

Lecture 12: Meteorites, Asteroids, Minor Planets & Comets

Planetary Systems

Tim Lichtenberg
Kapteyn Astronomical Institute
University of Groningen

2026

Learning Objectives

By the end of this lecture, you will be able to:

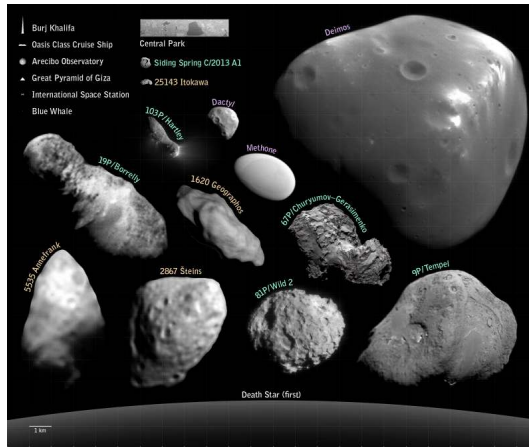
- Classify meteorites and derive the Pb-Pb isochron age of calcium-aluminium-rich inclusions (CAIs)
- Describe the asteroid-belt and trans-Neptunian populations and their dynamics
- Explain the origin, anatomy and volatile composition of comets, and read small bodies as fossils of planet formation

Recap: Where We Are in the Course

- Lectures 9–11 surveyed the major planets across the rocky and giant classes
- Today: the leftovers; asteroids, meteorites, KBOs, comets, and the Oort cloud
- Small bodies act as formation fossils preserving disk chemistry and migration history

Today: What do the leftovers reveal about the origin of planetary systems?





Small bodies visited by spacecraft, to scale with terrestrial landmarks.

Credit: NASA/JPL-Caltech.

Three reservoirs hold them: the main belt ($2.1\text{--}3.3\text{ AU}$, $\sim 4 \times 10^{-4} M_{\oplus}$), the Kuiper Belt, and the Oort cloud ($2,000\text{--}50,000\text{ AU}$, inferred, never directly observed).

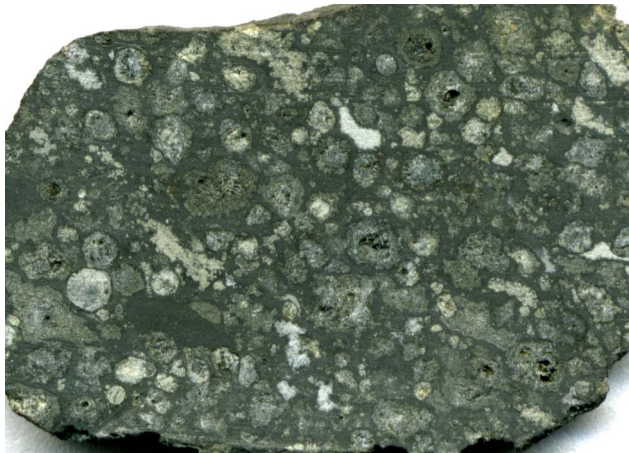


2. Meteorite Taxonomy

Allende meteorite (CV3 chondrite, fell 1969). J. St. John CC BY 2.0

Why Meteorites Matter

- **Laboratory access:** ~70,000 catalogued specimens; the primitive ones are older than the oldest terrestrial zircons (~ 4.4 Ga)
- **Presolar material:** primitive chondrites contain grains that condensed around other stars, older than the Sun
- **Anchor age:** CAI crystallization age of 4567.30 ± 0.16 Myr anchors solar system history



Allende slab: chondrules and bright CAIs in a dark matrix. Credit: James St. John, CC BY 2.0.

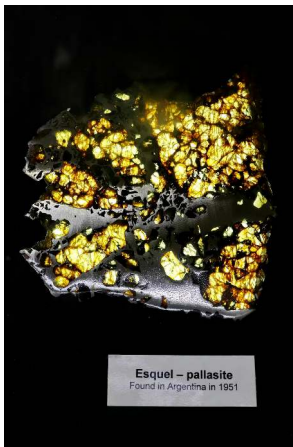
Chondrites never melted whole and keep their mm-scale chondrules; achondrites, irons and stony irons come from parent bodies that short-lived ^{26}Al melted and differentiated: irons are cores, achondrites crusts and mantles.



Widmanstätten pattern in an iron meteorite: a kamacite and taenite Fe-Ni lattice.

Credit: H. Raab, CC BY-SA 3.0 (Wikimedia Commons).

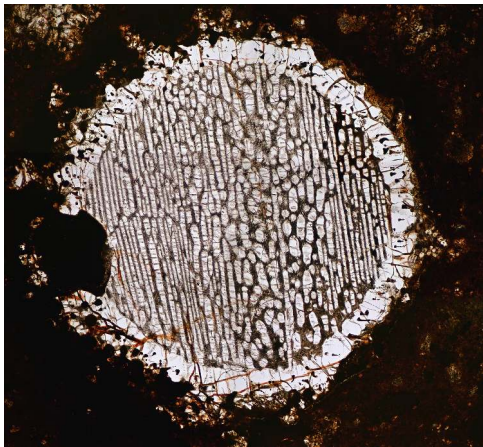
The lattice grows only at cooling rates $\leq 100 \text{ K Myr}^{-1}$, inside the metallic core of a body tens of km across; its spacing gives the original parent-body radius.



Esquel pallasite: yellow-green olivine in silvery Fe-Ni metal.

Credit: UCLA Meteorite Gallery, CC BY-SA 4.0 (Wikimedia Commons).

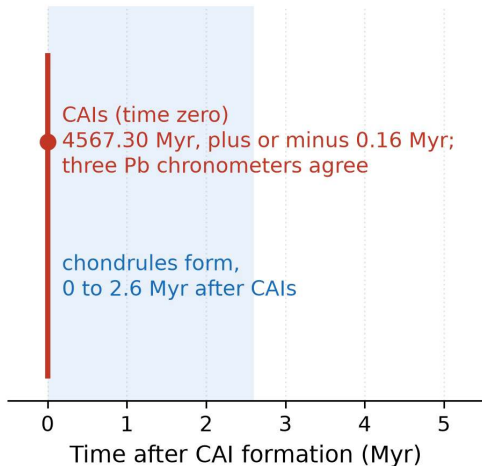
Likely a sample of a planetesimal's core-mantle boundary: molten metal mixed into the olivine of the mantle, possibly during a giant impact.



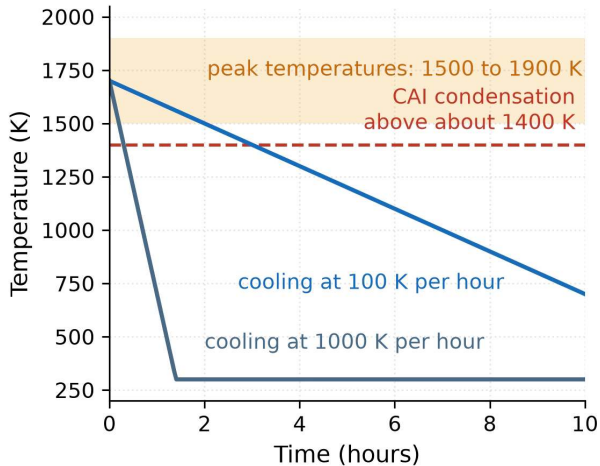
Cross-polarised thin section of NWA 5930: each chondrule is a mm-scale bead of olivine and pyroxene. Credit: H. Raab, CC BY-SA 3.0 (Wikimedia Commons).

Each chondrule froze from a fully molten droplet in seconds to hours from a peak of 1500–1900 K; how chondrules form remains an unsolved problem.

(a) The oldest solids



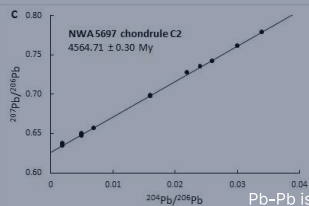
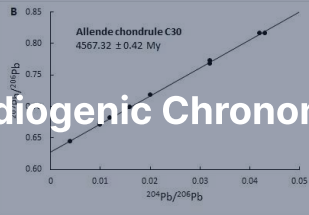
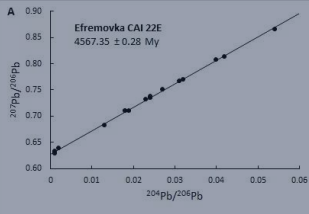
(b) A chondrule's heating event



(a) CAIs at 4567.30 Myr define $t = 0$ and individual chondrules date from $t = 0$ to 2.6 Myr; (b) a chondrule heating event from a 1700 K peak, cooling at 100 and 1000 K per hour.

Course figure.

3. Radiogenic Chronometers



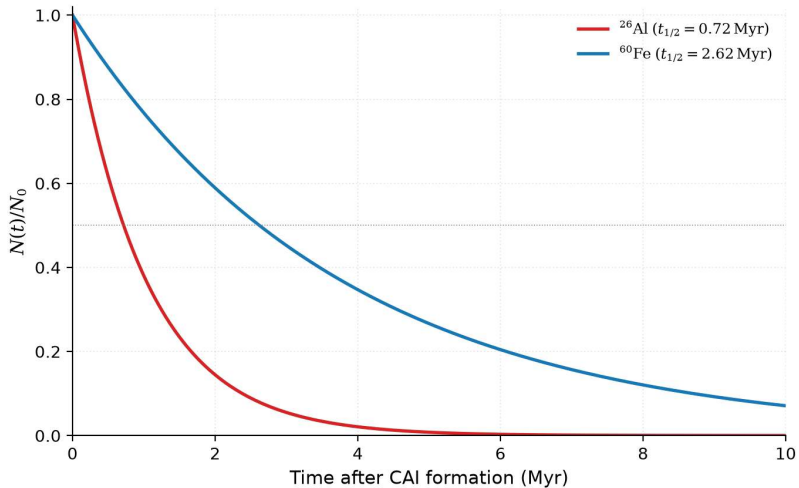
Pb-Pb isochrons for CAI 22E and chondrules. Connelly et al. (2012)

Decay Clocks and Early Solar System Timeline

Radioactive decay $\frac{dN}{dt} = -\lambda N$ ($t_{1/2} = \ln 2 / \lambda$) provides absolute and relative chronometers:

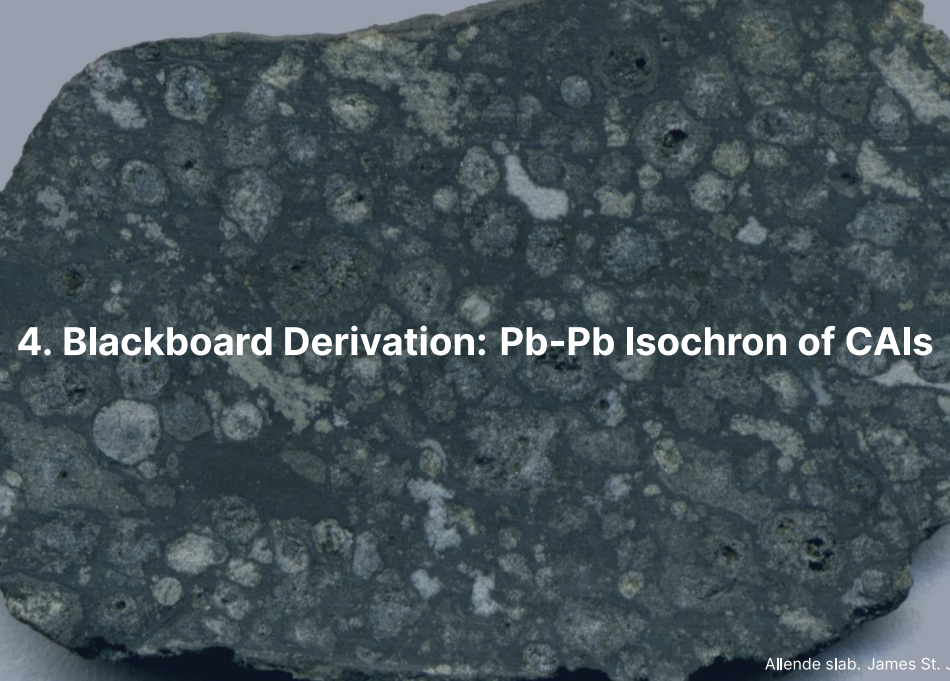
- **Long-lived:** ^{238}U , ^{235}U yield absolute ages; CAIs condense at $t_0 = 4567.30 \pm 0.16$ Myr
- **Short-lived (extinct):** ^{26}Al (0.717 Myr), ^{182}Hf (8.9 Myr) yield relative ages
- **Early chronology:** differentiation at 0.5–4 Myr, most chondrules at 1–3 Myr after CAIs

Long-lived chronometers anchor absolute time; extinct nuclides resolve events to < 1 Myr.



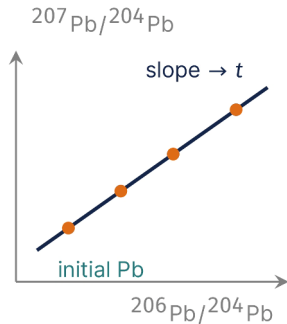
Decay of ^{26}Al (0.72 Myr half-life) and ^{60}Fe (2.62 Myr) after CAI formation. Course figure.

Their rapid decay powered early planetesimal melting and differentiation.



4. Blackboard Derivation: Pb-Pb Isochron of CAIs

Goal and Strategy



Goal: the age of the oldest solids from two parallel decay chains of one element.

- $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ (4.4683 Gyr) and $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ (0.7038 Gyr); ^{204}Pb is the stable reference
- Daughter since closure:
 $^{206}\text{Pb}^* = ^{238}\text{U} [e^{\lambda_{238}t} - 1]$, same for 207; add the initial Pb
- Divide the 207 line by the 206 line so the U/Pb of the rock drops out

To the board.

Step 3: The Pb-Pb Isochron

Cogenetic samples with unknown initial Pb fall on a line in ($^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$) whose slope depends only on t :

$$\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*} = \frac{^{235}\text{U}}{^{238}\text{U}} \frac{e^{\lambda_{235}t} - 1}{e^{\lambda_{238}t} - 1}, \quad \frac{^{235}\text{U}}{^{238}\text{U}} = \frac{1}{137.8}$$

The slope is independent of the initial Pb and of the U/Pb ratio: the age needs no assumption about the starting composition.

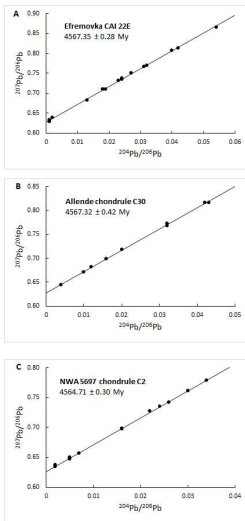
Step 4: The CAI Age

Connelly et al. (2012), CAIs from Efremovka (CV3), one from Allende, after acid leaching:

$$t_{\text{CAI}} = 4567.30 \pm 0.16 \text{ Myr}$$

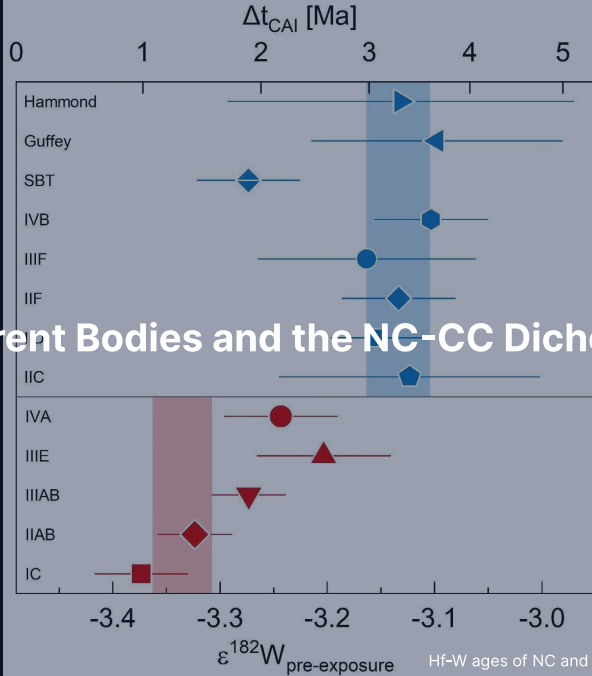
- Independent samples and labs agree to the same precision (Amelin et al. 2010)
- Chondrules from Allende and NWA 5697: 0 to 2.6 Myr younger
- The *zero point* of the solar system clock

Two parallel decay chains make the problem self-calibrating.



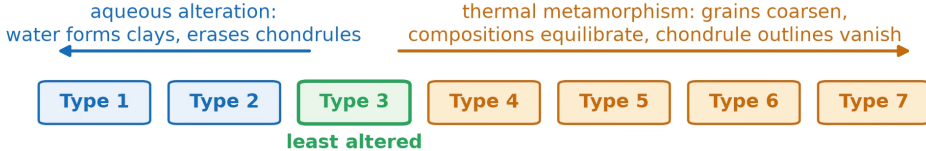
Pb-Pb isochrons for CAI 22E (Efremovka) and chondrules in the inverse form: the intercept of the mineral-fraction line at zero ^{204}Pb gives the radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ and so the age t , independent of the initial Pb. From Connelly et al. (2012).

5. Parent Bodies and the NC-CC Dichotomy

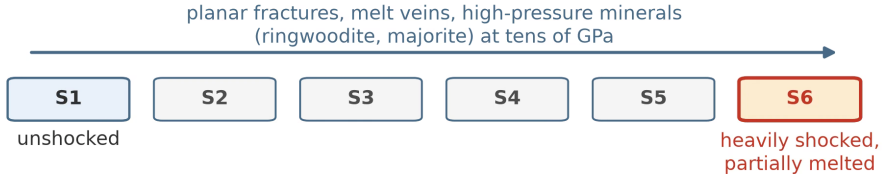


Two scales that record what happened on the parent body

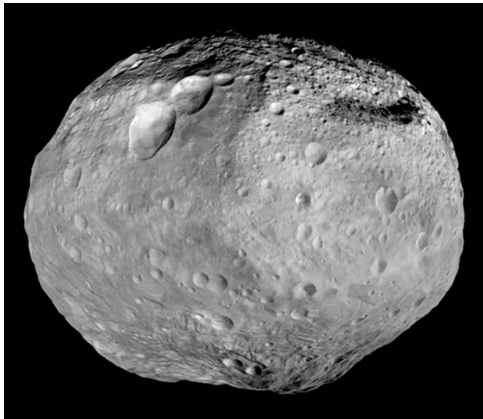
Petrographic type (scale 1 to 7)



Shock stage (scale S1 to S6)



Petrographic types 1 to 7 (aqueous alteration to thermal metamorphism) and shock stages S1 to S6 record what the parent body did. Course schematic.

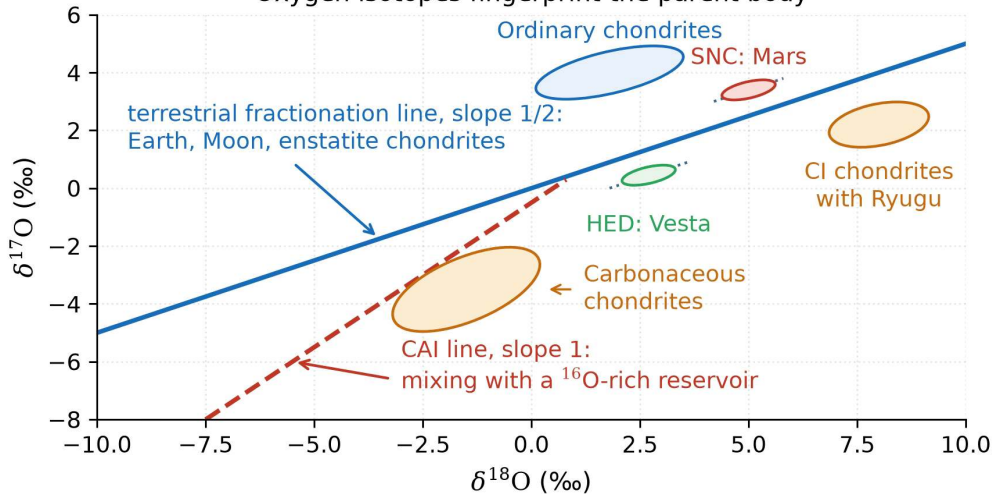


Vesta seen by Dawn (2011–2012), the parent body of the HED meteorites.

Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA, public domain.

HEDs (howardites, eucrites, diogenites, ~ 6% of falls) match Vesta in mineralogy and oxygen isotopes and were ejected from the Rheasilvia basin; lunar meteorites match the Apollo samples, Martian ones carry trapped Mars atmosphere.

Oxygen isotopes fingerprint the parent body

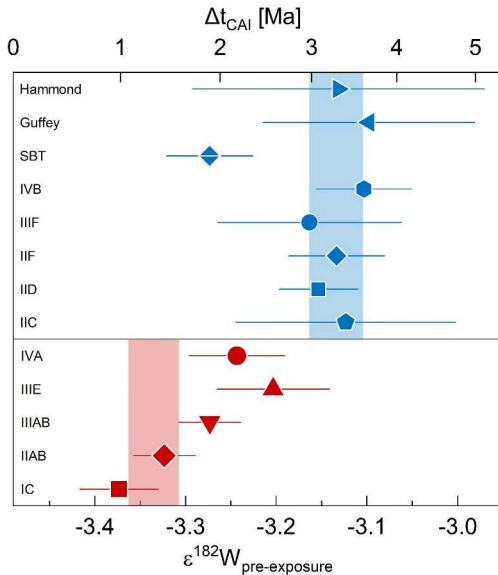


Oxygen three-isotope plot: the terrestrial line of slope 1/2, the CAI slope-1 mixing line towards pure ^{16}O , and the chondrite, HED and SNC fields. Course figure.

Two Isotopic Reservoirs

Nucleosynthetic anomalies in Ti, Cr, Mo, Ru and Ca divide solar system materials into two isolated reservoirs:

- **NC reservoir (non-carbonaceous):** ordinary and enstatite chondrites, HEDs, Earth, and Mars
- **CC reservoir (carbonaceous):** carbonaceous chondrites, several iron groups, and outer bodies
- **Prolonged isolation:** the two reservoirs did not mix isotopically for ~ 3–4 Myr after CAIs



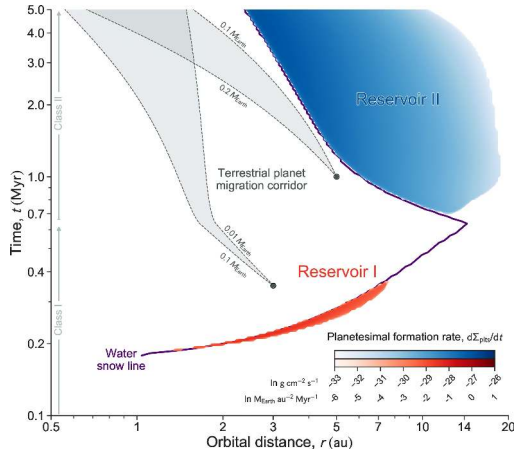
Hf-W ages of NC (red) and CC (blue) iron meteorites: $\epsilon^{182}\text{W}$ below, the age it gives above. Spitzer et al. (2021).

NC irons (-3.37 to -3.20) formed cores 1.0–2.6 Myr after CAIs, CC irons (-3.16 to -3.10) at 3.0–3.6 Myr. NC cores form ~ 2 Myr before CC cores.

Three Live Interpretations

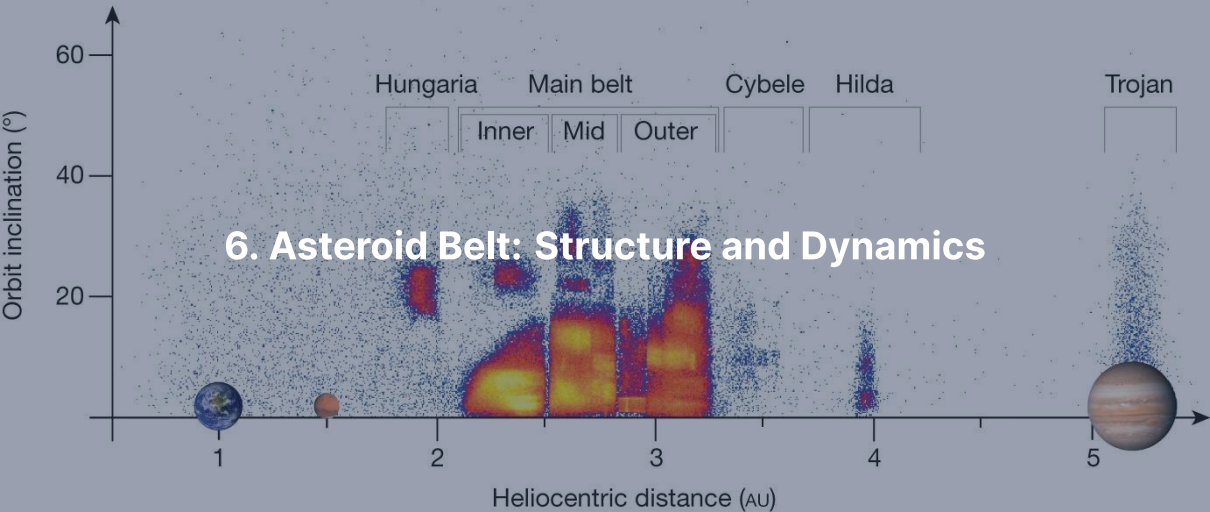
Three competing mechanisms explain the NC-CC dichotomy from identical cosmochemical data:

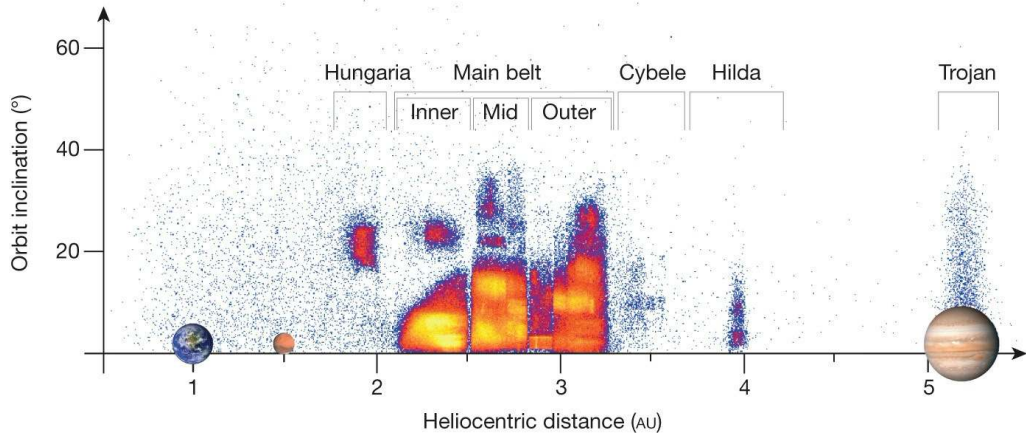
- **Jupiter barrier:** early proto-Jupiter ($\lesssim 1$ Myr) opens a gap, blocking inward pebble drift (Kruijer et al. 2017)
- **Snow line:** disk thermal evolution produces two successive planetesimal formation epochs (Lichtenberg et al. 2021)
- **Temporal change:** the inner-disk composition changed with time during infall (Schiller et al. 2018; Spitzer et al. 2020)



Disk simulation in time against orbital distance with two planetesimal formation reservoirs.
Lichtenberg et al. (2021).

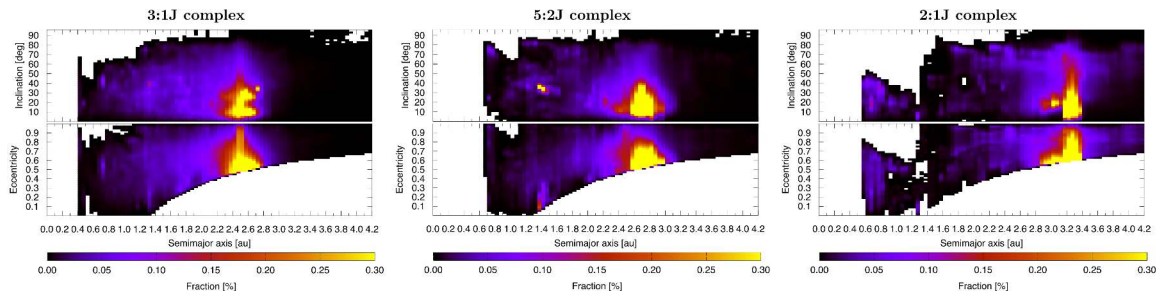
Reservoir I (red), early and dry in the inner disk, is NC; Reservoir II (blue), later and ice-rich in the outer disk, is CC: the bifurcation arises from disk evolution itself.





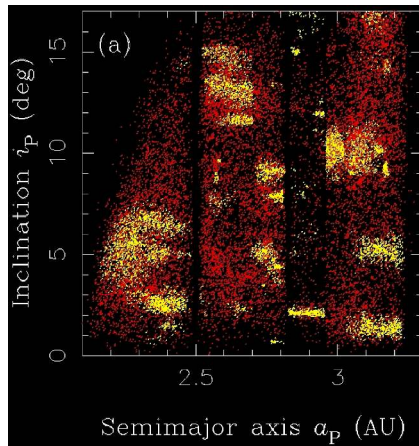
Asteroid inclination against distance: Hungarias, main belt, Hildas, Trojans.
DeMeo & Carry (2014).

A total mass of $\sim 4 \times 10^{-4} M_{\oplus}$ (Ceres $\approx 40\%$); the vertical gaps are the Kirkwood resonances with Jupiter.



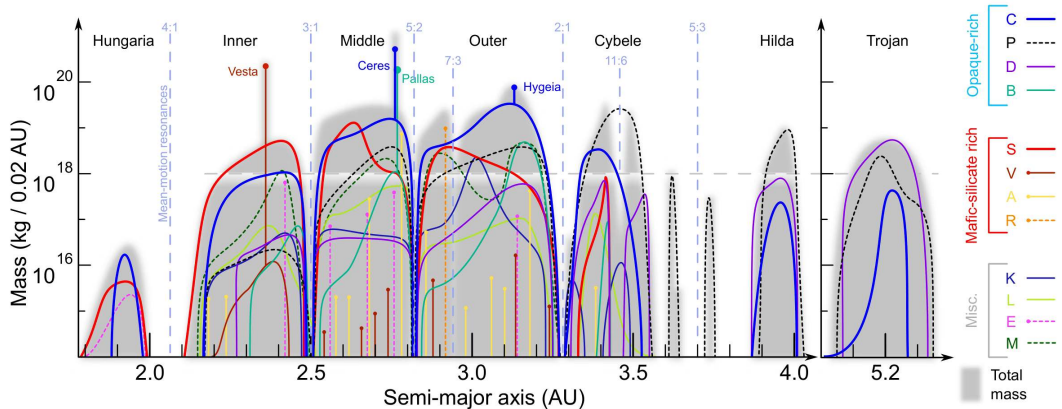
Orbits of the near-Earth objects that leave the main belt through the 3:1 (2.50 AU), 5:2 (2.82) and 2:1 (3.27) resonances with Jupiter. Granvik et al. (2018).

Periodic Jovian kicks add coherently and pump eccentricities to planet-crossing in 10^4 – 10^6 yr: the gaps are not empty but leaky, the dynamical sinks that feed the near-Earth population.



Asteroid families as clusters in proper inclination against proper semimajor axis: Themis, Eos, Koronis, Eunomia, Vesta, Flora. Nesvorný et al. (2015).

Each family is the debris of a single disruption event; its spread gives the original parent body's size and age.



Mass of the main belt by spectral class against semimajor axis. DeMeo & Carry (2014).

S-types (~ 15% albedo, ordinary-chondrite analogues) fill the inner belt, **C-types** (~ 4% albedo, volatile-rich) ~ 75% of the outer belt, **M- and V-types** are cores and Vesta's basaltic crust (2.4 AU). Radial sorting preserves the disk's primordial volatile gradient.

A photograph of a meteor streaking across a twilight sky. The meteor is a bright, white, elongated trail of smoke and dust, starting from the upper left and moving towards the lower right. Below the sky, a dark silhouette of a village with snow-covered roofs and bare trees is visible against the horizon. The overall scene is dimly lit, with the sky transitioning from a deep blue at the top to a lighter, hazy glow near the horizon.

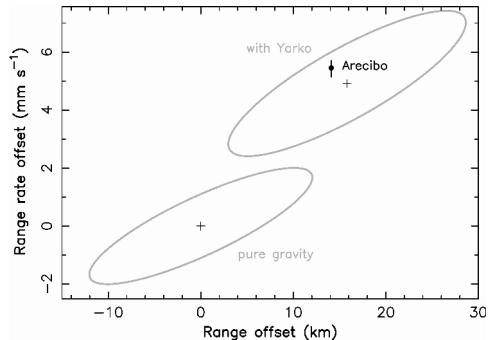
7. NEAs, Yarkovsky/YORP, and Planetary Defence

Near-Earth Asteroids and Resupply Channels

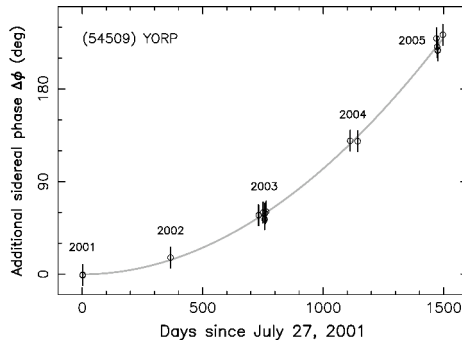
NEAs ($q < 1.3$ AU, residence time ~ 10 Myr) require steady-state resupply from the main belt:

- **Resonances:** Kirkwood (3:1, 5:2) and ν_6 secular resonance pump eccentricity
- **Yarkovsky drift:** thermal recoil drives slow semimajor axis drift,
$$\frac{da}{dt} \propto \frac{1}{D \rho \sqrt{a}}$$
- **Hazards:** $\sim 2,500$ Potentially Hazardous Asteroids ($D > 140$ m, MOID < 0.05 AU)

Yarkovsky and YORP Detected on Real NEAs

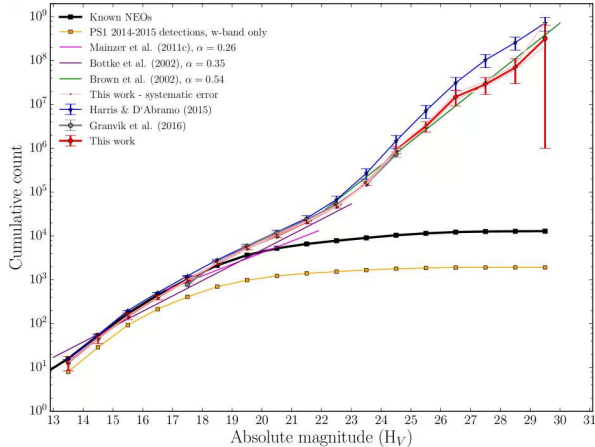


Yarkovsky: (6489) Golevka, Arecibo radar



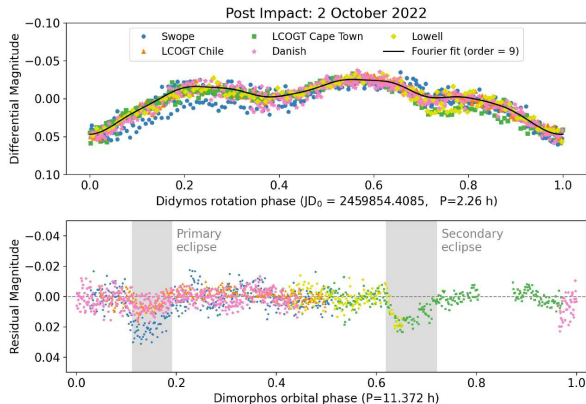
YORP: (54509) YORP rotational acceleration

YORP is the same thermal asymmetry acting on *spin*: it can spin small asteroids to fission or stop them.



Cumulative size-frequency distribution of near-Earth objects against absolute magnitude H_V , a power law over five orders of magnitude. Schunová-Lilly et al. (2017), Fig. 9.

Impact rates: 10 m per decade; 50 m (Tunguska) per 10^3 yr; 1 km per 5×10^5 yr; 10 km (Chicxulub) per 10^8 yr.



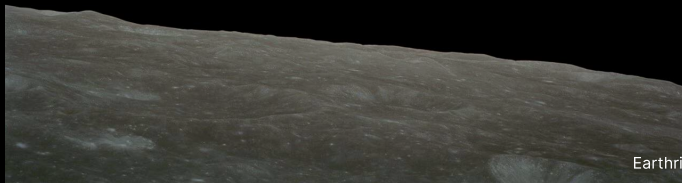
Light curves of Didymos (top, 2.26 h rotation) and Dimorphos (bottom, its new 11.372 h orbit) six days after the DART impact. Thomas et al. (2023), Fig. 3.

The orbital period fell by 33.0 ± 1.0 minutes (3σ) and the momentum enhancement $\beta \approx 3.6$ shows that ejecta recoil exceeds the direct push; Hera (ESA, launched 2024) measures the crater and β .

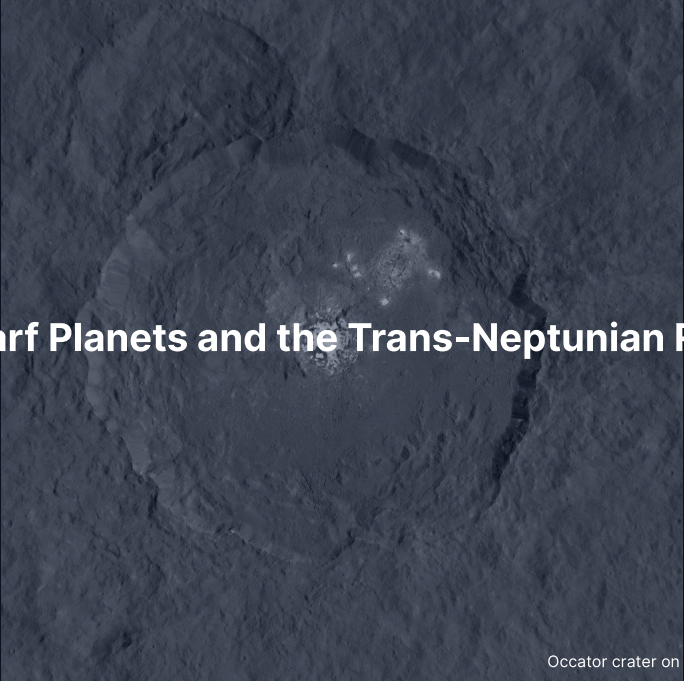
Break



End of Part 1: Meteorites & Inner Small Bodies
Part 2: Trans-Neptunian Region, Comets, Missions

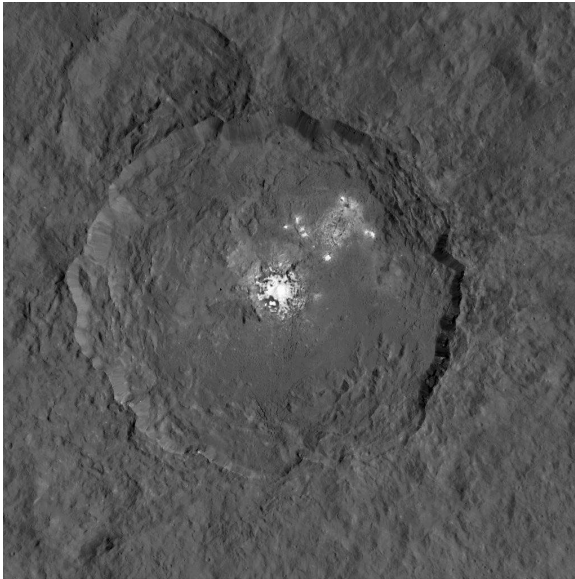


Earthrise, Apollo 8 (1968). Credit: NASA

A grayscale image of the Occator crater on the dwarf planet Ceres. The crater is a large, roughly circular feature with a prominent, bright, and irregularly shaped central region. The surrounding terrain is heavily textured with smaller craters and ridges. The overall appearance is dark and rugged.

8. Dwarf Planets and the Trans-Neptunian Region

Occator crater on Ceres, Dawn. NASA/JPL-Caltech



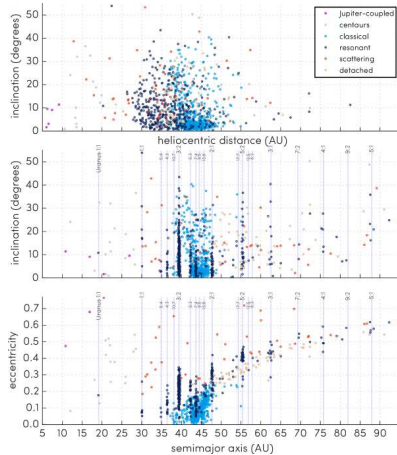
Occator crater on Ceres, Dawn (2015–2018): bright deposits of hydrated Na_2CO_3 and NH_4Cl from erupted brines. Credit: NASA/JPL-Caltech.

Ceres ($R = 470$ km, mass $\sim 1\%$ of the Moon) has, or had, a partially liquid water layer at depth, and may be a captured outer-solar-system body (Nice Model: a dynamical instability among the giant planets).

Trans-Neptunian Region: Five Sub-Populations

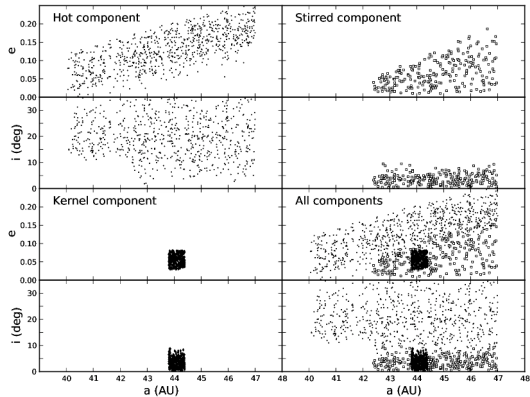
The orbits preserve the gravitational footprint of giant-planet migration:

- **Classicals ($a = 42\text{--}47$ AU):** dynamically unperturbed cold classicals ($i \lesssim 5^\circ$) and scattered hot classicals ($i \lesssim 30^\circ$)
- **Resonant (e.g. 3:2 plutinos):** bodies swept into mean-motion resonances during Neptune's outward migration
- **Scattered disk and detached:** Neptune-scattered bodies ($q \sim 30$ AU) and decoupled detached objects ($q > 40$ AU)



1142 characterised TNOs from OSSOS in orbital space; the vertical lines mark Neptune's resonances. Bannister et al. (2018).

The dense low-inclination cluster at 42–47 AU is the cold classical belt; the architecture is a fossil of giant-planet migration.

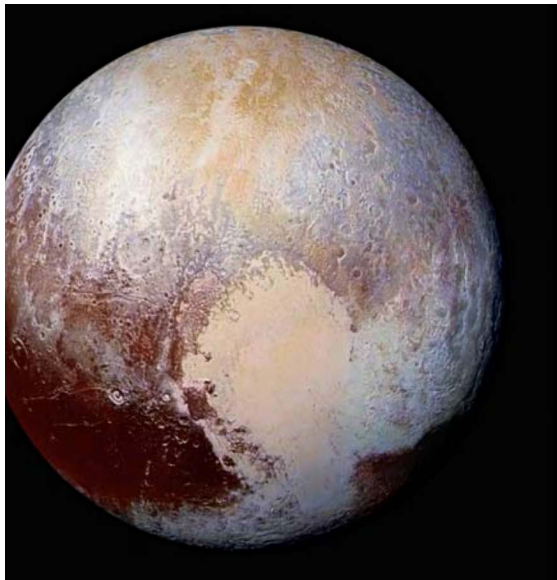


The three components of the CFEPS-L7 model of the classical Kuiper belt in e and i against a : hot, stirred, and the kernel near 44 AU. Petit et al. (2011).

Kernel and hot component share the same a but different (e, i) : the cold classicals were never strongly perturbed by Neptune, the hot classicals were excited by the giant-planet instability.

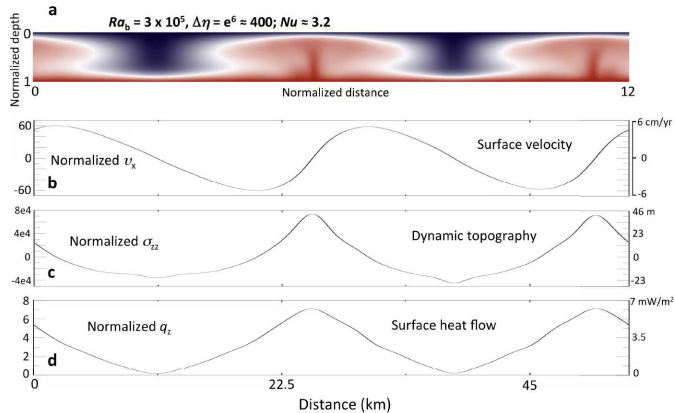


9. Pluto, Charon, Arrokoth



True-colour Pluto from New Horizons Ralph (2015), with Tombaugh Regio and Sputnik Planitia. Credit: NASA/JHUAPL/SwRI.

With $R = 1187$ km and $\rho = 1860$ kg m⁻³: water-ice bedrock under volatile frosts, a convecting N₂-ice basin younger than 10 Myr, a ~ 1 Pa N₂ atmosphere and a probable subsurface ocean.

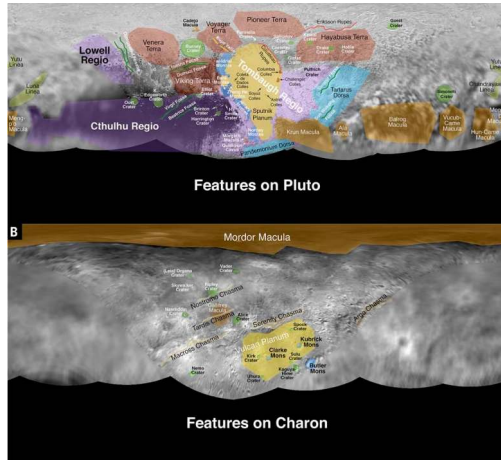


Solid-state convection in Sputnik Planitia, $Ra_b \sim 3 \times 10^5$ (model). McKinnon et al. (2016).

Cells tens of km across overturn in $\sim 10^6$ yr, driven by present-day radiogenic heat in the rocky core.

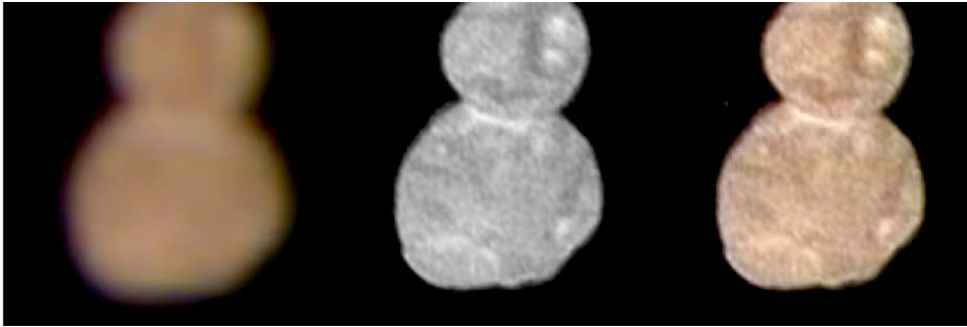


Charon from New Horizons: the dark reddish Mordor Macula of tholins from Pluto's escaping atmosphere, and equatorial extensional chasms. Credit: NASA/JHUAPL/SwRI, public domain.



Pluto and Charon with their named features, New Horizons (2015). Stern et al. (2015).

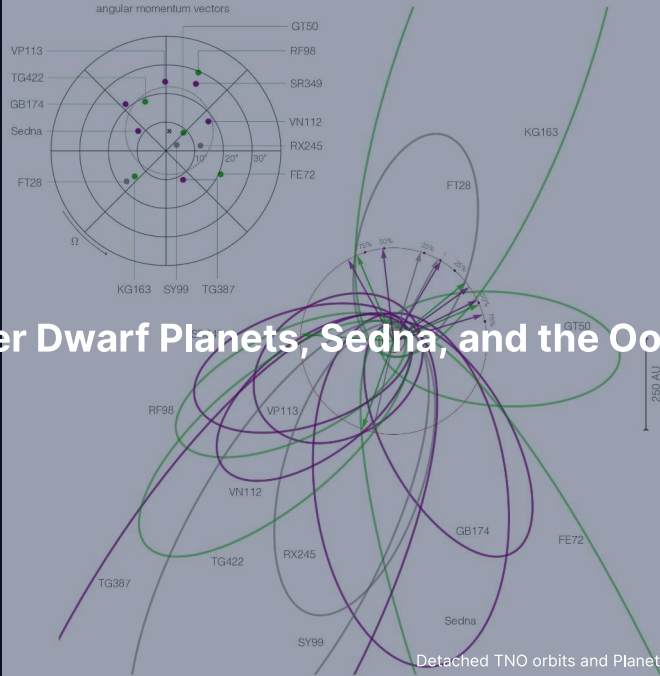
Charon ($R = 606$ km, $\sim 1/8$ of Pluto's mass) puts the barycentre *outside* Pluto; the four small moons Styx, Nix, Kerberos and Hydra are likely fragments of an early collisional event.



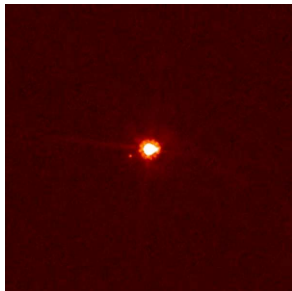
Arrokoth, a ~35 km **contact binary**, New Horizons flyby of 1 January 2019. Stern et al. (2019).

Two flat lobes joined at a narrow neck with no impact crater at the join: a merger at $\lesssim$ a few m s^{-1} , formation by streaming-instability gravitational collapse.

10. Other Dwarf Planets, Sedna, and the Oort Cloud

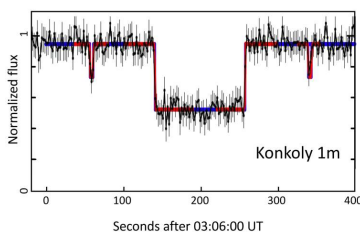


Eris, Haumea, Makemake



Eris + Dysnomia. More massive than Pluto.

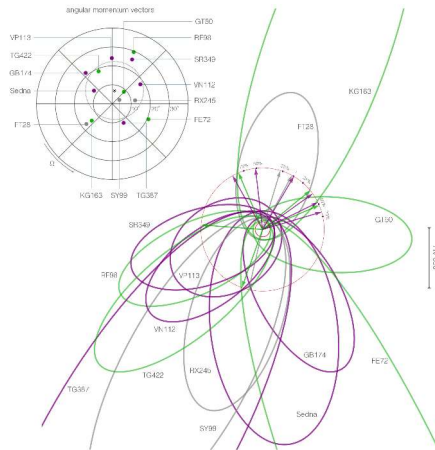
Plus dwarf-planet candidates: Gonggong, Quaoar, Orcus, Salacia, Sedna.



Haumea occultation: revealed a **ring**.

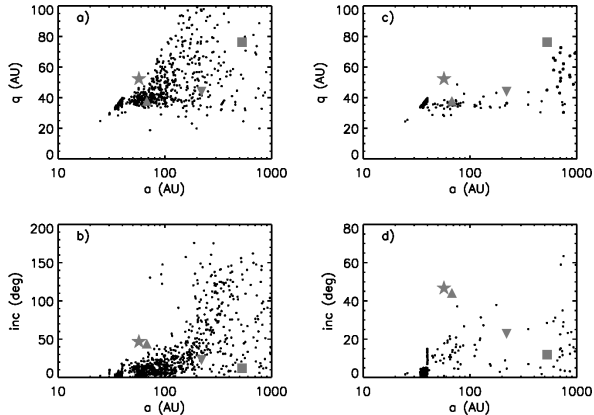


Makemake + small moon.
Methane-ice surface.



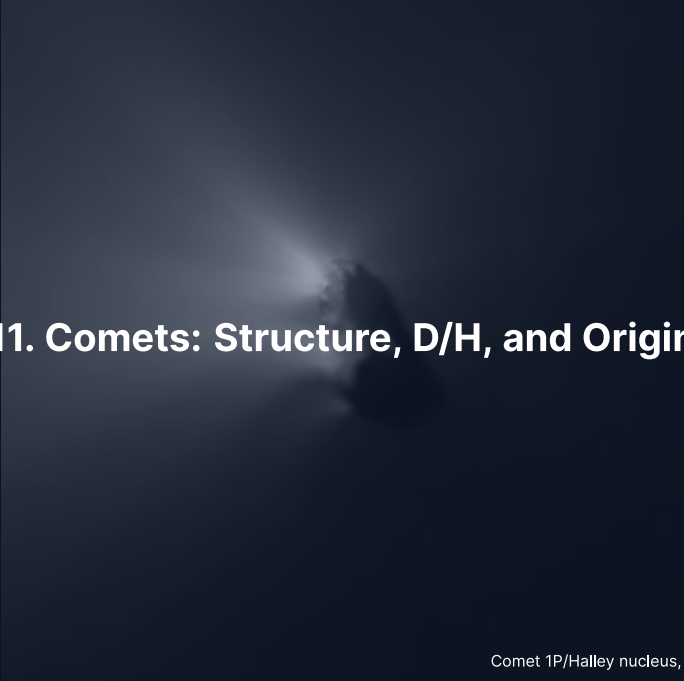
Orbits of the detached TNOs and the Planet 9 hypothesis. Batygin et al. (2019).

Sedna ($q = 76$ AU, $Q = 900$ AU, period 11,400 yr) is too far for Neptune and too close for present-day stars: an inner Oort cloud or birth-cluster relic; the orbital clustering motivates the **Planet 9** hypothesis.

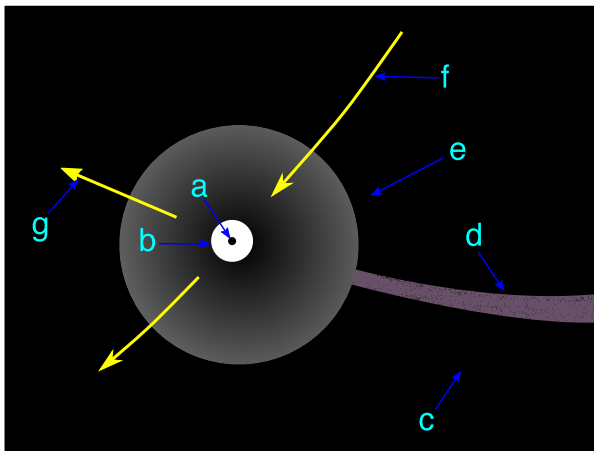


Oort cloud formation in two simulations: perihelion q (top) and inclination (bottom) against a .
 Kaib & Quinn (2008).

2,000–50,000 AU, roughly spherical, $\sim 10^{11}$ – 10^{12} objects of ~ 1 – $10 M_{\oplus}$ in total, planetesimals scattered from the Jupiter-Neptune zone and lifted by the galactic tide and passing stars; inferred by Oort in 1950, **never directly observed**.



11. Comets: Structure, D/H, and Origin



Anatomy of an active comet. Credit: Wikimedia Commons, public domain.

Whipple's dirty snowball: a dark, porous **nucleus** of 1–30 km (67P : 533 kg m^{-3} , ~ 70% porosity) of ices, dust and organics. Inside ~ 5 AU water sublimation feeds a 10^4 – 10^6 km **coma**, a straight anti-sunward **ion tail** and a curved **dust tail**.



Halley's nucleus ($15 \times 8 \times 8$ km) with jets from small active patches, Giotto Halley Multicolour Camera, 13–14 March 1986. Credit: ESA/MPAe Lindau.

A 76-year retrograde orbit with $T_J \approx -0.6$: an Oort-cloud comet captured to a short period.

Short-Period vs Long-Period: The Tisserand Parameter

$$T_J = \frac{a_J}{a} + 2\sqrt{\frac{a}{a_J}(1-e^2)\cos i}, \quad a_J = 5.20 \text{ AU}$$

A conserved dynamical invariant that separates asteroids from Jupiter-family and long-period comets:

- **Asteroids** ($T_J > 3$): main-belt orbits decoupled from Jupiter encounters (e.g. Ceres, $T_J \approx 3.3$)
- **Jupiter-family comets** ($2 < T_J < 3$): Kuiper-belt-derived comets controlled by Jupiter (e.g. 67P, $T_J \approx 2.7$)
- **Long-period comets** ($T_J < 2$): Oort-cloud visitors on high-inclination orbits; Halley-type comets ($T_J \approx -0.6$) are Oort-derived but captured to short orbits (76 yr)



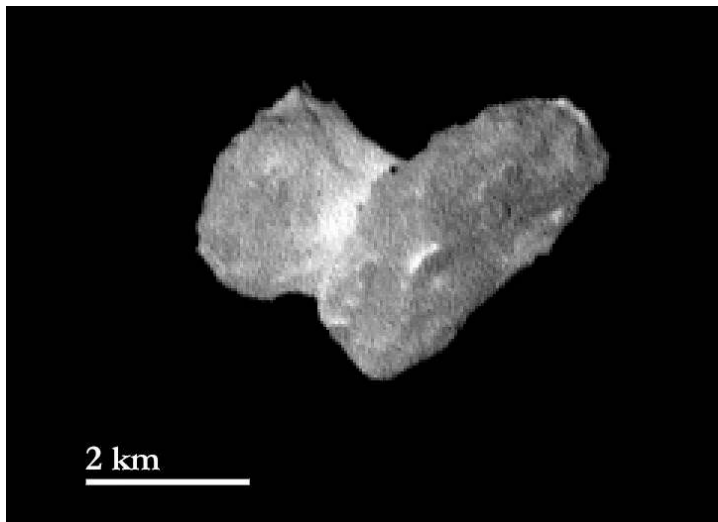
103P/Hartley 2 (EPOXI, 2010), whose water D/H matches Earth's oceans.

Credit: NASA/JPL-Caltech/UMD.

Earth's oceans have $D/H = 1.56 \times 10^{-4}$ (VSMOW); Hartley 2 matches, 67P is $\approx 3\times$ and long-period comets $\approx 2\times$ VSMOW. No comet class matches Earth: carbonaceous chondrites dominate Earth's water, comets supply at most a minor fraction.



12. Recent Missions and Sample Return



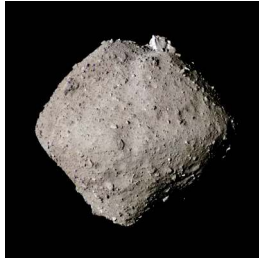
Bilobed nucleus of Jupiter-family comet 67P/Churyumov-Gerasimenko ($T_J \approx 2.7$), two lobes joined at a narrow neck by a gentle primordial merger, Rosetta OSIRIS.

Credit: ESA/Rosetta/MPS for OSIRIS Team.

Three Sample Returns: Itokawa, Ryugu, Bennu



Hayabusa, 2010: 1,500 grains.
Itokawa = LL chondrite parent.

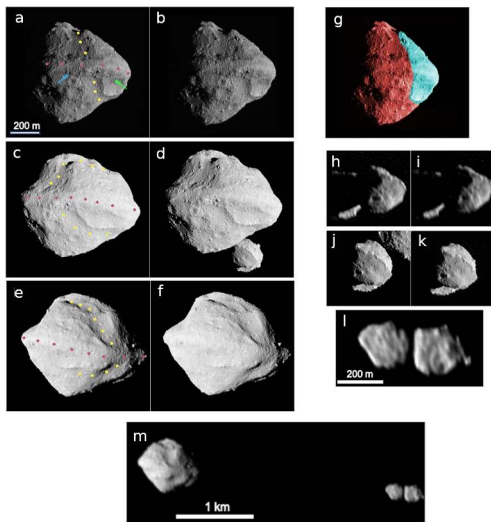


Hayabusa2, 2020: 5.4 g. Ryugu
≈ CI chondrite. Amino acids,
nucleobases.

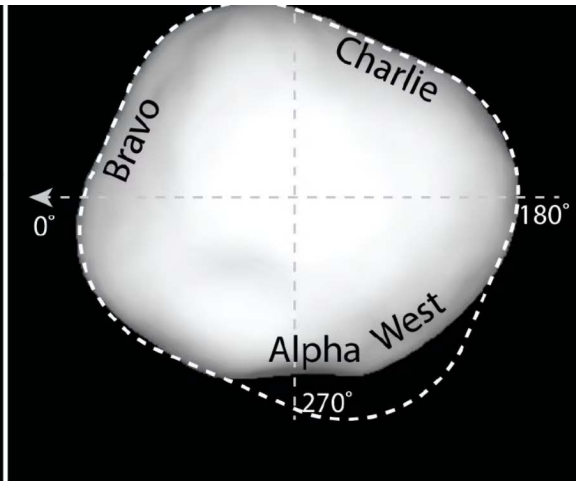
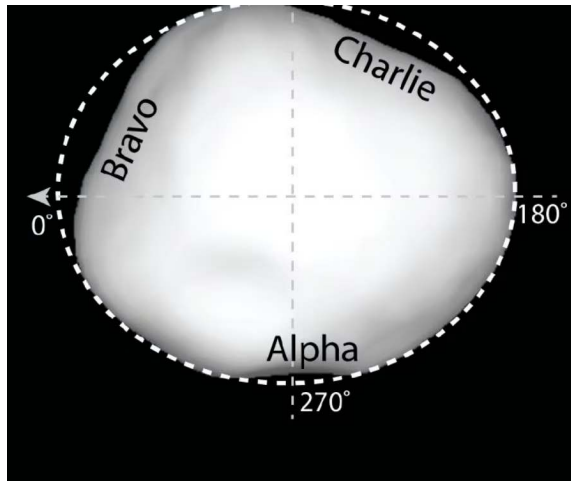


OSIRIS-REx, 2023: 121 g.
Bennu CI-like, Mg carbonate
veins.

Each rock → specific parent body with a known orbit and full in-situ context.



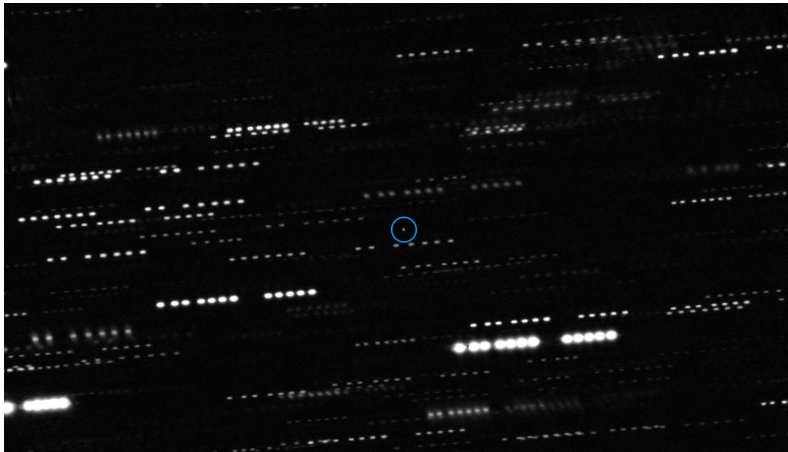
The Dinkinesh-Selam system from the Lucy flyby of 1 November 2023: the ~720 m main-belt asteroid with its equatorial ridge, and the moonlet Selam, a contact binary of two ~210 and 230 m lobes. Levison et al. (2024).



The shape of (16) Psyche from radar and adaptive-optics data, seen from above its south pole, with the regions Alpha, Bravo and Charlie where the body falls short of the best-fit ellipsoid. Shepard et al. (2021).



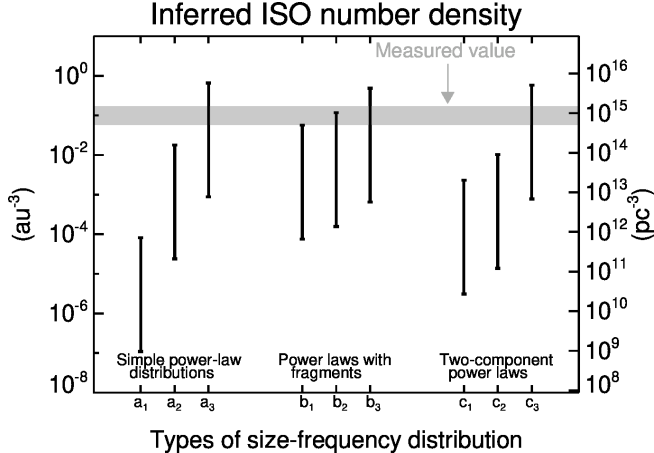
13. Interstellar Visitors



1I/'Oumuamua at the centre; the stars trail as the telescope tracked it.

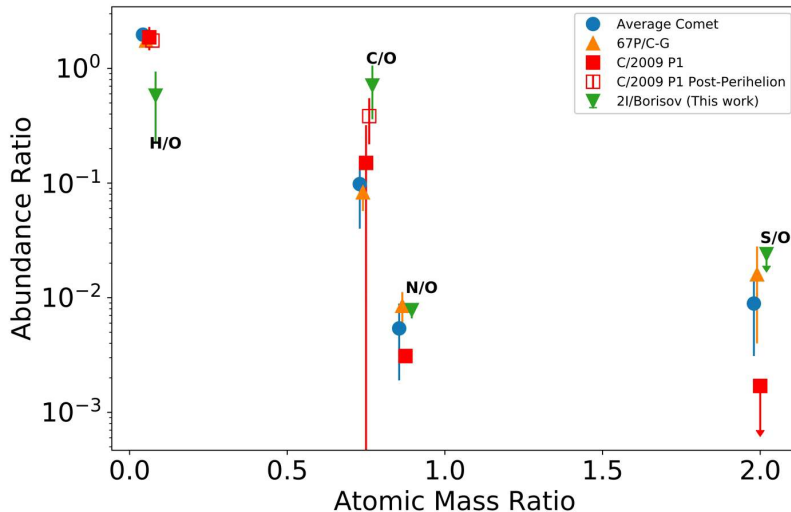
Credit: ESO / K. Meech et al.

No detectable coma at the limit of stacked imaging, yet the outgoing trajectory shows a non-gravitational acceleration; its nature is still debated.



Number density of interstellar objects implied by 'Oumuamua. 'Oumuamua ISSI Team (2019).

One detection implies $\sim 10^4$ ISOs larger than 100 m within Neptune's orbit *at any moment*, each a sample of a different planetary system; the density exceeds the pre-discovery predictions by orders of magnitude.



Volatile composition in the coma of interstellar comet 2I/Borisov against solar-system comets: elevated C/O and depleted H/O point to formation beyond the CO snowline of its host system.

Bodewits et al. (2020), Fig. 3.

Summary

1. Small bodies are **formation fossils**; **Pb-Pb dating** anchors the solar system's absolute clock at 4567.30 ± 0.16 Myr
2. The **NC-CC dichotomy** separates inner and outer reservoirs for ~ 3–4 Myr; resonance gaps and Yarkovsky thermal recoil drive steady-state NEA delivery
3. Cometary D/H shows carbonaceous chondrites delivered most of Earth's water

Next: Lecture 13 turns to the exoplanet revolution.

Questions?

Next: **Lecture 13. Exoplanets**

Lecture notes: `formingworlds.github.io/IntroductionToPlanetaryScience`