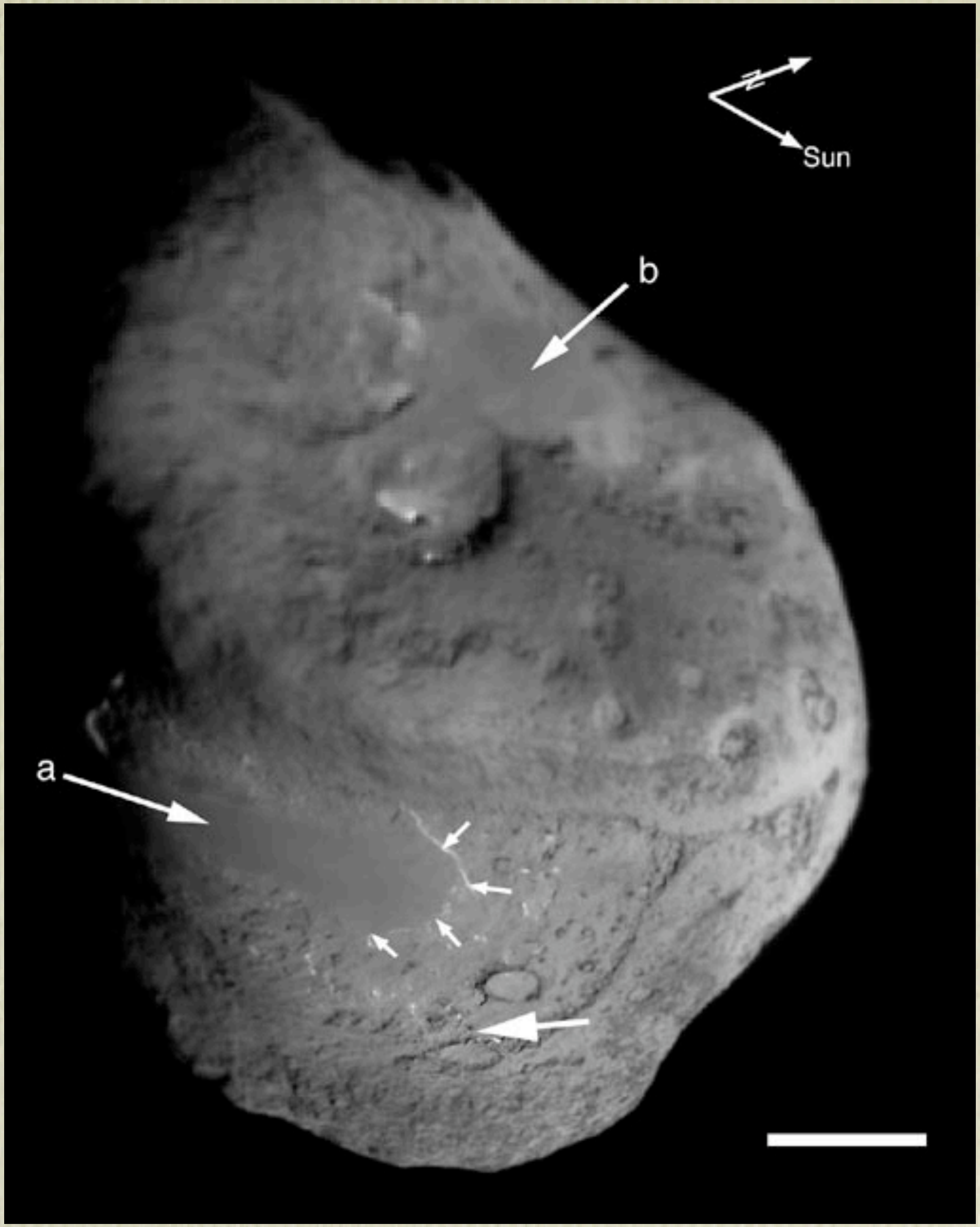
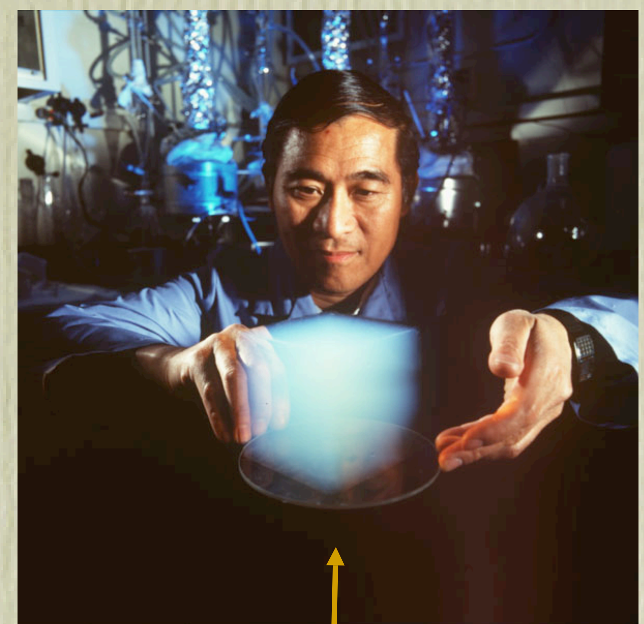
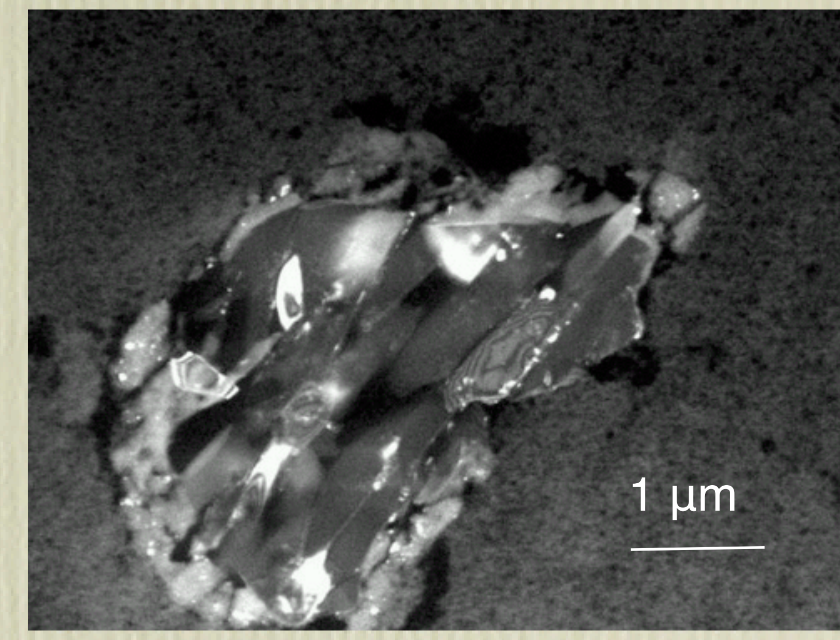


Image: NASA/Deep Impact

STARDUST: Cometary Dust Brought to Earth

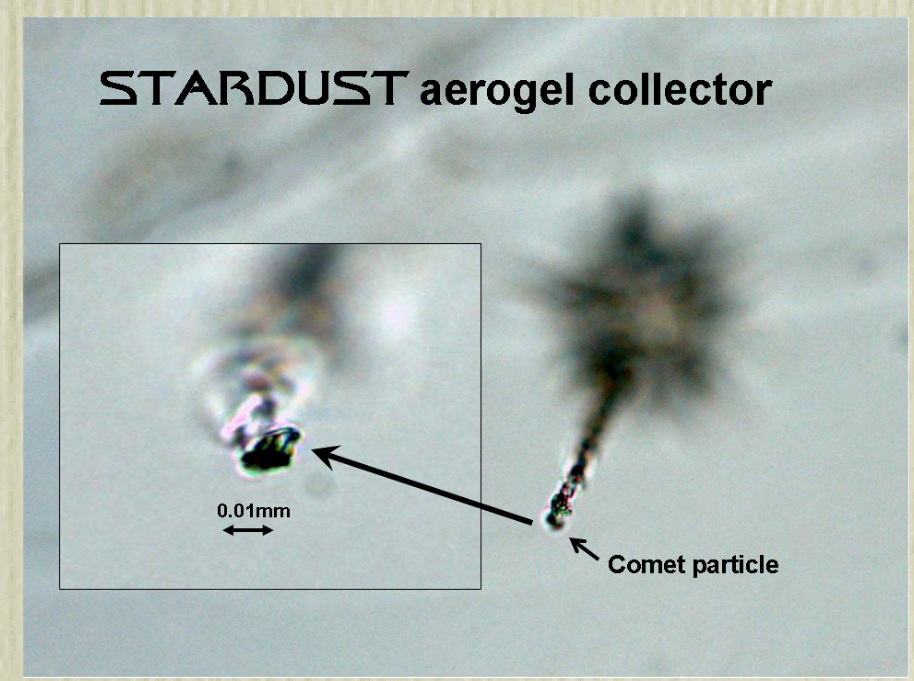
Aerogel collector

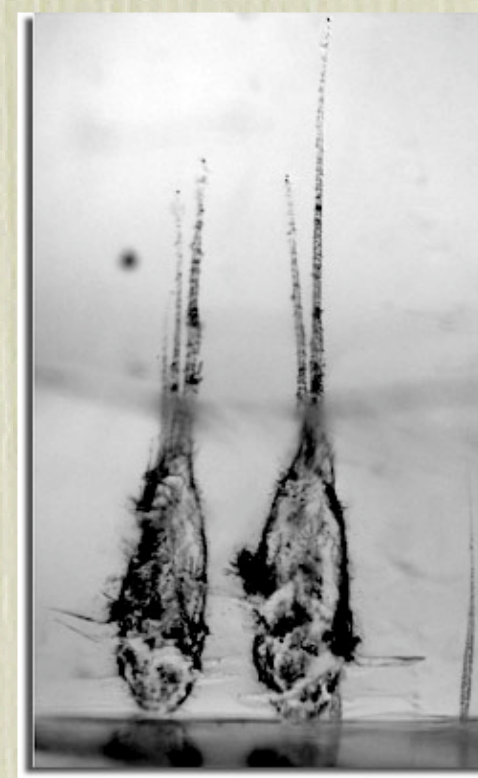




FeS crystal

Recovery of reentry capsule

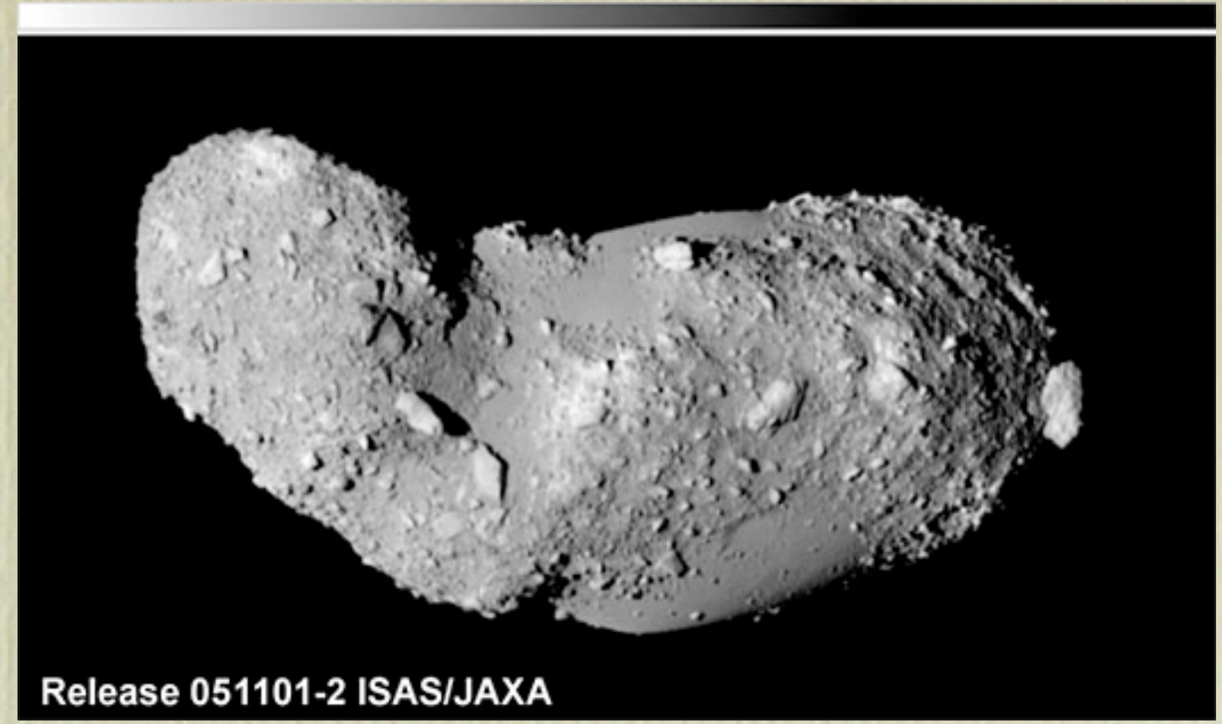




Tracks in Aerogel

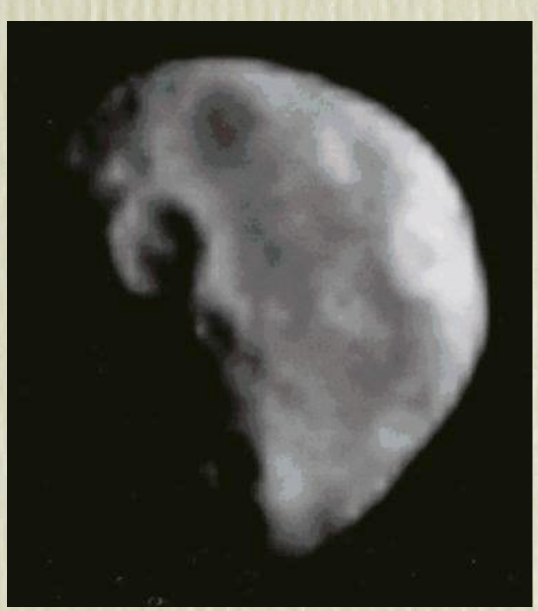
Asteroids

439 115 objects with orbital elements (January 2009)
Estimated number of objects > 1 km: 1 - 2 Mio.



Itokawa

Gaspra

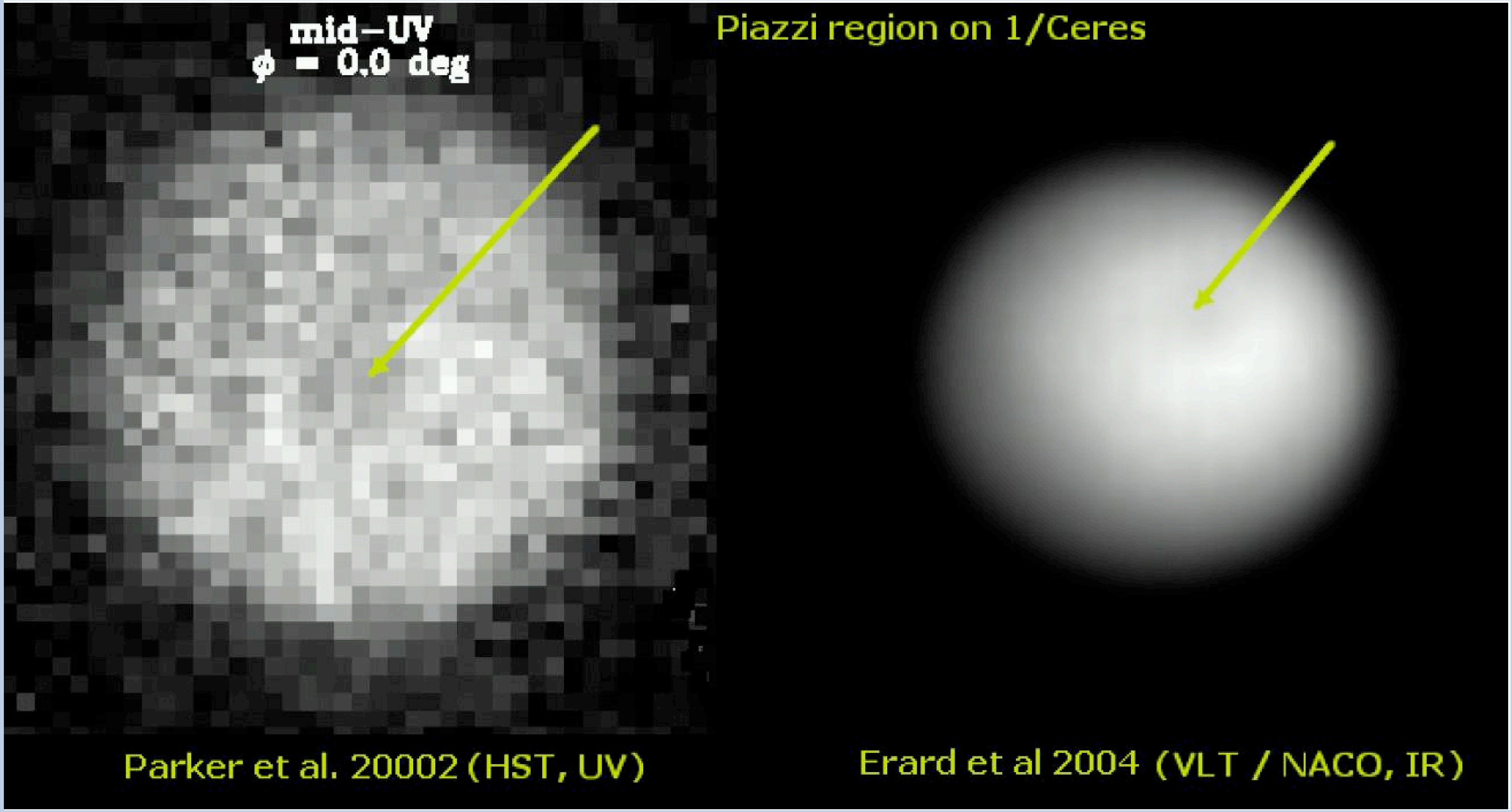


Ida

Bilder: NASA/Galileo

Ida's moon Dactyl

Der Asteroidengürtel: Entdeckung neuer Welten



Ceres, Beobachtung mit 8 m Teleskop in Chile

Asteroid Eros

Movie: NASA/NEAR-Shomaker

Asteroid Taxonomy

Asteroid Characteristics by Type

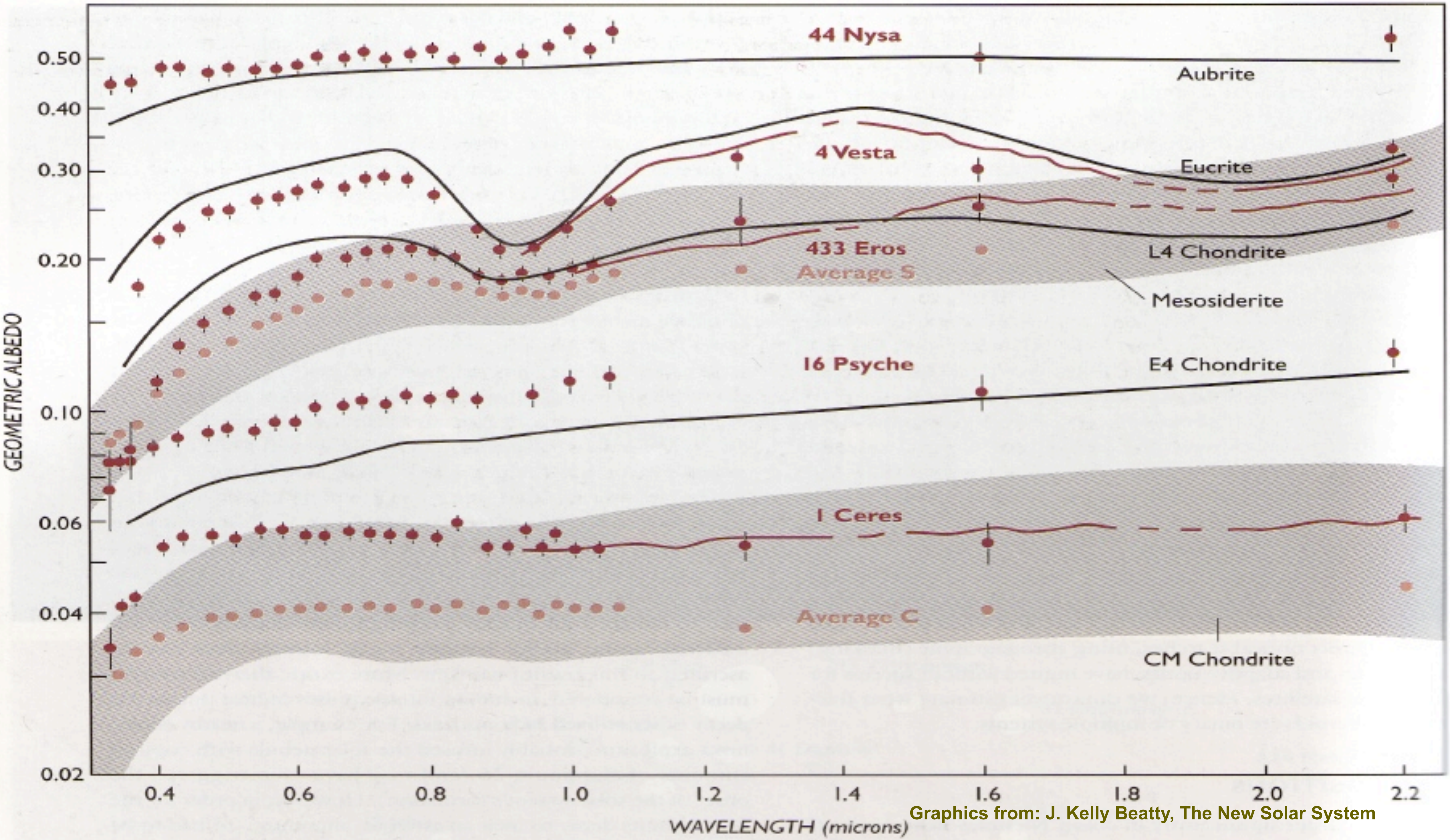
Type	*Albedo*	*Reflectance spectrum*	*Meteorite analog(s)*
C	0.03–0.07	Fairly flat longward of 0.4μ; UV and sometimes 3μ absorption bands	Carbonaceous chondrites (CM)
B	0.04–0.08	C-like, but slightly brighter and more neutral in color	Carbonaceous chondrites (?)
F	0.03–0.06	Flat (neutral color) with no ultraviolet absorption	?
G	0.05–0.09	C-like, but brighter and with very strong ultraviolet absorption	Carbonaceous chondrites (?)
P	0.02–0.06	Linear and slightly reddish (like M, but with very low albedo)	None
D	0.02–0.05	Redder than P's, especially longward of 0.6μ; very low albedo	None (kerogens?)
T	0.04–0.11	Reddish, esp. at shorter wavelengths; intermediate between D and S	?
S	0.10–0.22	Reddish shortward of 0.7μ; weak to moderate absorptions near 1μ and 2μ	Stony-irons and ord. chondrites
M	0.10–0.18	Linear and slightly reddish (like P, but with moderate albedo)	Irons; enstatite chondrites
E	0.25–0.60	Linear, flat or slightly reddish	Aubrites
A	0.13–0.40	Strong absorptions in UV and near 1.1μ due to olivine	Brachina
Q	moderate	Like S, but with stronger absorptions	Ordinary chondrites (unweathered)
R	mod. high	Like S, but with stronger absorptions (particularly due to olivine)	?
V	mod. high	Like S, but with stronger absorptions (particularly due to pyroxene)	Basaltic achondrites

nain belt, including many Trojans and some of Jupiter's small outer satellites (see Chapter 23). We can speculate that these colors may be due to "ultraprimitive" organic compounds, perhaps like the non-icy components of comets.

Table 1. **Astronomers find that asteroids exhibit a number of characteristics that can be used to subdivide them into taxonomic classes. The most important of these are the shape and slope of their reflectance spectra (the listed albedos are typical but do not define the classes). Several other types have been defined, but these are the most notable ones. The symbol *μ* stands for microns.**

Similarities between asteroid and meteorite spectra used for classification and identification of surface material

Table from: J. Kelly Beatty, The New Solar System



Graphics from: J. Kelly Beatty, The New Solar System

Figure 8 (above). The principal means for deducing the compositions of distant asteroids is to compare their reflectance spectra with those of meteorites, seen here for visible through infrared wavelengths. Asteroid data, in shades of reddish brown, consist of points with error bars (from filter spectrophotometry), lines (from Fourier spectroscopy), and shaded circles (average values for the S- and C-type asteroids). Laboratory measurements of meteorite powders are reproduced in shades of gray; two classes occupy the ranges of values indicated by wide bands. Investigators deduce surface mineralogy primarily from the shapes of these curves rather than from the objects' precise albedos. Evidently, the diverse mineral assemblages found in our meteorite collections are also represented in the asteroid belt.

Figure 9 (below). A schematic representation of successive stages in the evolution of an asteroid that is heated early in its history. The original body of primitive composition *(left panel)* is heated to the point that constituent iron separates and sinks to its center, forming a core *(middle)*. Partially melted rock from the mantle floats upward through cracks in the crust, erupting onto the surface as basaltic lava flows. As heat radiates away, the body cools, the iron solidifies, olivine accumulates in the deep interior, and crustal magmas solidify. Repeated collisions fragment the mantle and crustal rocks into a "megaregolith" and ultimately eject the rocks, exposing the iron core and any embedded rocks *(right)*. Most asteroids were not heated much beyond the first stage; 4 Vesta reached stage 2, but was not fragmented thereafter. Some M- or S-type asteroids *(right)* may be the parent bodies for iron and stony-iron meteorites.

Graphics from: J. Kelly Beatty, The New Solar System

Distribution of Taxonomic Classes in Asteroid Belt

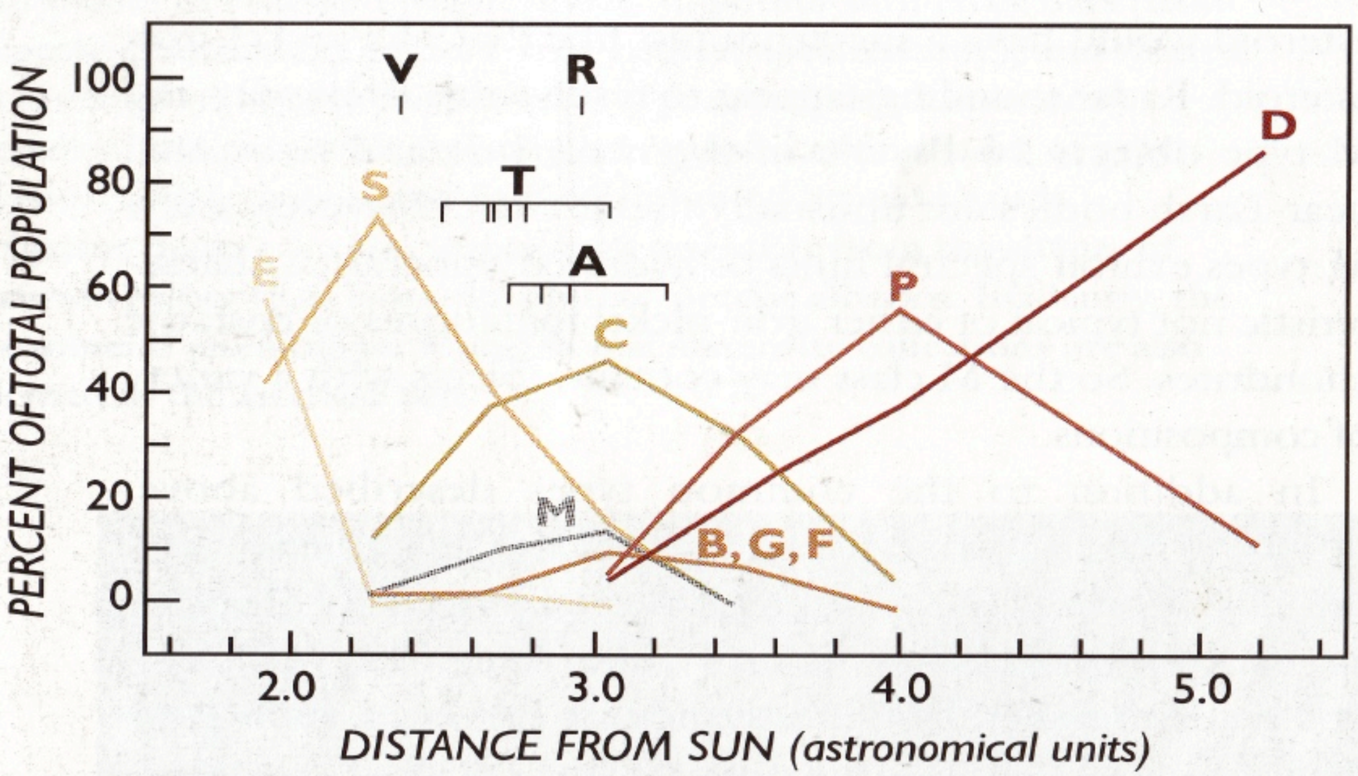
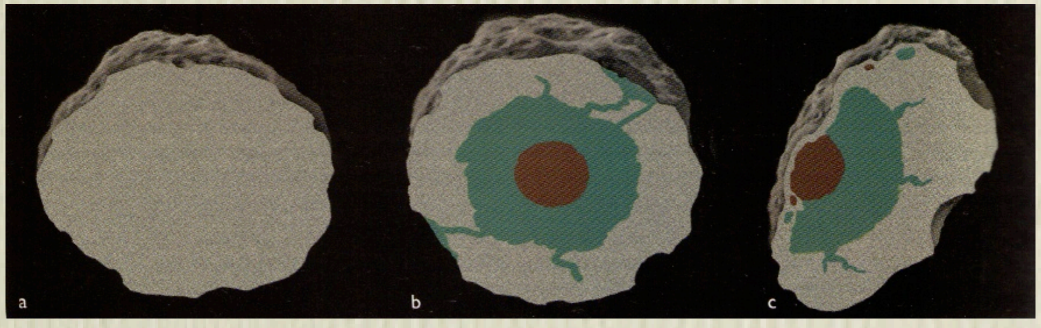


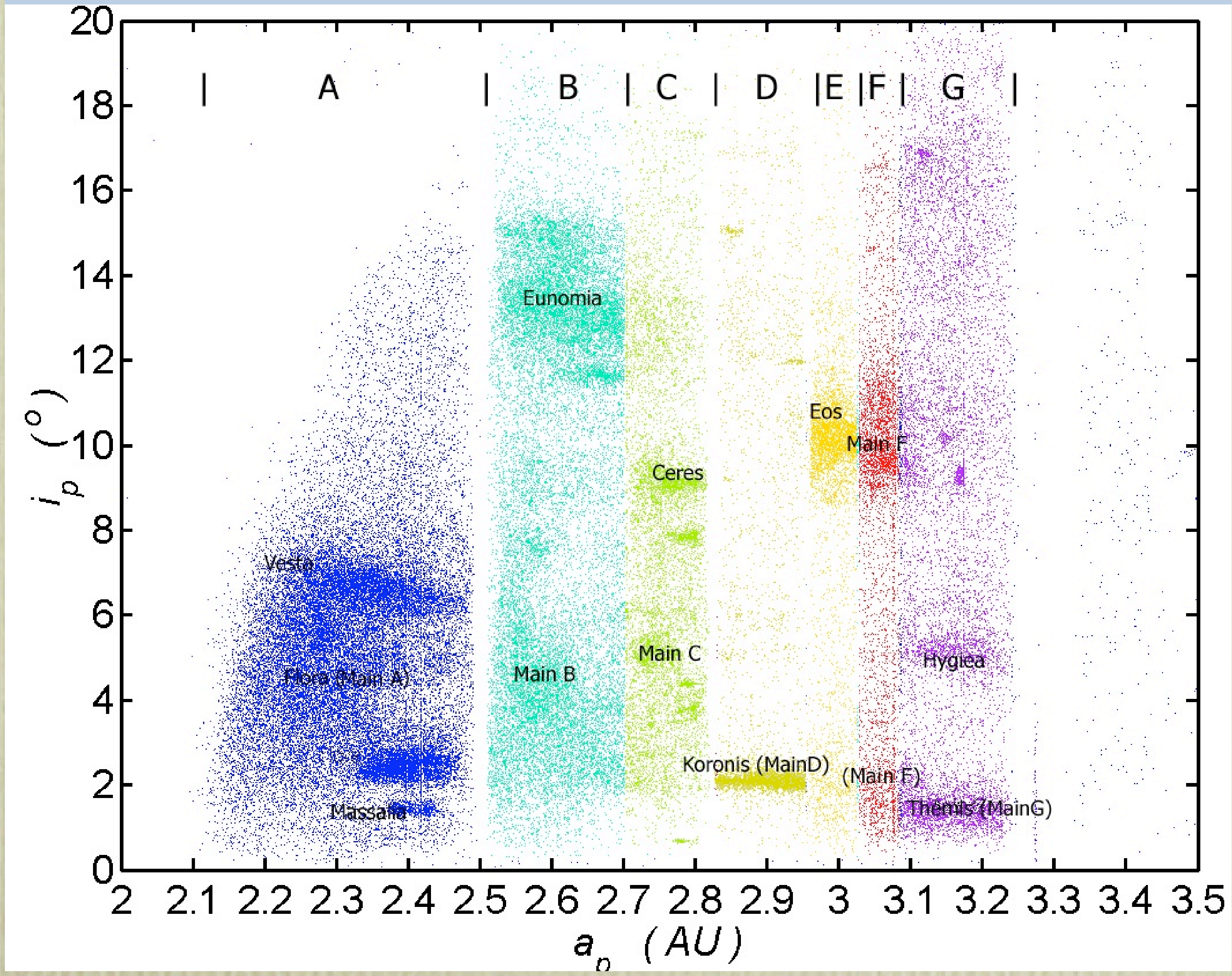
Figure 11. Asteroids of different compositions are systematically distributed with respect to their distance from the Sun. A telescopic survey made in eight colors and data from other observational programs have been corrected to eliminate biases against dark, fainter asteroids. This makes it possible to derive the fraction of asteroids above a certain size (determined by observational limitations and varying with distance) within each class. The letter designations, which refer to different spectral types, are summarized in *Table 1.*

- Outer belt: more primitive classes.
- Inner belt: more processed classes (more silicate-rich and metal-rich).
- Formation scenario: differentiation of asteroid interior due to heating by early sun preferentially in inner belt. Larger asteroids may have developed molten interiors due to gravitational or radioactive heating.



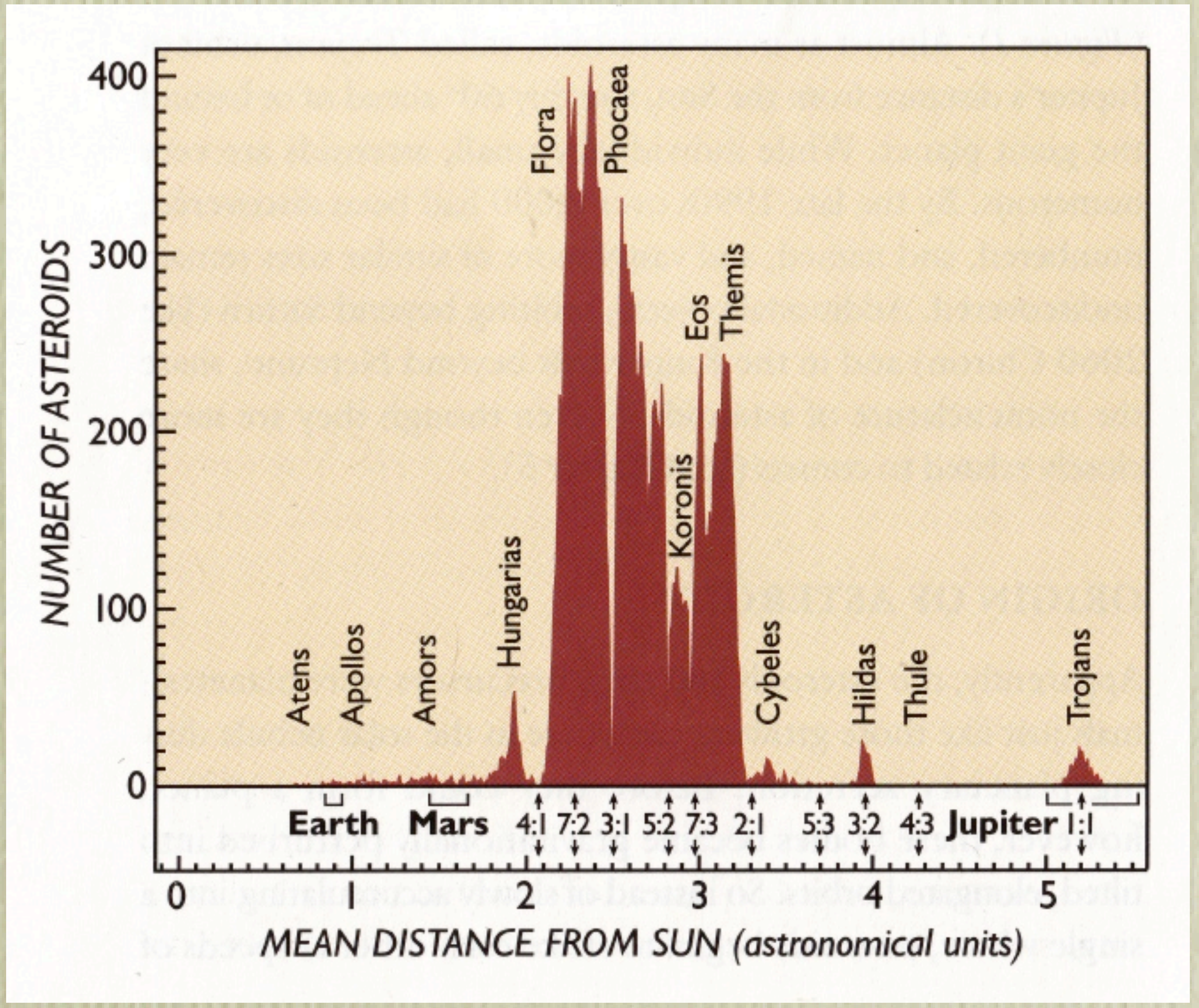
Graphics from: J. Kelly Beatty, The New Solar System

Asteroid Orbits: Collision Families



- clustering of asteroid orbits with certain orbital parameters (a,i) or (a,e): Hirayama families.
- formed by collisions.
- family members can have different taxonomic properties because the can originate from different parts of potentially differentiated bodies (e.g. S-type from crust or M-type from core).

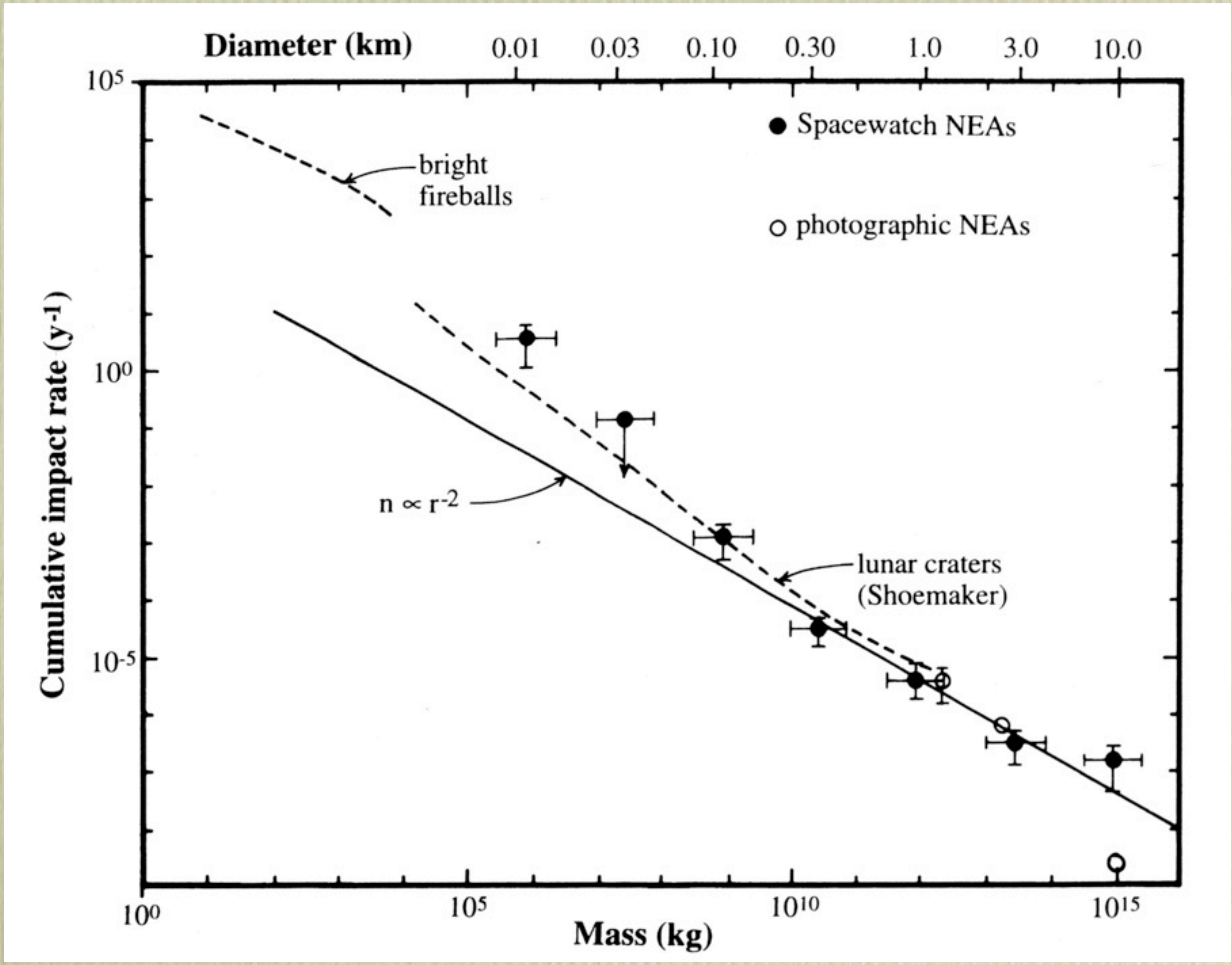
Asteroid Orbits: Resonances



Graphics from: J. Kelly Beatty, The New Solar System

- gaps with low number density in asteroid belt (Kirkwood gaps).
- gaps located at resonances between asteroid's and Jupiter's orbital periods.
- Jupiter's gravity increases eccentricity of asteroid orbit when in resonance. Leads to short lifetime in resonance orbit. Asteroid orbits of terrestrial planets and can collide with a planet.

Near Earth Asteroids: Size Distribution



Graphics from: Lewis, Physics and Chemistry of the Solar System

Distinction between Asteroids and Comets

Asteroids

- appear star-like; no activity
- mostly circular orbits with low inclinations
- likely formed in-situ. Jupiter inhibited the formation of a planet
- irregular shape except large ones
- Kirkwook gaps: orbital resonances
- Asteroid families: collision groups
- Taxonomy classes: differentiated bodies

Comets

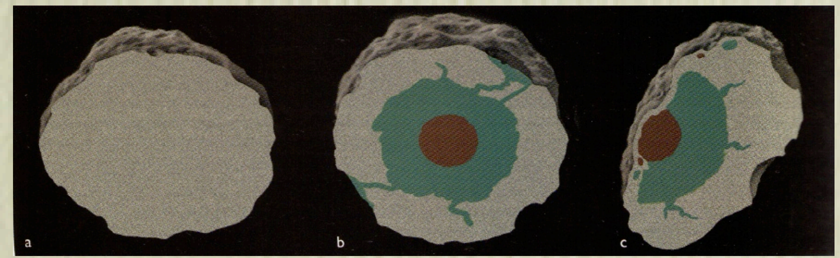
- appear ‘fuzzy’; volatile-rich sublimation-driven activity
- elliptical or hyperbolic orbits with large range in inclinations
- two reservoirs: Kuiper-Belt (short-period) and Oort cloud (long-period)
- nucleus: dirty snowball
- composition: water, silicates, some organics. Possibly primordial (frozen)

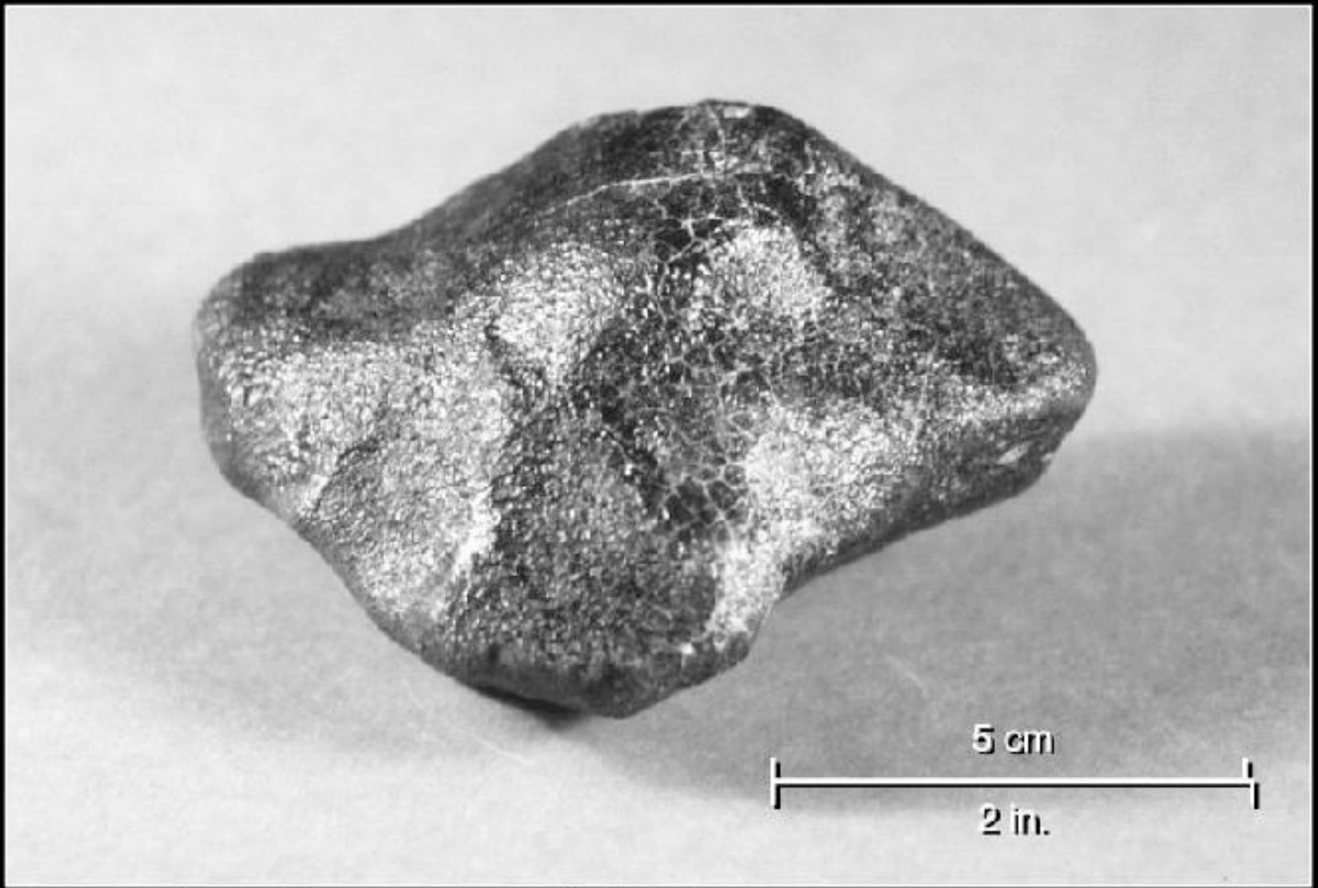
But there are exceptions: Main Belt Comets!

Meteorites

Meteorite Classification

- Undifferentiated meteorites: most original, unprocessed material from the formation of the solar system (or before). Chondrite types classified by iron content. 81 % normal chondrites, 5 % carbonaceous chondrites.
  - Chondrules: spherical (~ mm to cm in size) inclusions of silicates (e.g. olivine) in meteorite matrix. Formed by melting to ~ 1600 K and very rapid cooling. Formation process still unclear, either during early solar system phase or even earlier (pre-solar).
- Differentiated meteorites: contain processed material, i.e. they were part of a larger differentiated body and became meteorite after collision in the asteroid belt. Iron meteorites (4 %, molten core), stony-irons (1%, mantle-crust), achondrites (9 %, crust).
  - ⇒ differentiated meteorites have a clear link to asteroids.
  - Widmannstätten pattern in iron meteorites nickel content determines crystallisation.





Meteroite · Fragment of Vesta

Lab Photograph · Russel Kempton, New England Meteoritical Services

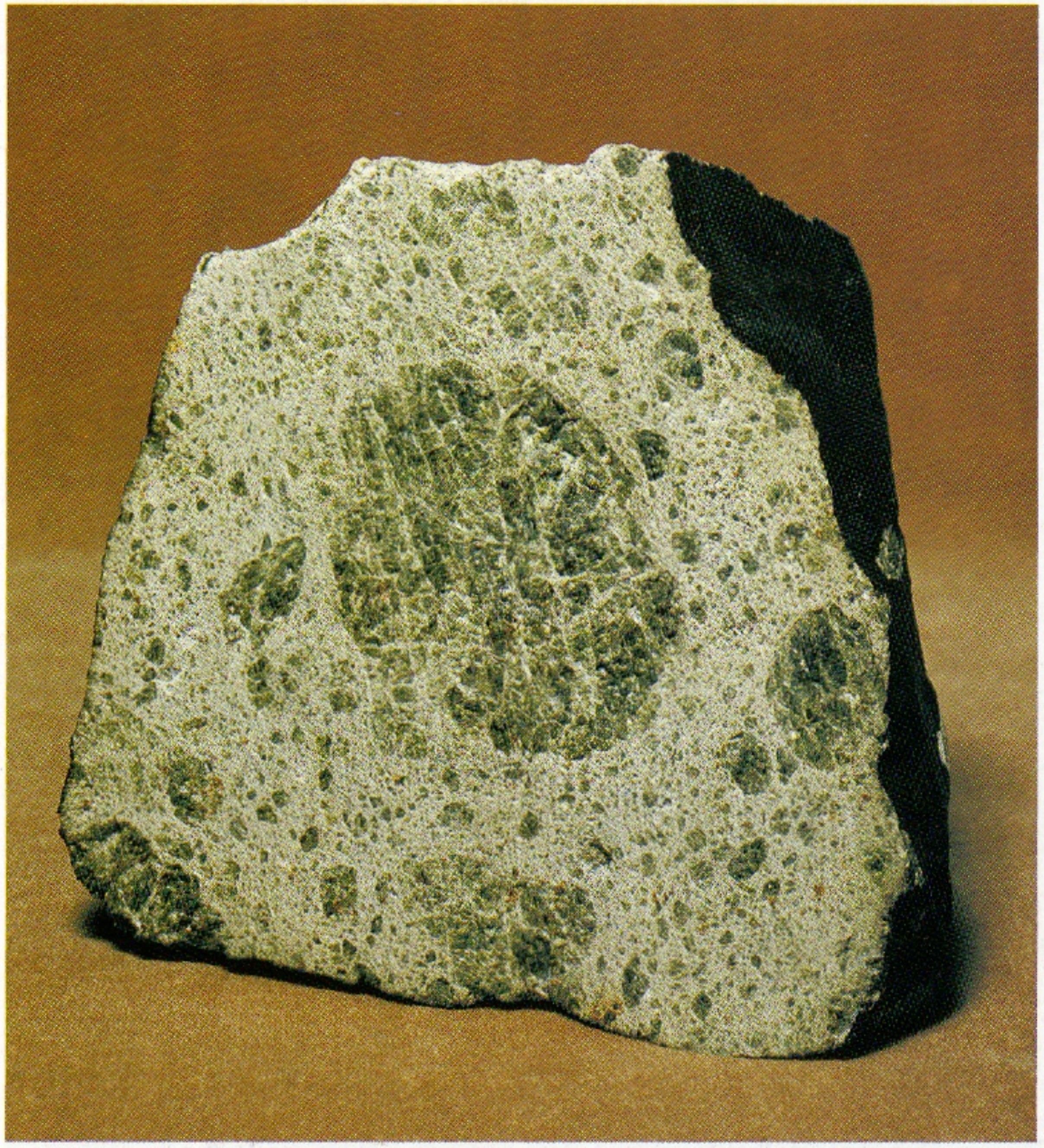


Figure 7. The Johnstown, Colorado, achondrite is of a type called diogenite, thought to be a sample of asteroid 4 Vesta. This sawed surface, 10 centimeters wide, shows clasts of igneous rock that have been broken by impact and then recemented together on the asteroid parent body.

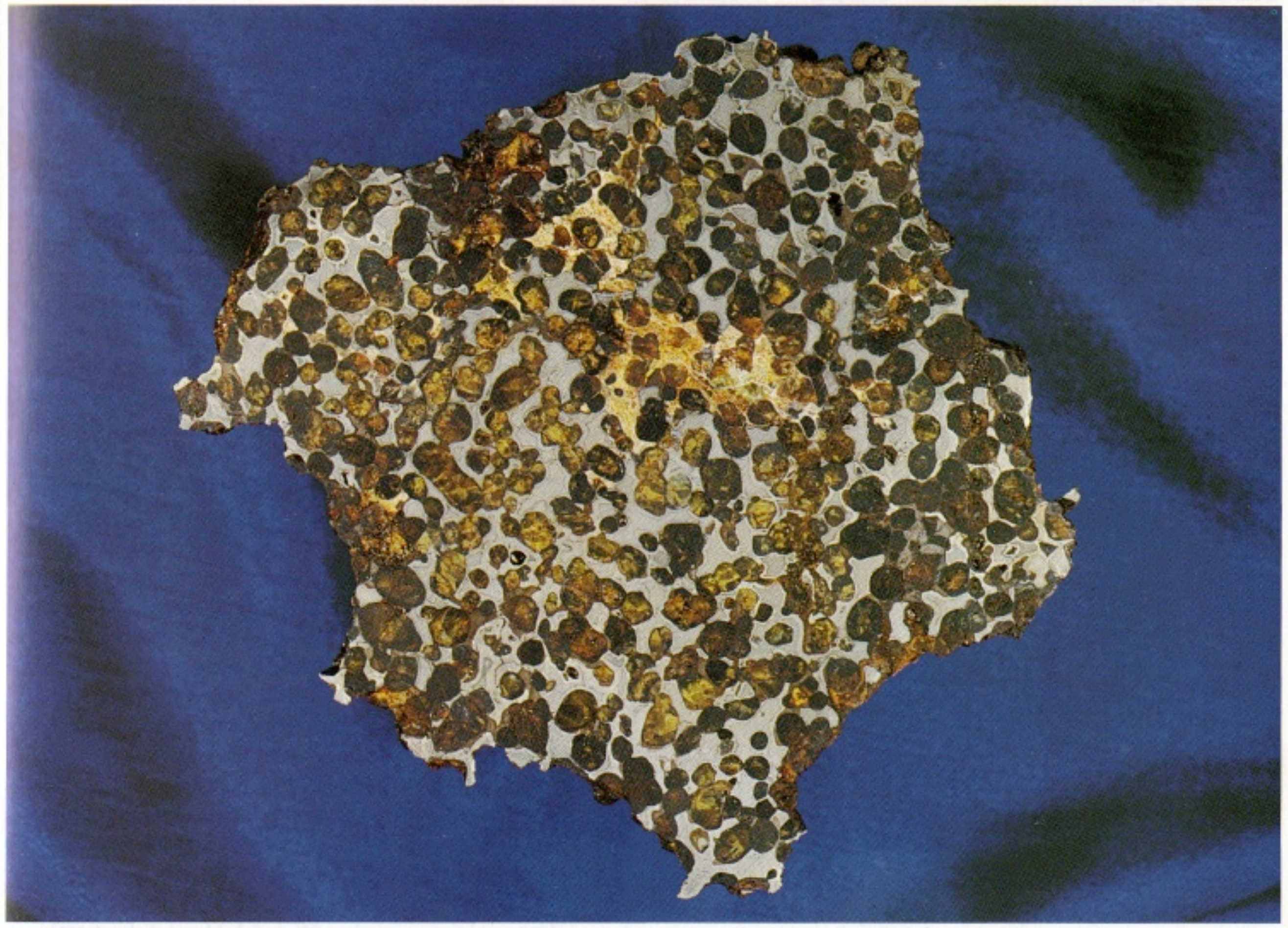
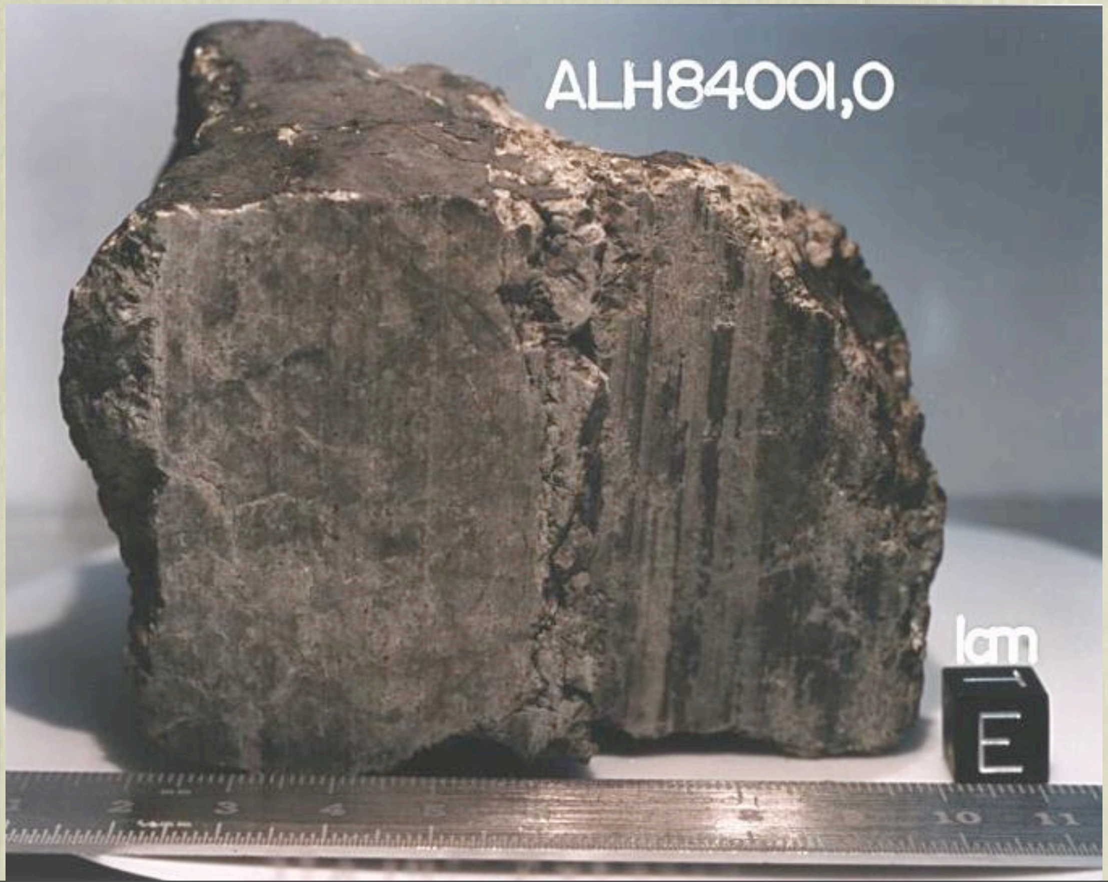
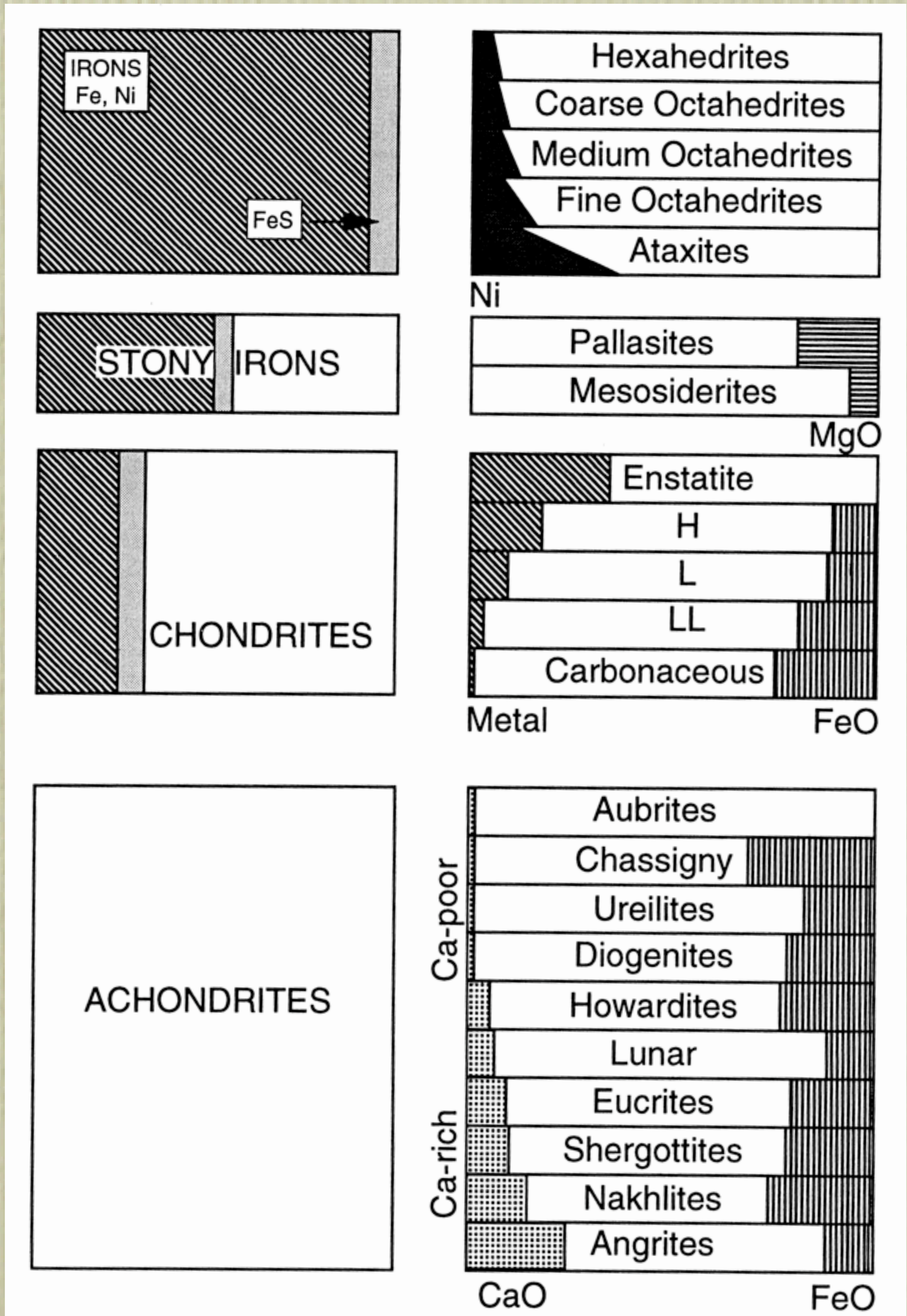


Figure 10. This polished section of the Springwater, Canada, pallasite shows rounded olivine crystals embedded in iron-nickel metal. The mixture of silicates and metal, which normally should separate because of pronounced differences in density, is thought to have occurred as the meteorite solidified at a core-mantle boundary. Pallasites are among the most beautiful of all meteorites.



A Meteorite Fall

Meteorite Classes



Almost all meteorites contain iron.

Known Meteorites (1997)

Class	Falls	Finds	Total	Antarctic finds
All meteorites	933	2487	3420	8982
Chondrites*	803	1700	2503	8497
H chondrites	305	860	1165	4622
L chondrites	340	641	981	3190
LL chondrites	73	93	166	401
E chondrites	15	12	27	52
C chondrites	33	28	61	160
Achondrites*	73	49	122	391
Eucrites	28	12	40	147
Howardites	15	9	24	54
Diogenites	10	0	10	85
Aubrites	9	2	11	4
Ureilites	5	16	21	38
SNC meteorites	4	2	6	6
Lunar meteorites	0	2	2	11
Stony-iron meteorites*	12	57	69	29
Pallasites	5	36	41	10
Mesosiderites	7	21	28	13
Iron meteorites*	45	681	726	65
Octahedrites	27	481	508	56
Hexahedrites	6	52	58	2
Ataxites	0	43	43	7

Lunar Meteorites

Designation	Discovery location	Discovered	Mass (g)
1 Y 791197	Yamato Mountains	20 Nov. 1979	52.4
2 Y 793169	Yamato Mountains	8 Dec. 1979	6.1
3 Y 793274	Yamato Mountains	3 Jan. 1981	8.7
4 ALHA 81005	Allan Hills	18 Jan. 1982	31.4
5 Y 82192	Yamato Mountains	13 Jan. 1983	36.7
Y 82193*	Yamato Mountains	13 Jan. 1983	27.0
Y 86032*	Yamato Mountains	9 Dec. 1986	648.4
6 EET 87521	Elephant Moraine	20 Dec. 1987	30.7
7 Asuka 881757	Nansen Ice Field	20 Dec. 1988	442.1
8 MAC 88104	MacAlpine Hills	13 Jan. 1989	61.2
MAC 88105*	MacAlpine Hills	13 Jan. 1989	662.5
9 Calcalong Creek	Calcalong Creek, Australia	1960	19
10 QUE 93069	Queen Alexandra Range	11 Dec. 1993	21.4
QUE 94269*	Queen Alexandra Range	10 Dec. 1994	3.2
11 QUE 94281	Queen Alexandra Range	12 Dec. 1994	23.4
12 EET 96008	Elephant Moraine	14 Dec. 1996	53
13 Dar al Gani 262	Al Jufrah, Libya	23 Mar. 1997	513
14 Dar al Gani 400	Al Jufrah, Libya	10 Mar. 1998	1,425

Martian Meteorites

Designation	Discovery location	Discovered	Mass (g)
1 Chassigny	Haute Marne, France	**3 Oct. 1815**	4,000
2 Shergotty	Gaya, Bihar, India	**25 Aug. 1865**	5,000
3 Nakhla	Alexandria, Egypt	**28 June 1911**	40,000
4 Lafayette	Tippecanoe County, Indiana	before 1931	800
5 Governador Valadares	Minas Gerais, Brazil	1958	158
6 Zagami	Katsina province, Nigeria	**3 Oct. 1962**	18,000
7 ALHA 77005	Allan Hills	29 Dec. 1977	480
8 Y 793605	Yamato Mountains	14 Nov. 1979	16
9 EETA 79001	Elephant Moraine	13 Jan. 1980	7,900
10 ALH 84001	Allan Hills	27 Dec. 1984	1,930.9
11 LEW 88516	Lewis Cliff	22 Dec. 1988	13.2
12 QUE 94201	Queen Alexandra Range	16 Dec. 1994	12.0
13 Dar al Gani 476	Al Jufrah, Libya	1 May 1998	2,015

Meteorite Parent Bodies

Asteroid class	Inferred major surface minerals	Meteorite analogues
Z	Organics + anhydrous silicates? (+ice??)	None (cosmic dust?)
D	Organics + anhydrous silicates? (+ice??)	None (cosmic dust?)
P	Anhydrous silicates + organics? (+ice??)	None (cosmic dust?)
C (dry)	Olivine, pyroxene, carbon (+ice??)	"CM3" chondrites, gas-rich/blk chondrites?
K	Olivine, orthopyroxene, opaques	CV3, CO3 chondrites
Q	Olivine, pyroxene, metal	H, L, LL chondrites
C (wet)	Clays, carbon, organics	CI1, CM2 chondrites
B	Clays, carbon, organics	None (highly altered CI1, CM2??)
G	Clays, carbon, organics	None (highly altered CI1, CM2??)
F	Clays, opaques, organics	None (altered CI1, CM2??)
W	Clays, salts????	None (opaque-poor CI1, CM2??)
V	Pyroxene, feldspar	Basaltic achondrites
R	Olivine, pyroxene	None (olivine-rich achondrites?)
A	Olivine	Brachinites, pallasites
M	Metal, enstatite	Irons (+EH, EL chondrites?)
T	Troilite?	Troilite-rich irons (Mundrabilla)?
E	Mg-pyroxene	Enstatite achondrites
S	Olivine, pyroxene, metal	Stony irons, IAB irons, lodranites, windonites, siderophyres, ureilites, H, L, LL chondrites

Oxygen Isotopics

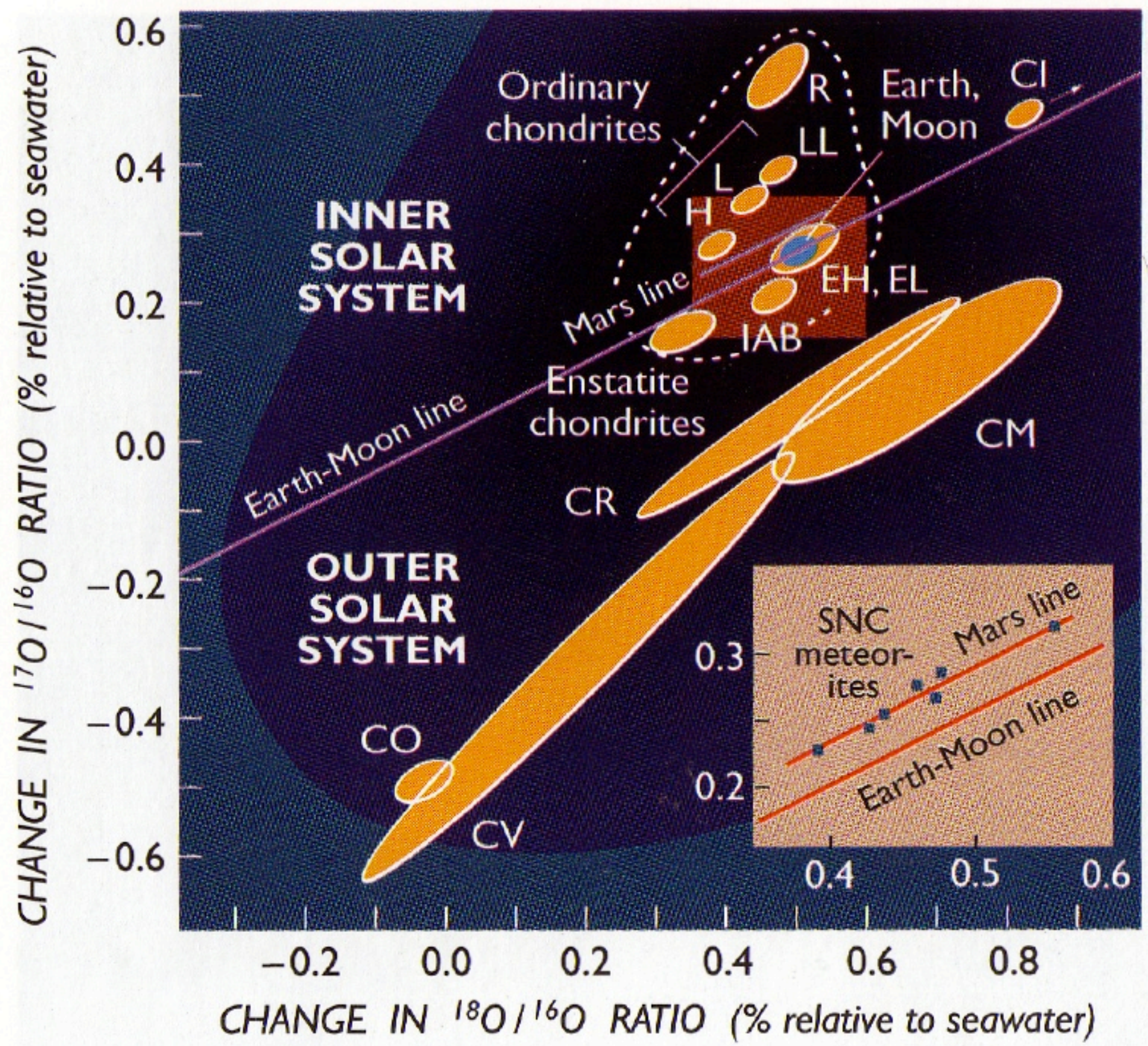
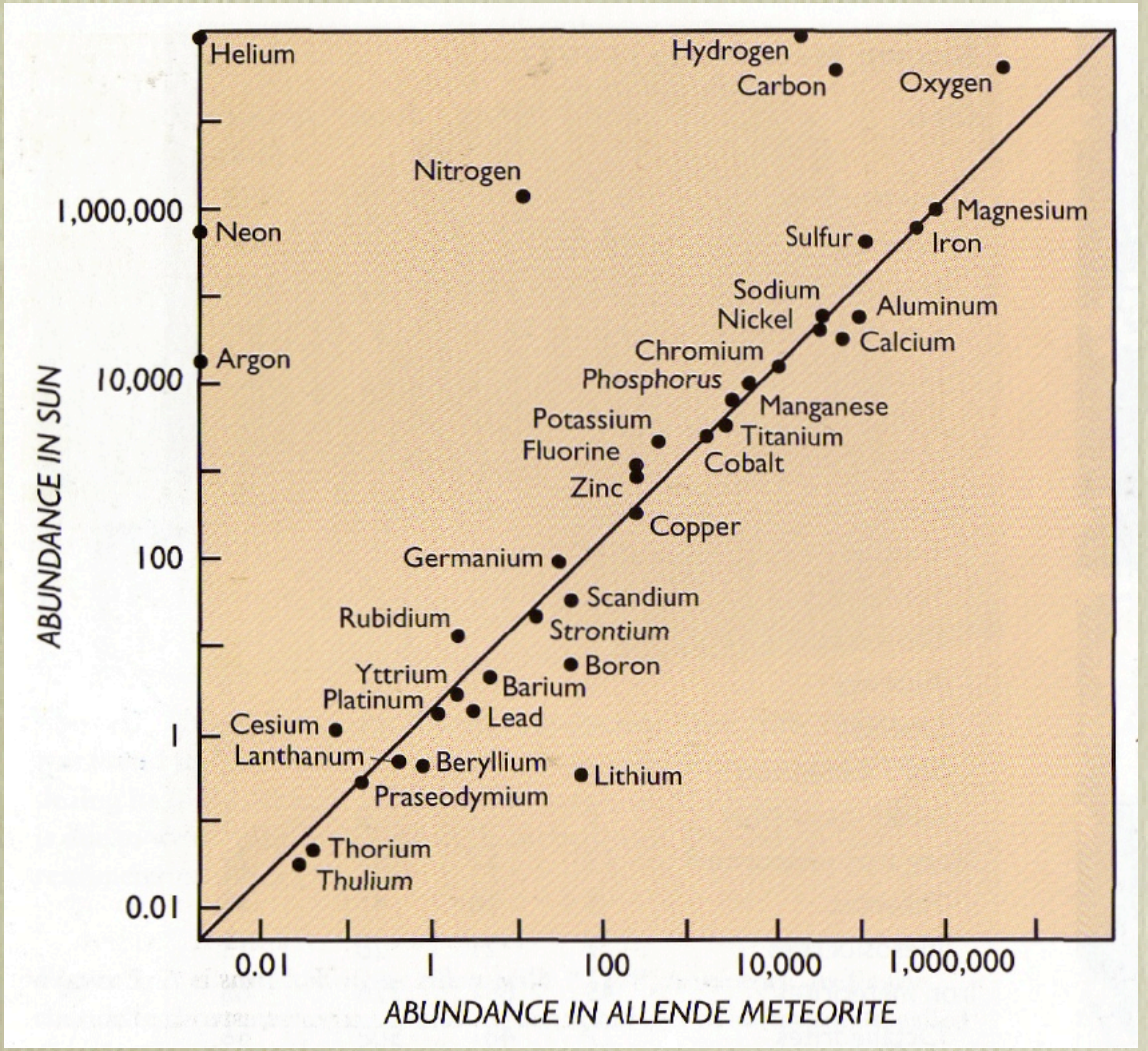


Figure 13. Cosmochemists rely on isotopic "fingerprints" to determine the origin and age of solar-system objects. Ratios of oxygen's three isotopes are particularly diagnostic. Terrestrial and lunar rocks have the same oxygen ratios, arguing that they formed at the same distance from the Sun. But the ratios in various classes of meteorites (shaded ovals) suggest different origin locations, presumably in the asteroid belt. The ratio values for the Martian SNC meteorites (inset) trend along a line that parallels the Earth-Moon line. Achondrites (not shown) also fall on straight lines that parallel that of terrestrial samples.

- ^{16}O, ^{17}O, ^{18}O: mass difference between ^{16}O and ^{18}O is twice that between ^{16}O and ^{17}O, Thus, a reaction that is mass-dependent (like physical changes or chemical reactions) and alters the $^{16}O/^{18}O$ ratio by a given amount, will alter the $^{16}O/^{17}O$ by half that amount. ⇒ mass fractionation line must have slope 1/2.
- Earth, Moon and some meteorites close together. ⇒ they formed all from the same oxygen reservoir.
- Some meteorite classes offset from Earth-Moon line (e.g. CV, CO, CR, CM chondrites).
- ⇒ Solar nebula was isotopically inhomogenous

Graphics from: J. Kelly Beatty, The New Solar System

Meteorite Composition

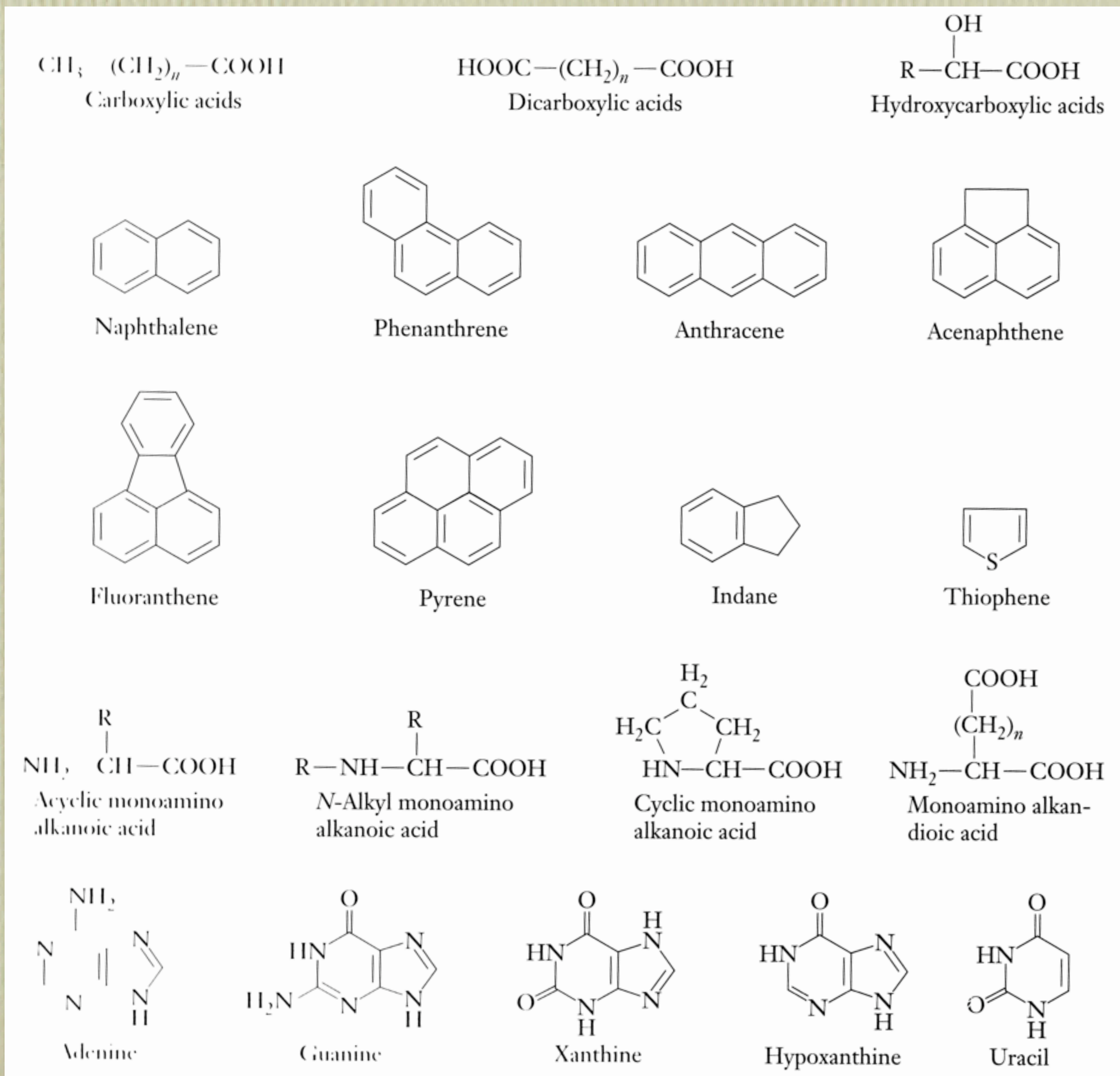


Elemental composition of CI condrites is basically identical with that of the solar photosphere (exceptions: light elements)

Graphics from: J. Kelly Beatty, The New Solar System

Meteorite Composition: Organics

Examples of organic molecules found in comets.



- More than 400 organic compounds found in meteorites.
- All non-biogenic, but some of pre-biotic relevance (amino-acids, e.g. Murchison).
- Many organics were never heated above ~300 K, otherwise they would not exist.
- Hydration: chemical modification due to presence of water (also hydrated minerals).

Graphics from: L. McFadden et al., Encyclopedia of the Solar System

Meteorites: Age Determination

- Age determination via radioactive nuclides.
- Oldest objects in the solar system: CI chondrites.
- Age of solar system: 4.567×10^9 yr.
- Nuclides used (examples):
  - $^{40}K \rightarrow {}^{40}Ar$, $t_{1/2} = 1.25 \times 10^9$ yr
  - $^{87}Rb \rightarrow {}^{87}Sr$, $t_{1/2} = 4.9 \times 10^{10}$ yr
  - $^{187}Re \rightarrow {}^{187}Os$, $t_{1/2} = 5 \times 10^{10}$ yr
  - $^{129}I \rightarrow {}^{129}Xe$, $t_{1/2} = 1.7 \times 10^7$ yr

Dust

Interplanetary Dust

Pleiades

Comet Hale-Bopp

Zodiacal Light

Picture: M. Fulle

Interplanetary Dust: Leonids

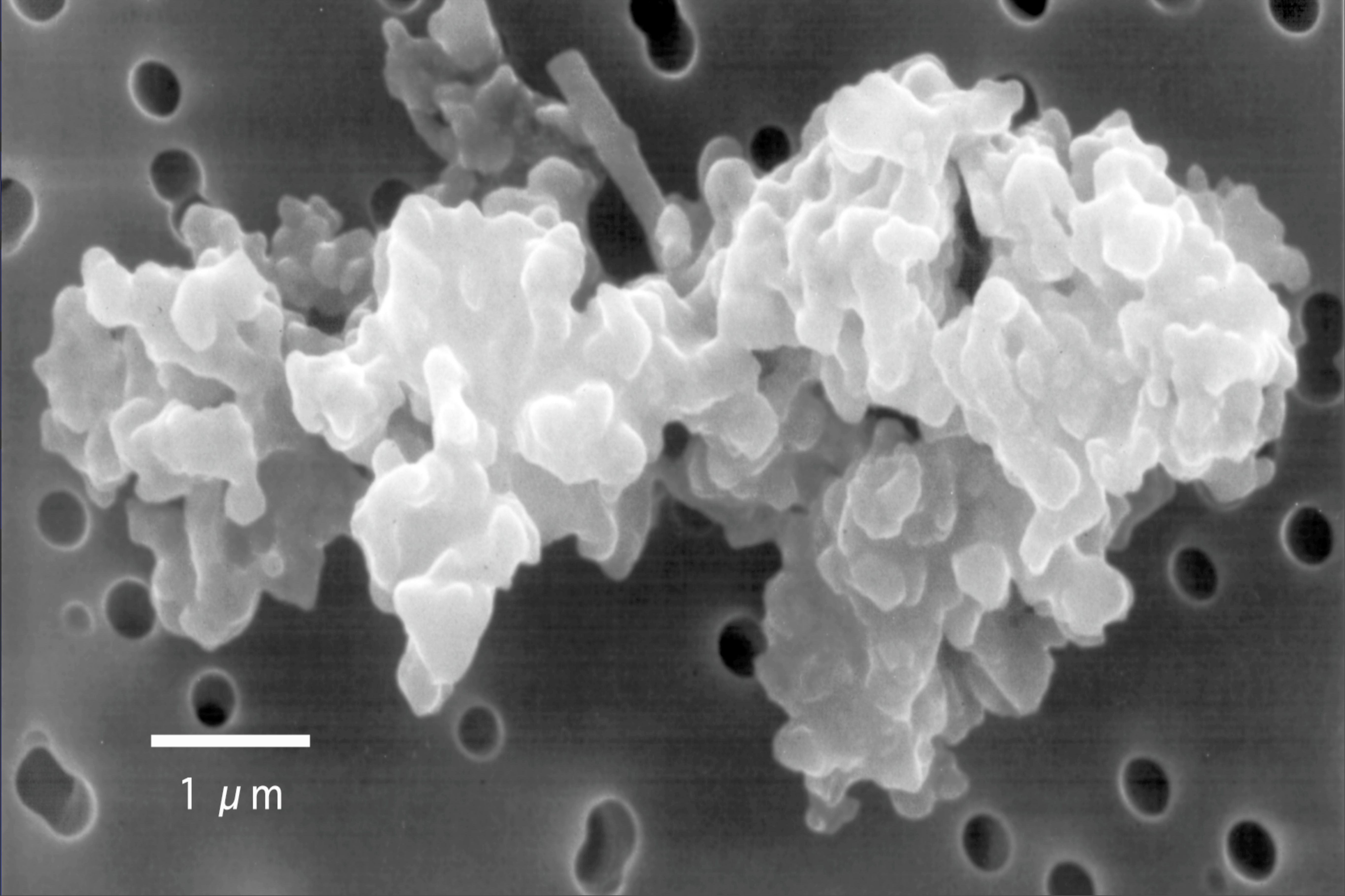
Meteor Streams

Some Comets Associated with Meteor Showers

Comet	Period (years)	Associated meteor shower	Date of maximum	ZHR
1861 I (Thatcher)	410	Lyrid	21 Apr	15
1P/Halley	75.7	Eta Aquarid	5 May	35
1P/Halley	75.7	Orionid	21 Oct	30
109P/Swift-Tuttle	134	Perseid	12 Aug	80
21P/Giacobini-Zinner	6.6	Draconid (Giacobinid)	9 Oct	20
2P/Encke	3.3	Taurid	3 Nov	10
55P/Tempel-Tuttle	33.2	Leonid	17 Nov	15
3200 Phaethon	1.4	Geminid	13 Dec	90
8P/Tuttle	13.6	Ursid	23 Dec	10

Table from: J. Kelly Beatty, The New Solar System

How Does Cosmic Dust Look Like?



Dust Detection Methods

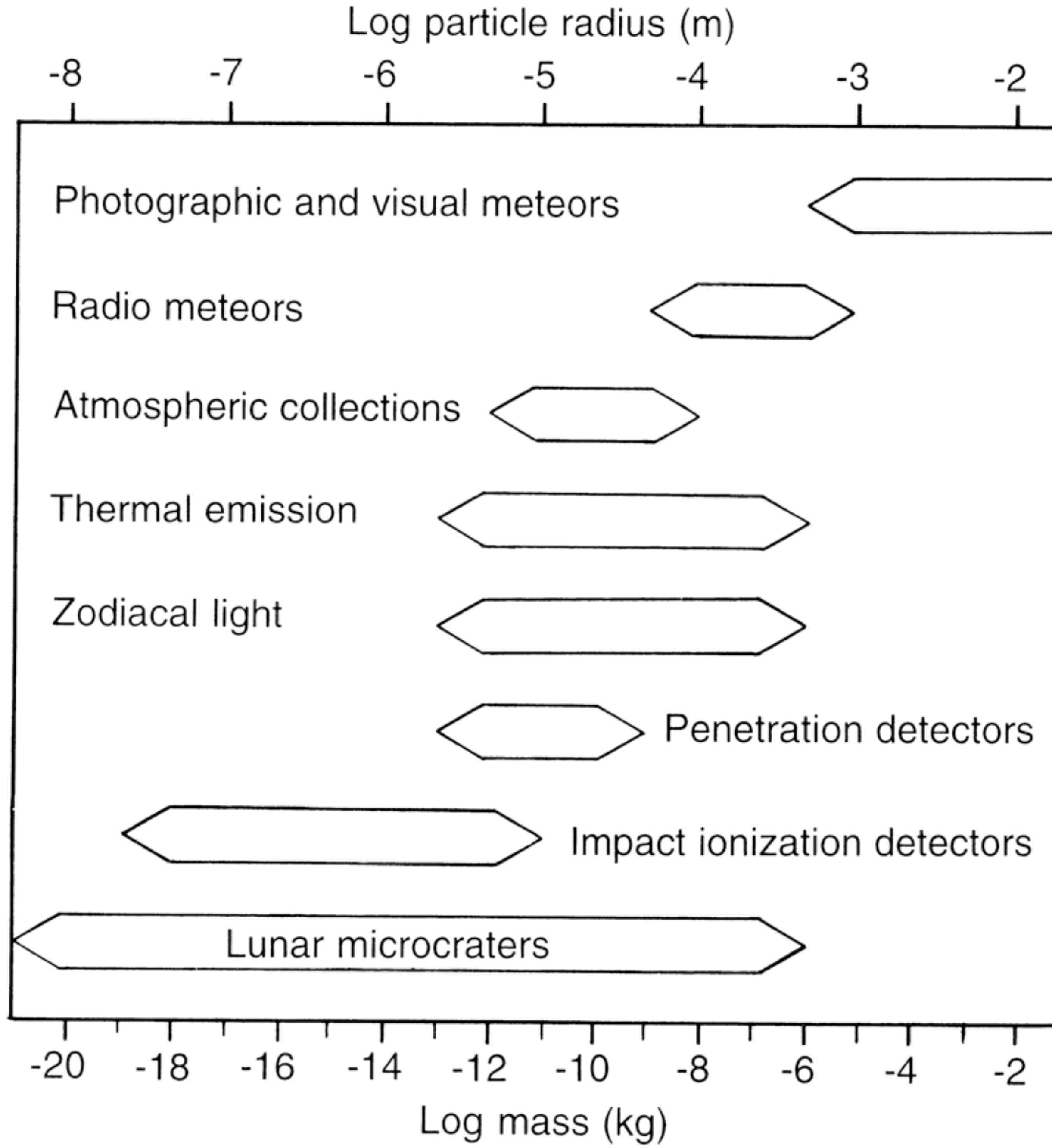
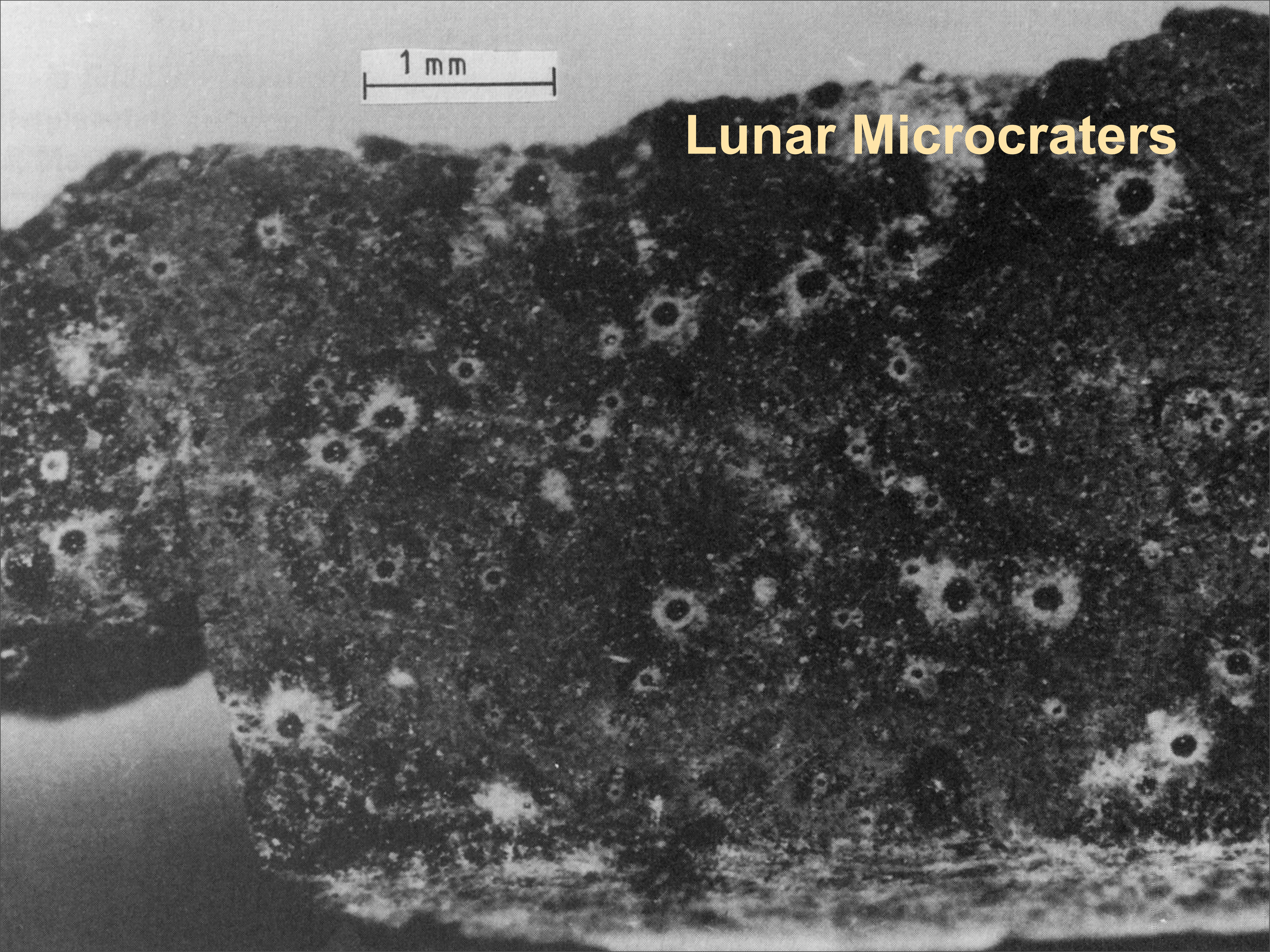
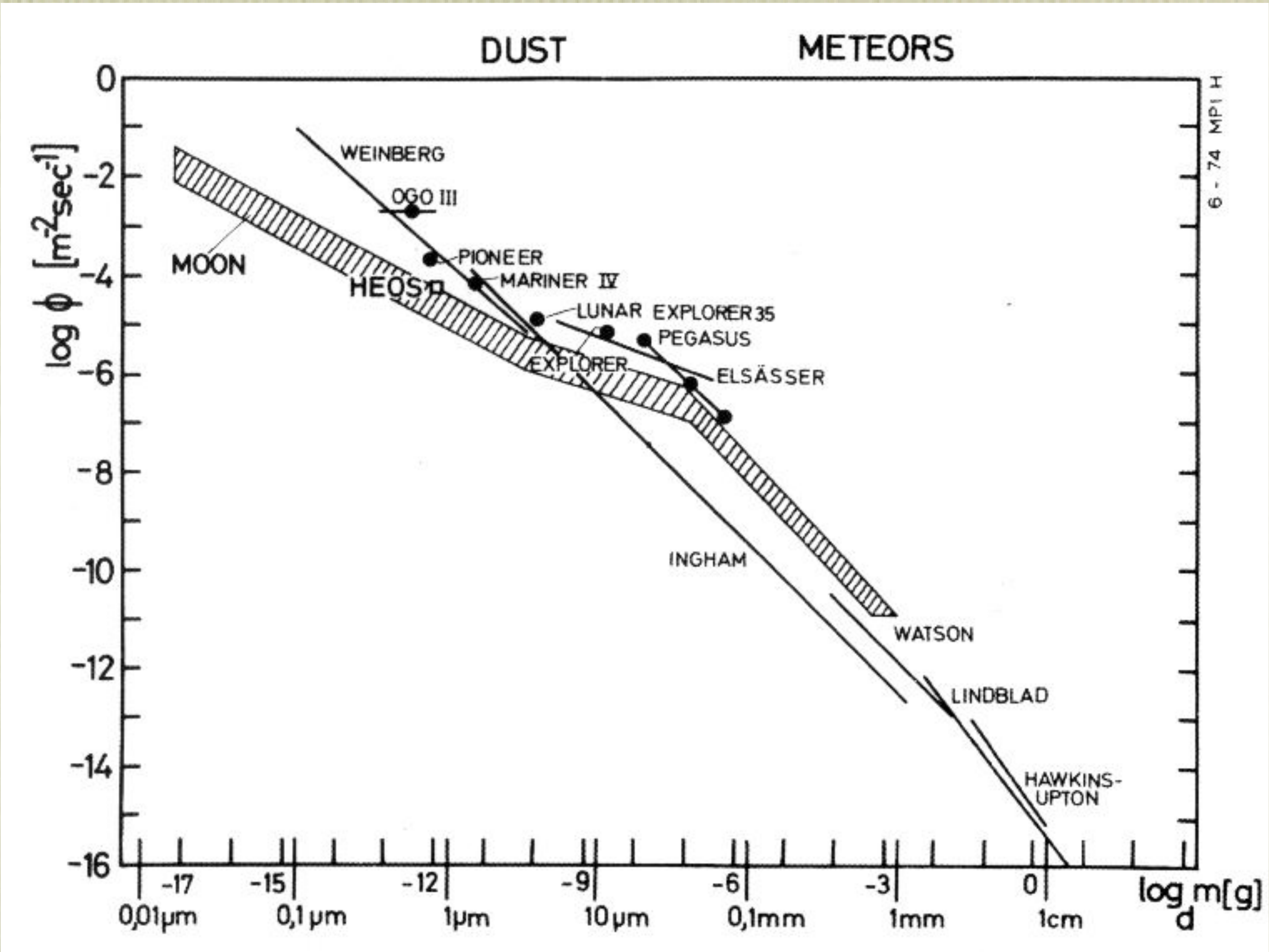


FIGURE 3 Comparison of meteoroid sizes and masses covered by different observational methods.

- Zodiacal light: scattered sunlight. Visibible close to horizon after sunset or before sunrise. Disk-like structure in inner solar system, approximately aligned with the ecliptic plane.
- Meteors: trails of excited mostly atmospheric molecules in entry channel of mm to cm sized dust. Altitude: 60 to 120 km.
- Radio meteors measured with radar.
- Atmospheric collections with airplanes in stratosphere.
- Penetration and impact ionization detectors on spacecraft.


1 mm
Lunar Microcraters

Dust Size Distribution



Typically power-law size distributions.

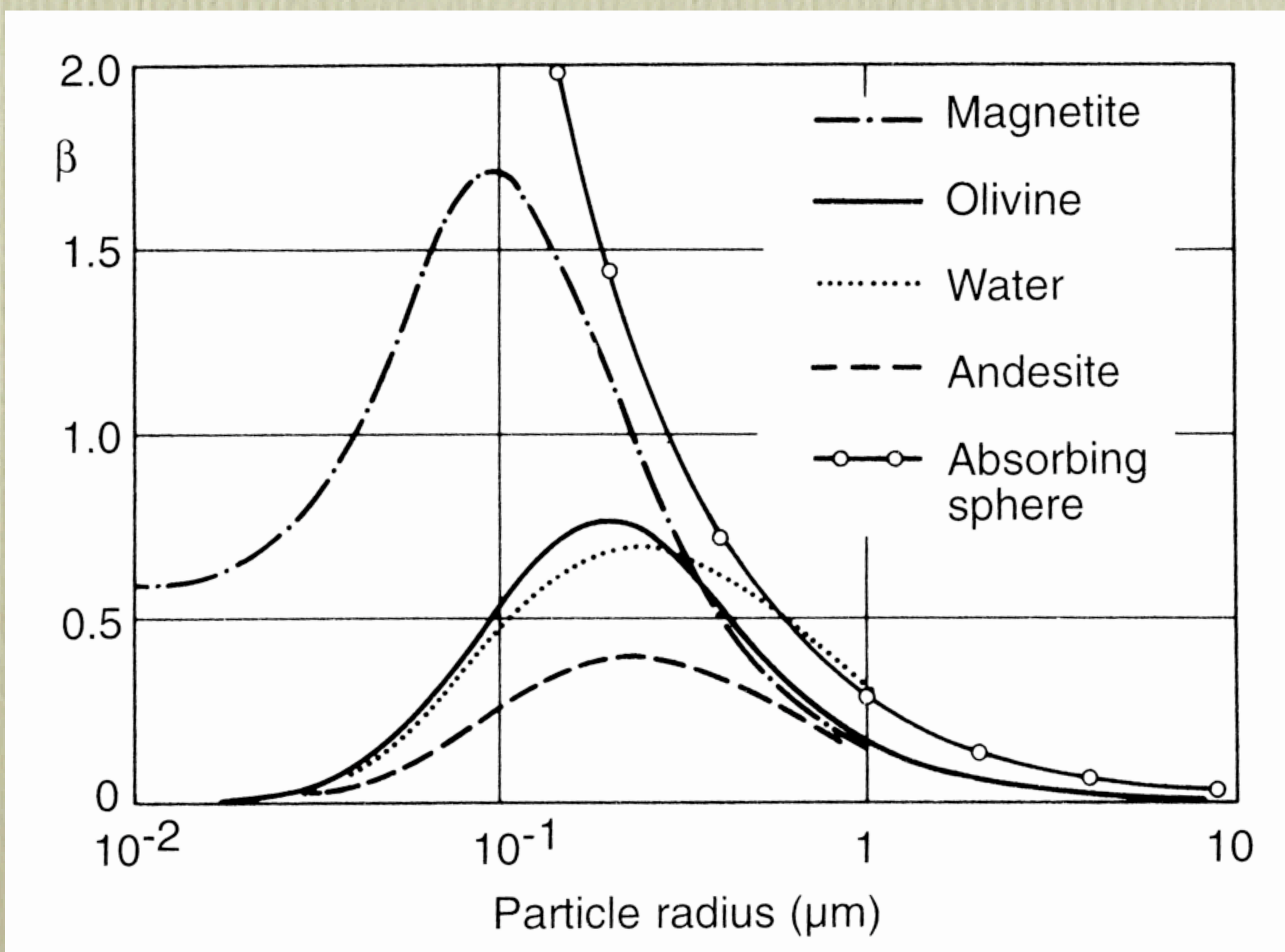
Dust Dynamics

Radiation pressure

$\beta = F_{rad}/F_{grav}$

$\beta = 1$: radiation pressure cancels gravity.

$\beta > 1$: grains ejected from solar system.



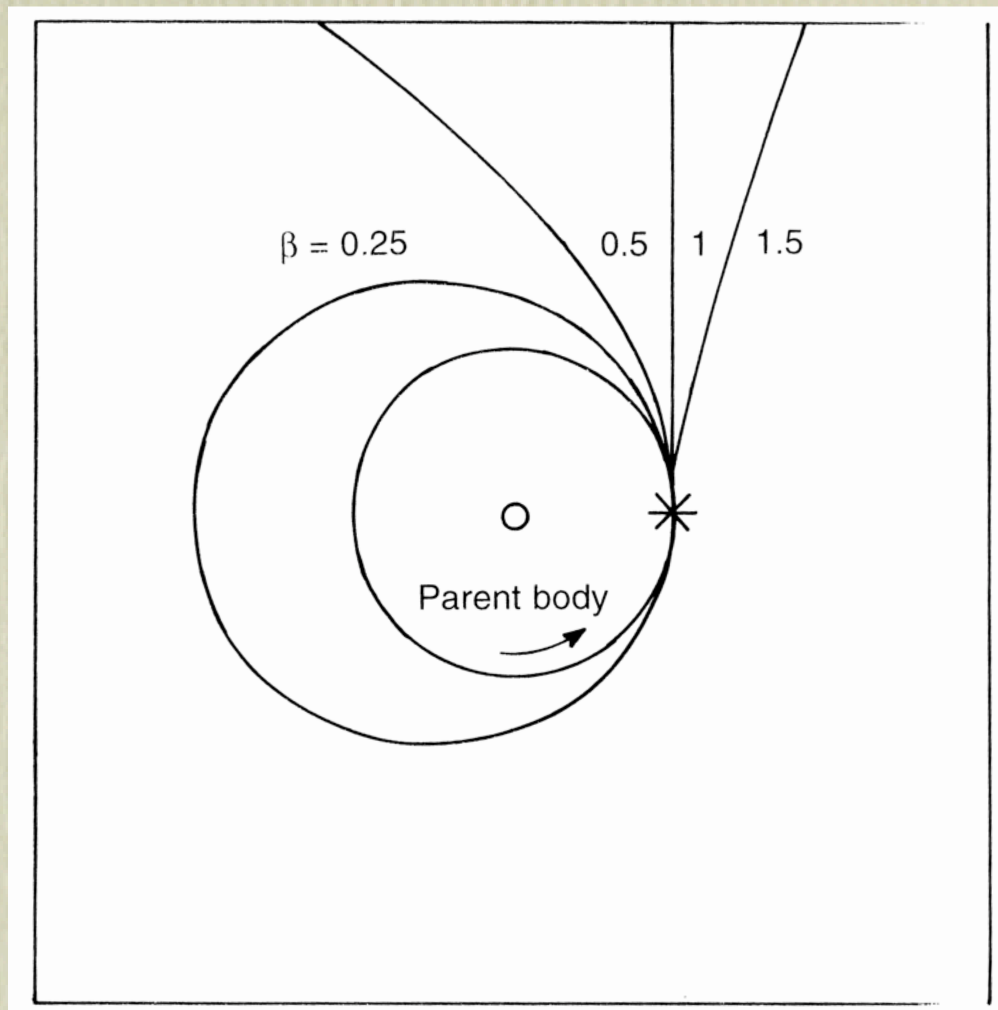
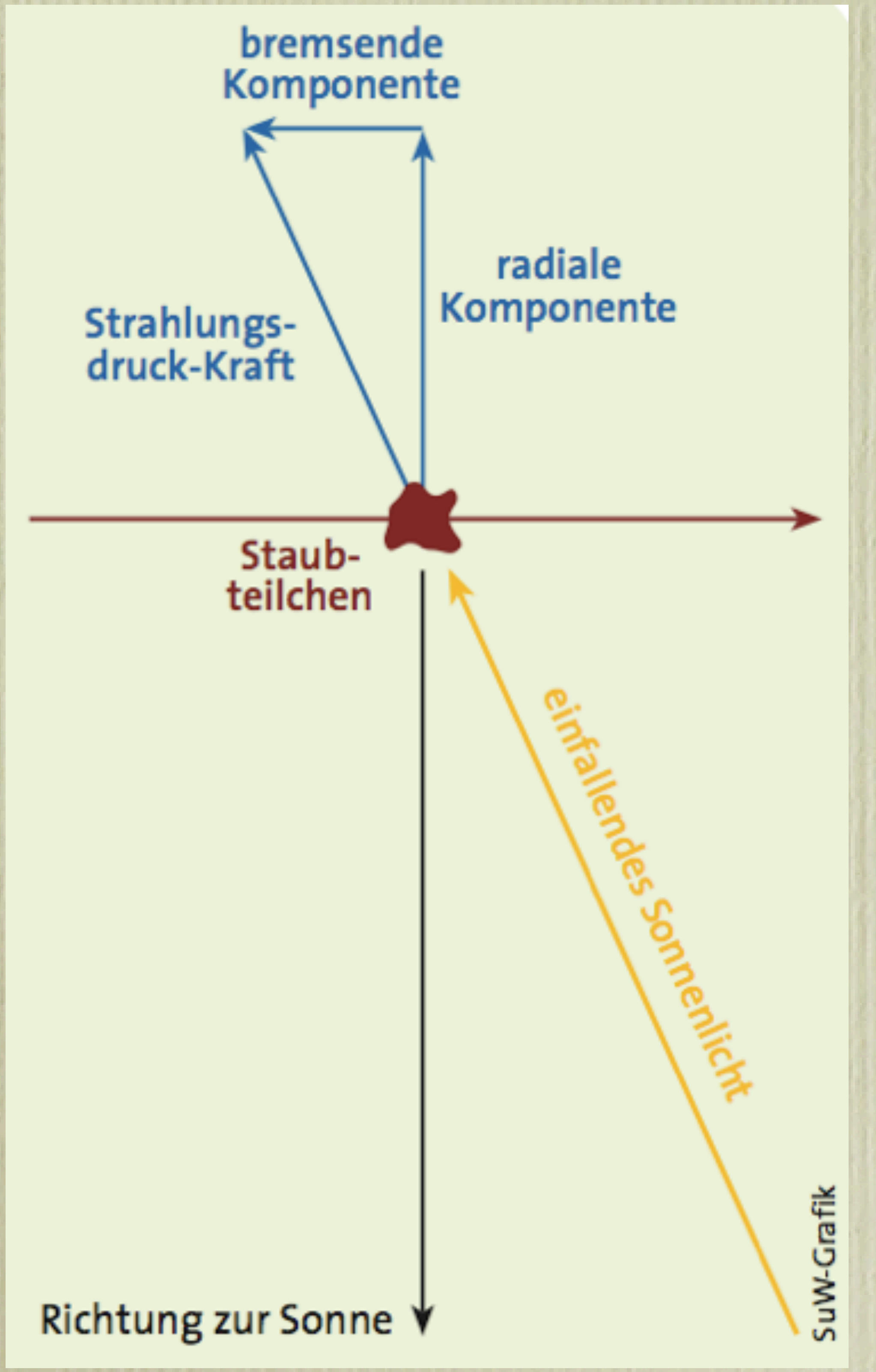


FIGURE 21 Orbits of beta-meteoroids that were generated from a parent body at the position indicated by the asterisk. β values of differently sized fragments are indicated; big β values refer to small particles.

Poynting-Robertson Drag



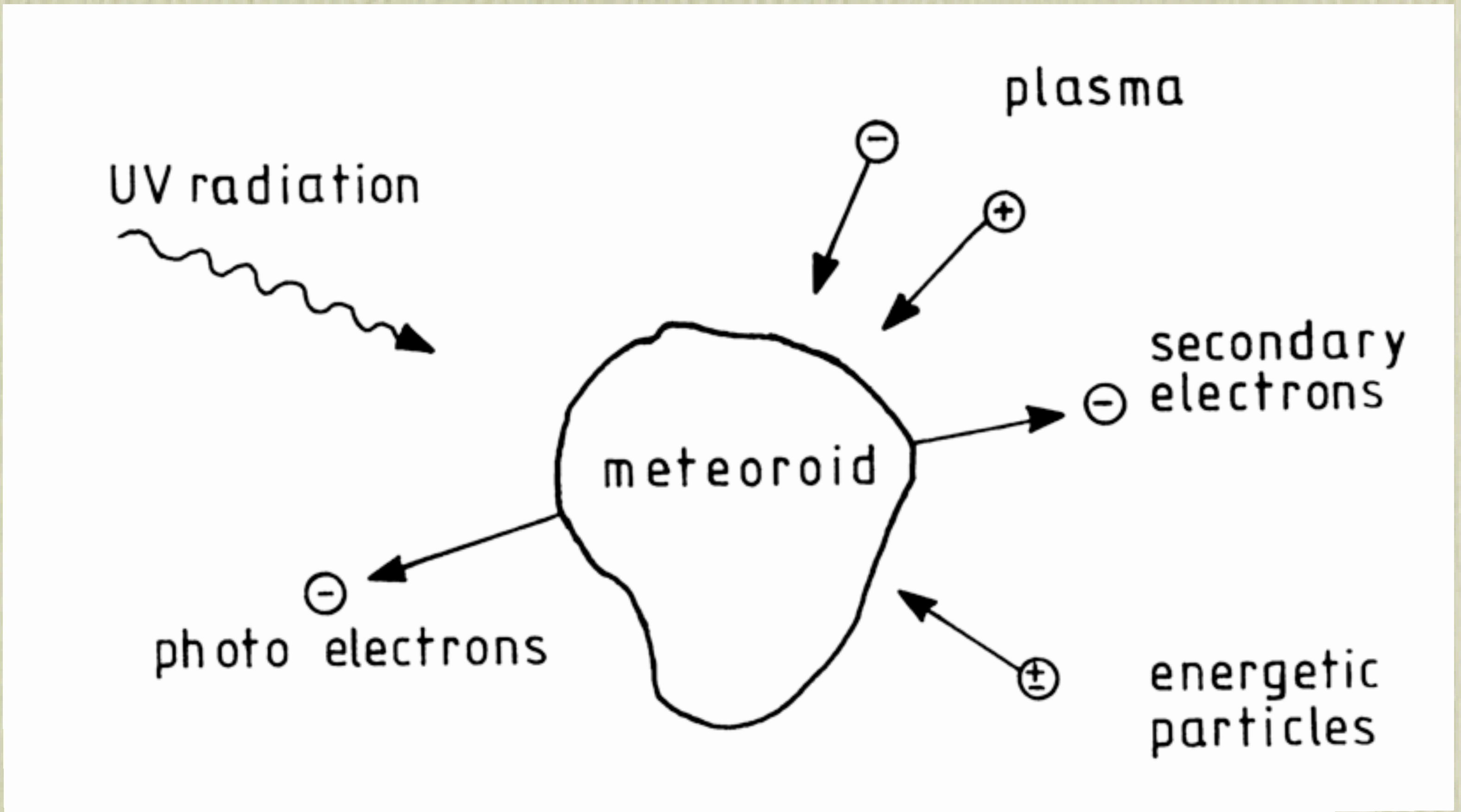
Tangential component of solar radiation pressure leads to a deceleration of dust grains moving on heliocentric orbits (aberration).

Most efficient for ~ micron-sized grains.

Particles spiral into the Sun on timescale 10^4 yr.

⇒ Continous replenishment of dust required to maintain the zodiacal cloud.

Dust Charging Processes



Dust particles exposed to the space environment almost immediately an electric charge (space dust is always charged!)

Photo effect is the dominant charging mechanism in interplanetary space: grains are positively charged.

Trans-Neptunian Objects (TNOs)

Trans-Neptunian Objects

- Orbits mostly between 35 and 50 AU.
- Large number of objects, but small total mass.
- Signatures of collisions: double objects, size distribution, collision families.
- Icy objects (water, methane) with maximum radius of ~ 1000km.
- Likely processed surfaces: collisions, high-energy radiation, activity(?)
- Reservoir for short-period comets.

Estimated Size Distribution

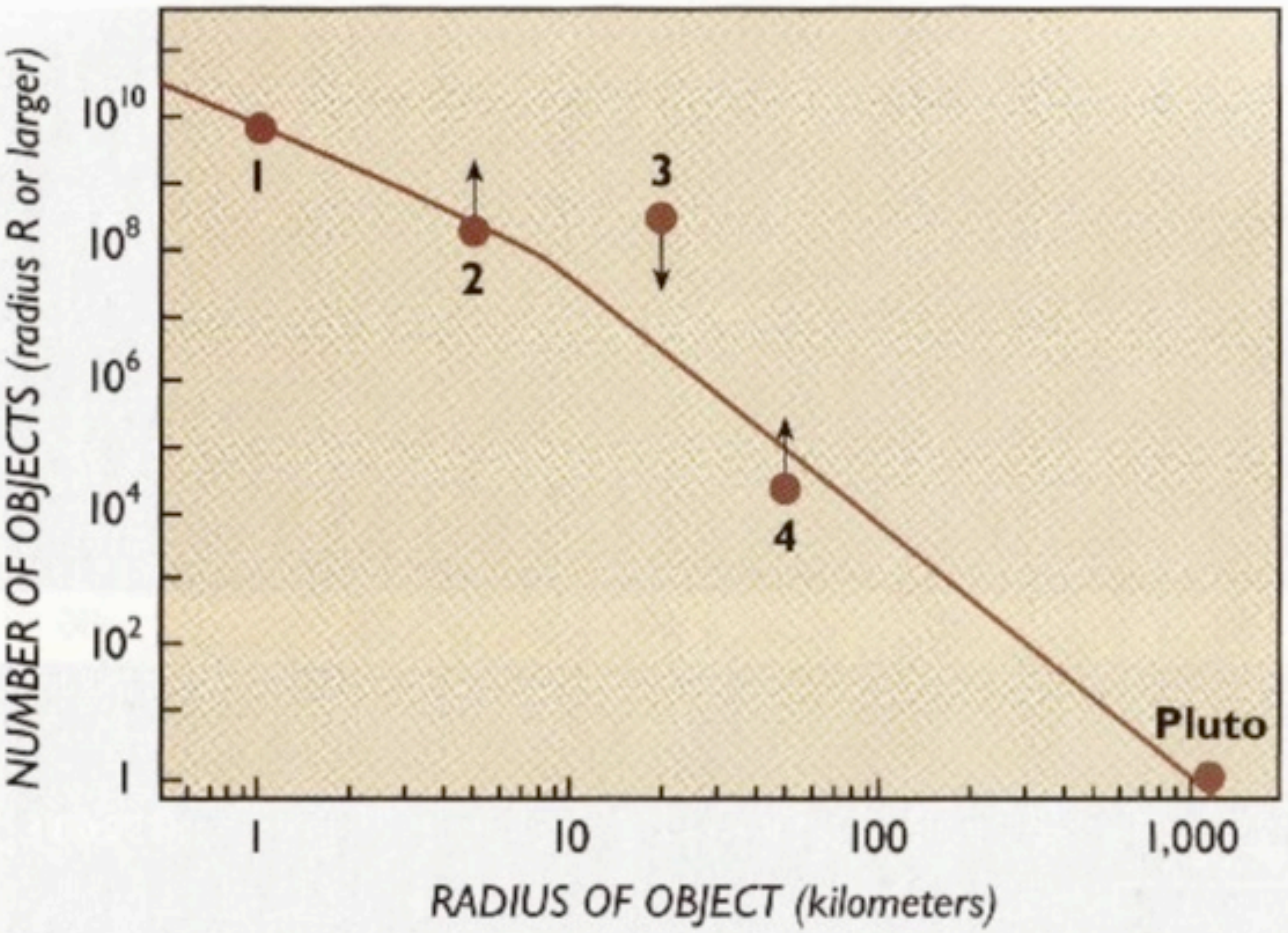
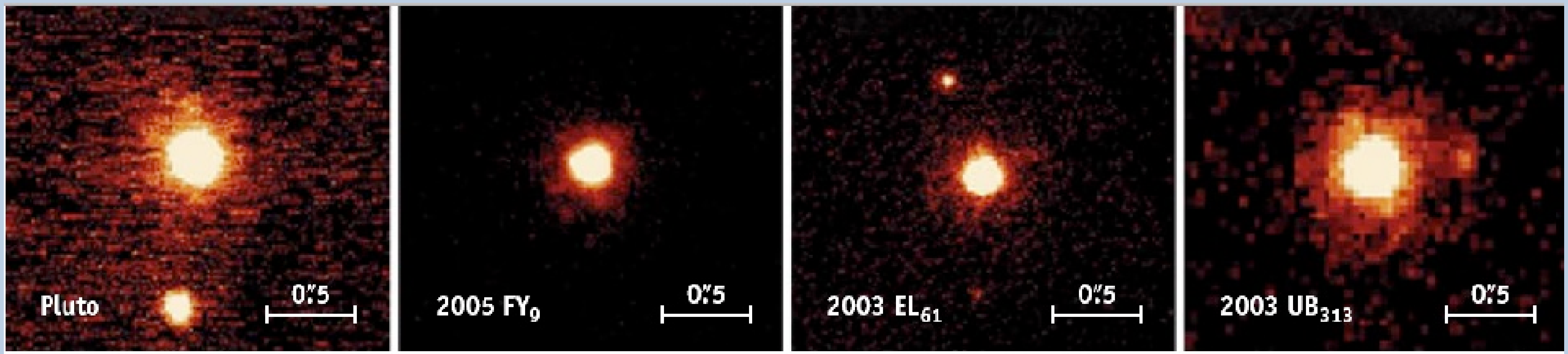
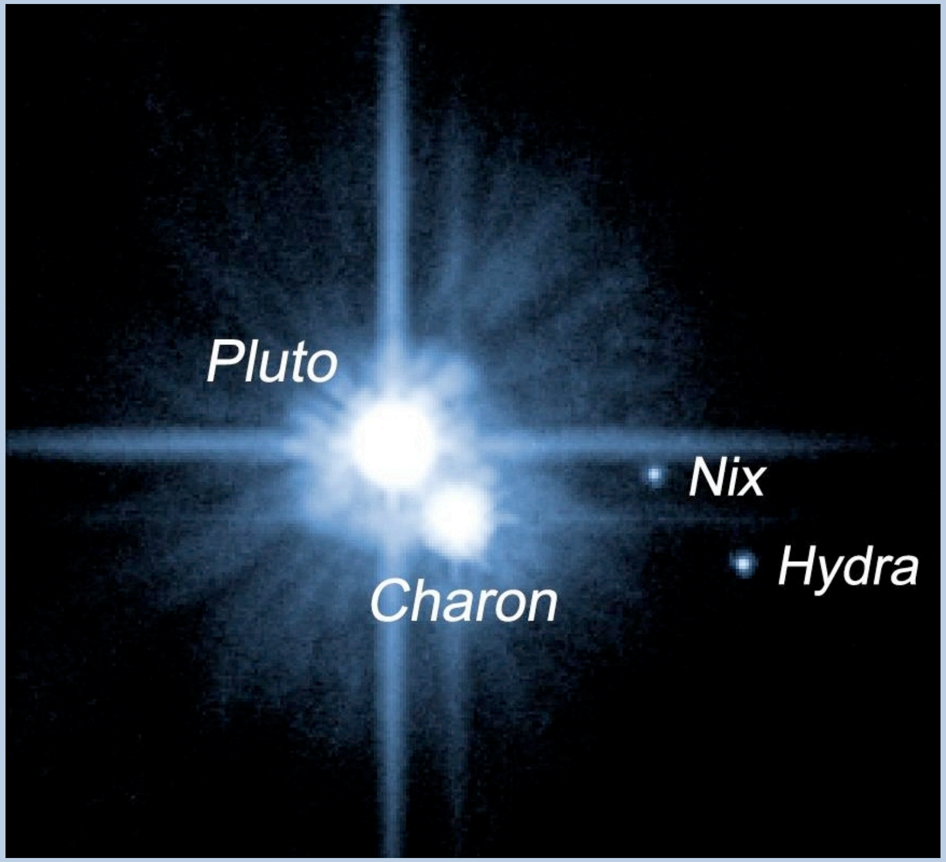
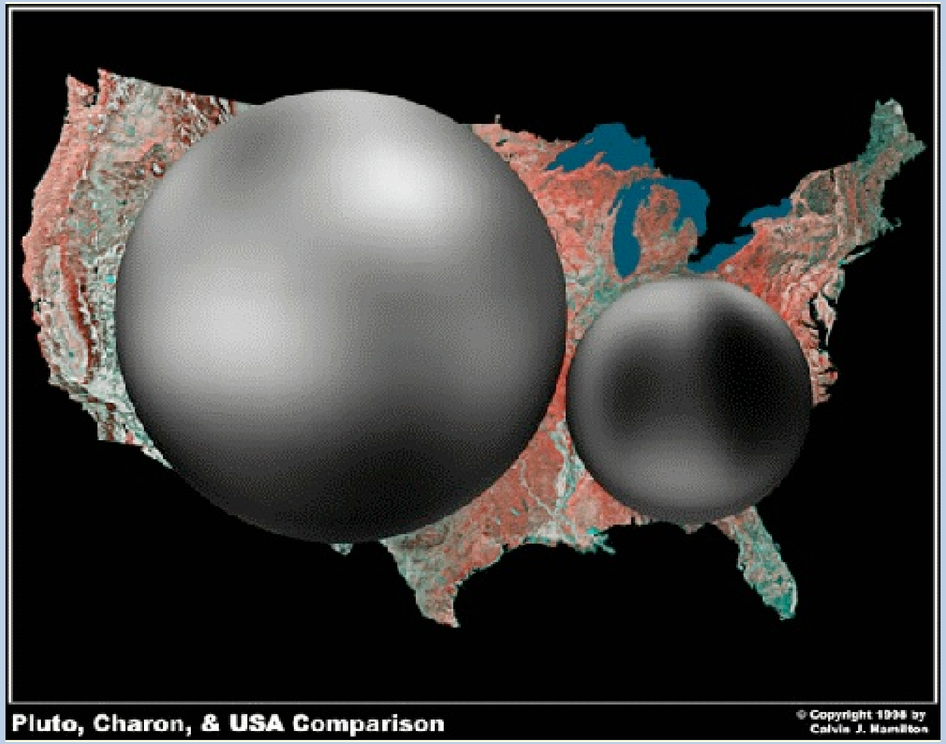


Figure 11. Estimating the total number of comets of a given size involves several observational inputs. For example, *1* is the number of objects required to provide all the short-period comets observed in the planetary region. *2* is the total number of comets implied by faint Kuiper-belt detections made with the Hubble Space Telescope. *3* is the number of comets needed to maintain the slight eccentricity in the orbit of Charon, Pluto's satellite. Point *4* is the estimated number of Kuiper-belt objects at least 100 km across, based on discovery statistics to date. The resulting size distribution is called a *broken power law*, in that the slope is shallower for small comets (radii less than 20 km) and steeper for large ones.

Trans-Neptunian Objects



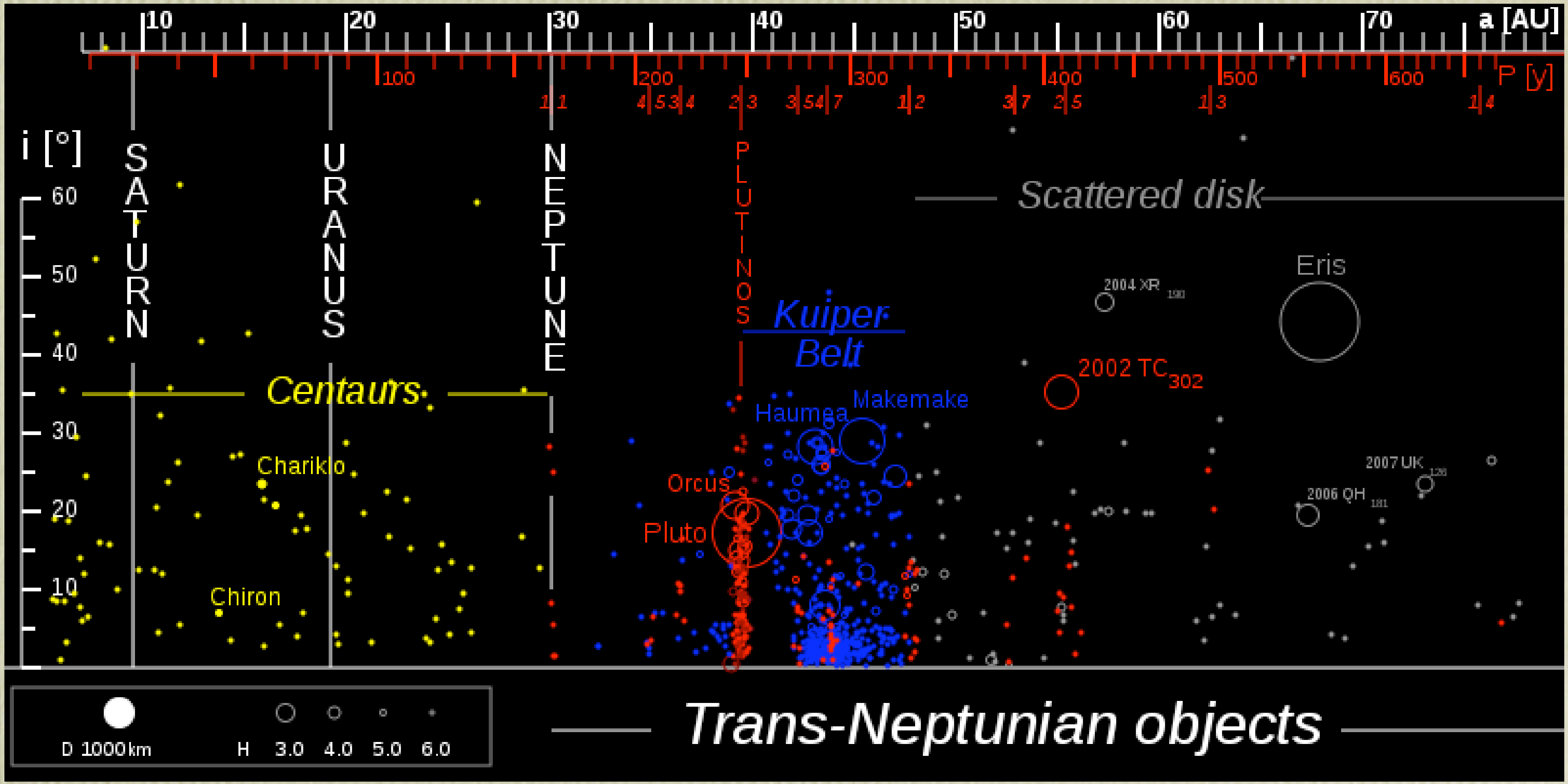




Transneptunische Objekte, HST

Saturn’s moon Phoebe - a Kuiper Belt Object?

Categories of TNOs



Object	Radius [km]	Albedo
Pluto	1150	0.5-0.6
Charon	590	0.3-0.35
1993SC	160	0.02
1996TL66	320	0.03
2000WR106	450	0.07
Chiron	180	0.15
Pholus	190	0.04
Chariklo	300	0.045

Trans-Neptunian Objects

- Kuiper Belt: mainly between 30 an 50 AU; ~ 1300 objects known; Estimated number > 100 km: 70000; estimated total mass: 3 - 30 M_{Earth}; 20 - 200 times the mass of the asteroid belt; dynamically very stable; contain water ice, methane, ammoniak; prominent objects: Pluto, Haumea, Makemake.

- Centaurs: comet-like objects that move between gas planets; ca. 250 objects known; Neptune's moon Triton probably a captured Centaur.

- "Scattered Disk": scattered, unbound objects; more than 100 objects known; semi-major axis $a > 50$ AU; dynamically unstable; source for intermediate period comets with 20 yr < P < 200 yr; formed when Neptune's orbit moved outward; prominent objects: Eris, Sedna.