

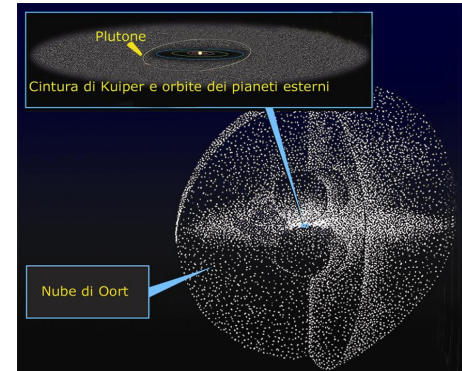
Minor bodies in the outer Solar System

Planets and Astrobiology (2019-2020)

G. Vladilo and S. Ivanovski

Transneptunian objects (Kuiper belt)

- The discovery of Pluto in 1930 suggested that a debris disk of icy material could be present in the outer Solar System



- The existence of such disk was predicted independently by Edgeworth and Kuiper ~1940-1950
 - Hypothesis: the disk of small bodies that formed the giant planets perhaps extended past Neptune, with a density too low (or perhaps the formation times too long) to form planets; small bodies that did not succeed to form a planet should still be there
 - Transneptunian objects were too faint to be observed with telescopes of that time
 - Dynamical studies showed that the mass of the debris disk should be no more than 1.3 Earth masses

Transneptunian objects (Kuiper belt)

- Around 1980 it was proposed that the hypothetical disk of small bodies beyond Neptune (called the “Kuiper Belt”) could be the source reservoir for short-period comets
 - This proposal lead observers to search for small bodies in the Kuiper belt with the astronomical instrumentation of new generation
 - The first detection of a Kuiper belt object came in 1992
 - Currently we know about a thousand KBOs
 - We estimate that $\sim 10^5$ KBOs with diameter > 50 km may exist

1992 QB1

Discovery of the first trans-Neptunian object

TNOs are hard to observe:

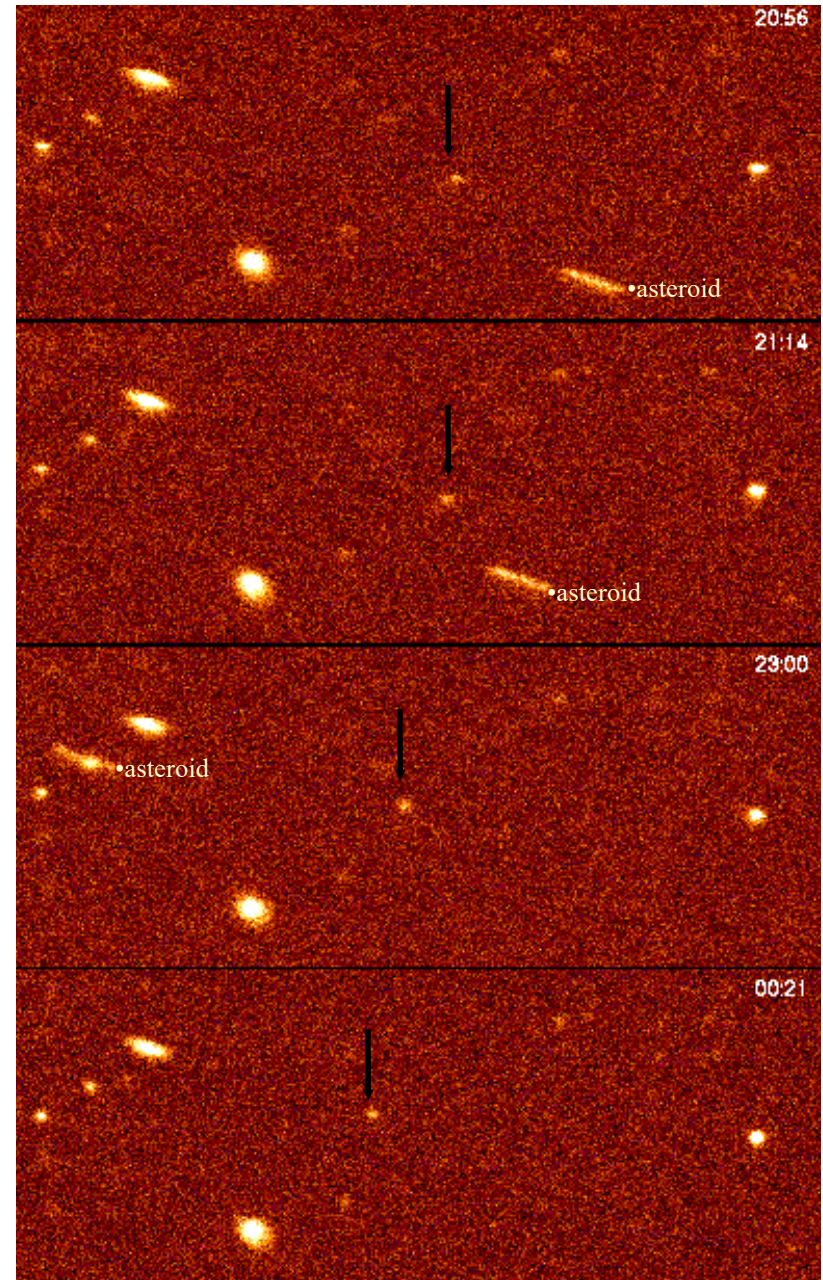
Flux vary with $p \times D^2 \times R^{-4}$

An object with given size D and albedo p is 10^4 times fainter beyond Neptune ($R = 30$ au) than in the asteroid belt ($R = 3$ au)

distance 41.2 AU

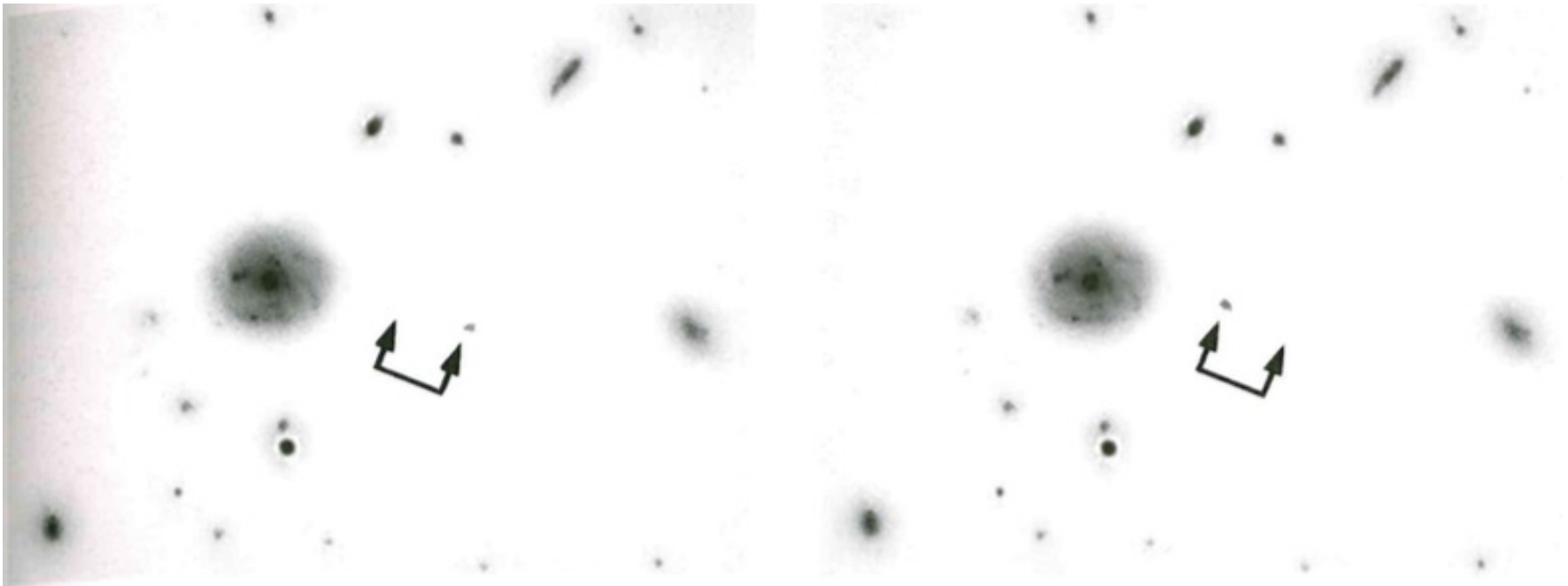
magnitude 23.5

10^7 fainter than a star at naked eye



Detection of minor objects of the outer Solar System from measurements of proper motion

- **Motion of a Solar System object relative to the background stars and galaxies**
 - Comparison of two 300 sec images taken with the 10-m Keck telescope at an interval of one hour. A body with high proper motion relative to the fixed background pattern is found. The proper motion is due to the Earth's and the body's revolution about the Sun. Such motion is how we discover minor bodies of the outer Solar System.



Dynamical classification of transneptunian objects

Distribution of KBOs with well determined orbits

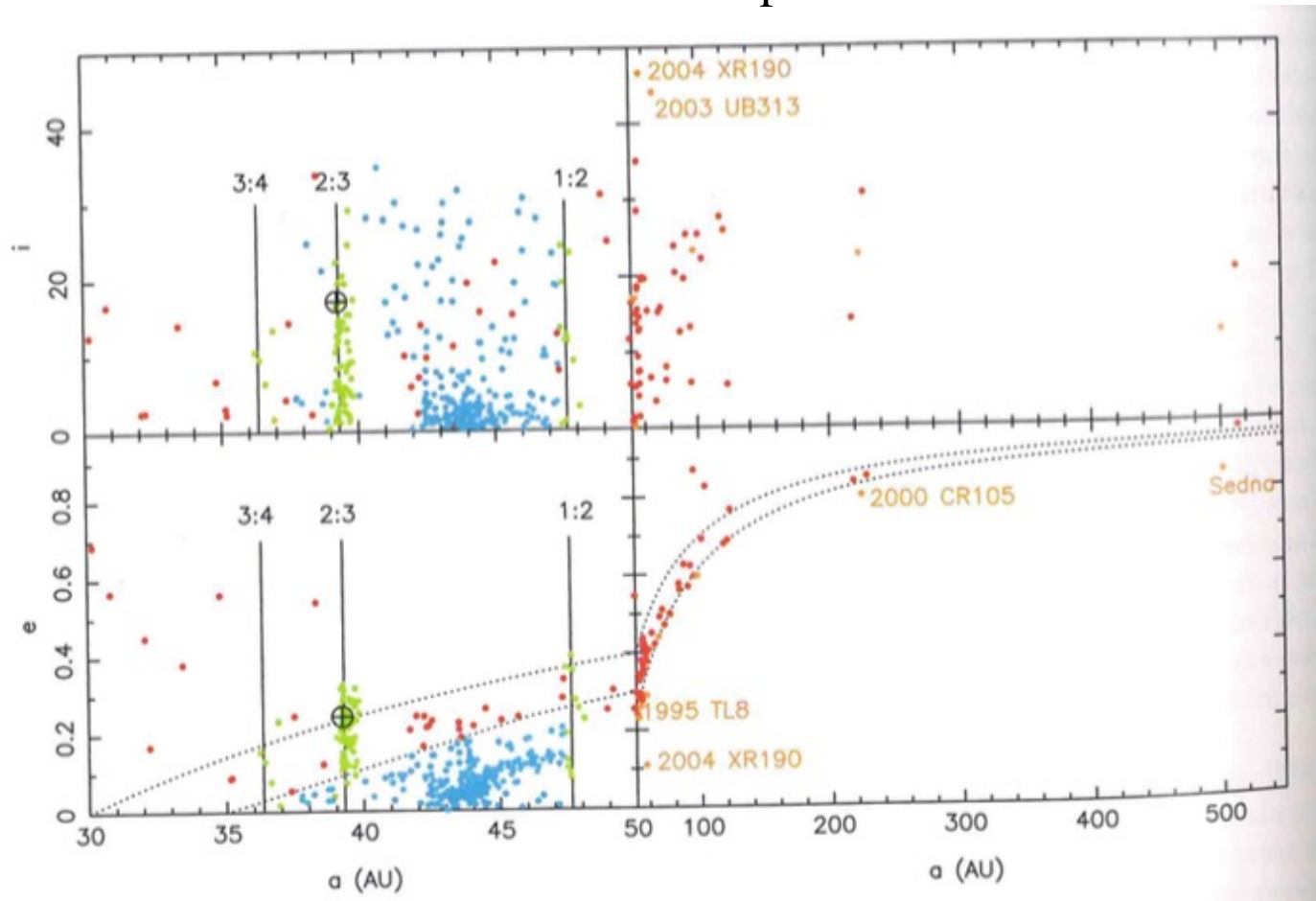
Top panels: inclinations. Bottom panels: eccentricities.

Blue dots: *classical Kuiper Belt*. Red dots: *scattered disk*.

Green dots: *resonant populations*.

Vertical lines: 3:4, 2:3, 1:2 mean motion resonances with Neptune.

Big crossed circle: Pluto. Dotted curves: perihelion distances 30 and 35 AU

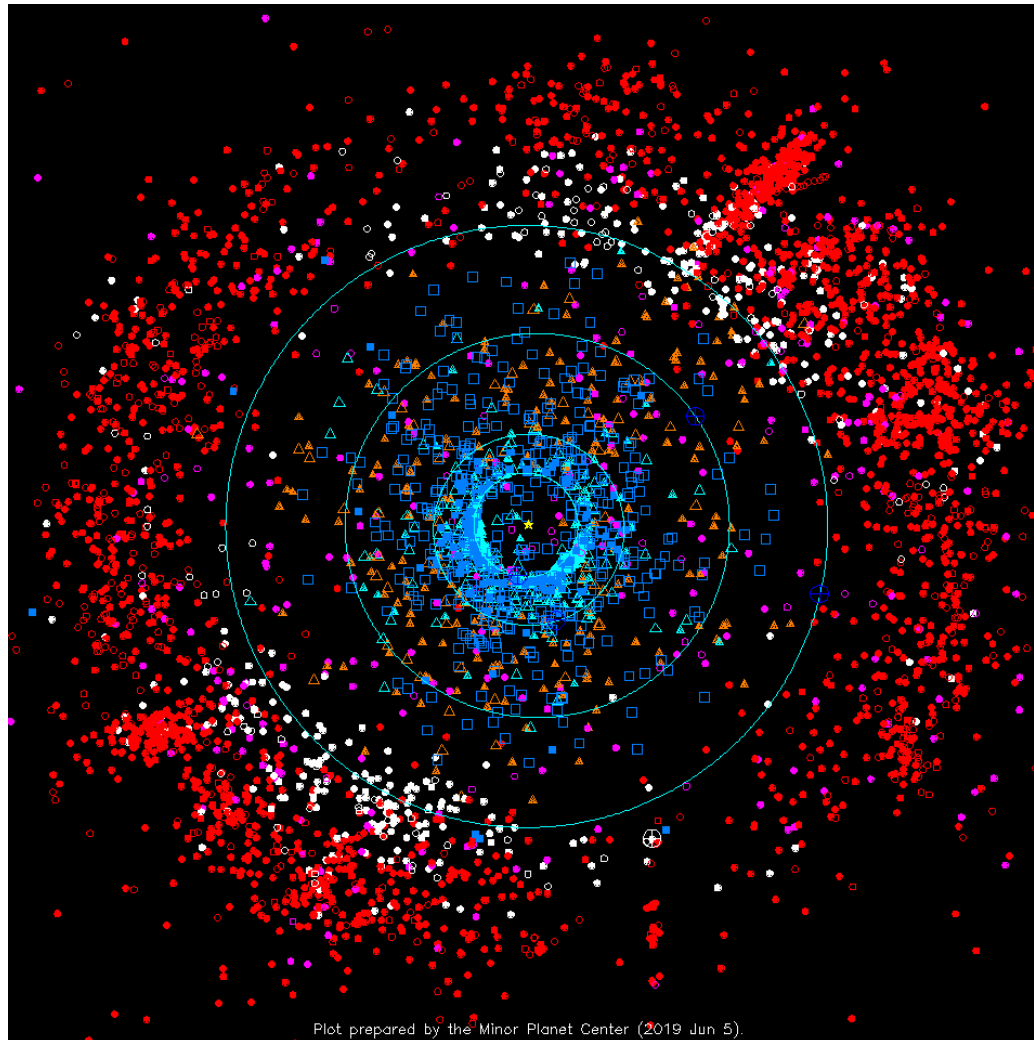


Centaur objects

- Centaur objects are recent escapees from the Kuiper Belt
 - They are on elliptical orbits about the Sun that cross the near-circular orbits of Saturn, Uranus and Neptun
 - Within a few tens of millon years after a Centaur object escapes from the Kuiper Belt, the giant planets scatter it into the Sun or a planet, or cause it to migrate into the region of terrestrial planets
 - By virtue of their relatively close approach, many Centaur objects become bright enough for certain physical studies that are not possible on fainter KBOs

Recent census of minor bodies in the outer Solar System

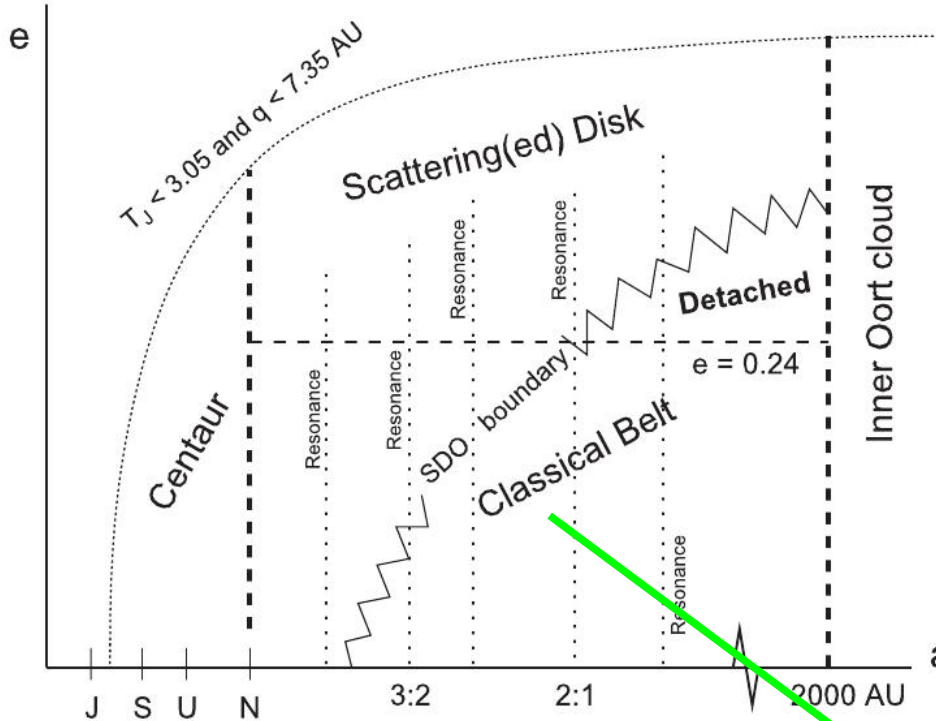
Red dots:
KBOs



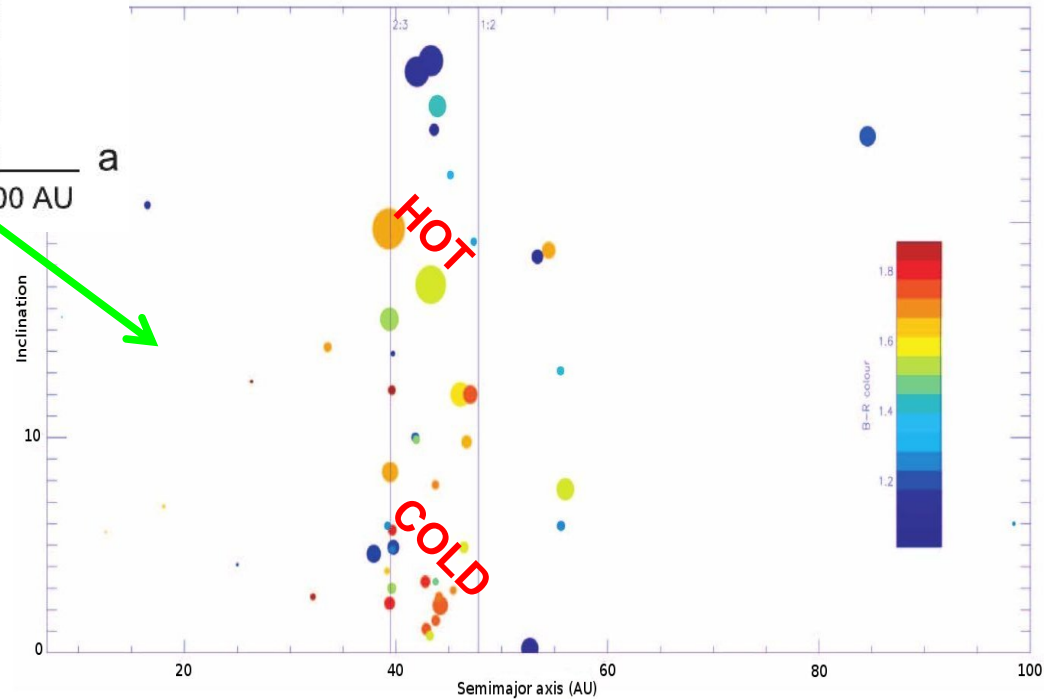
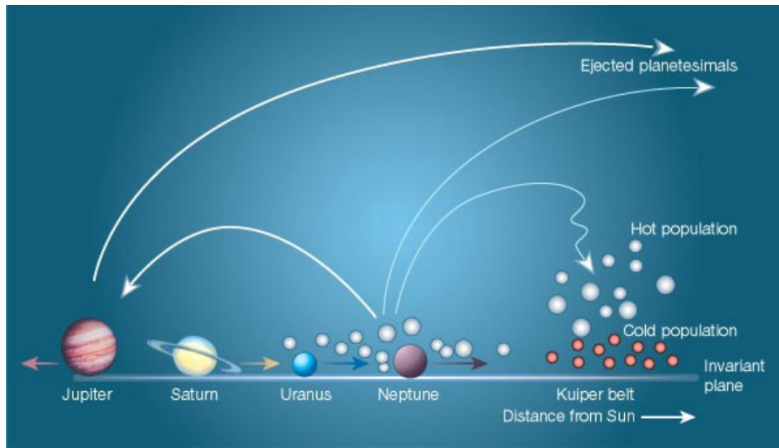
Orange
triangles:
Centaur

<http://www.minorplanetcenter.net>

Trans-Neptunian Objects and Centaurs



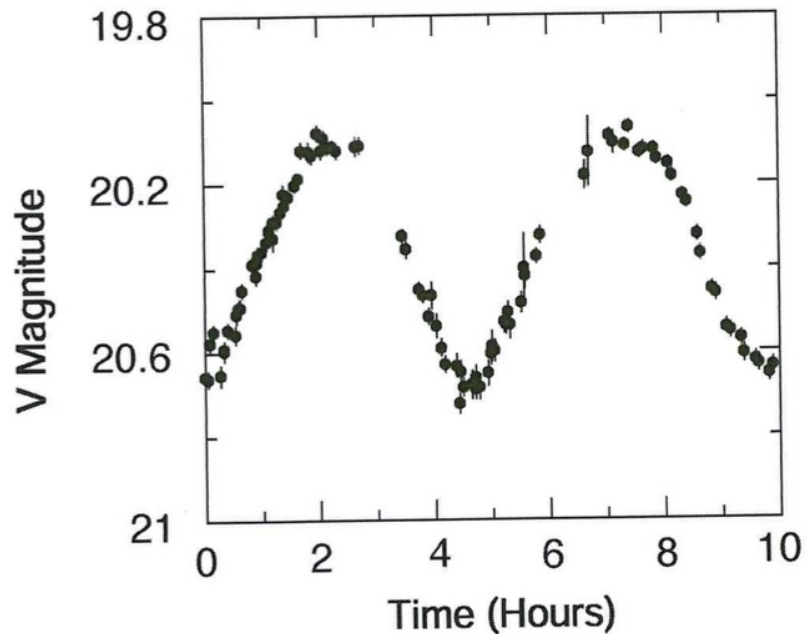
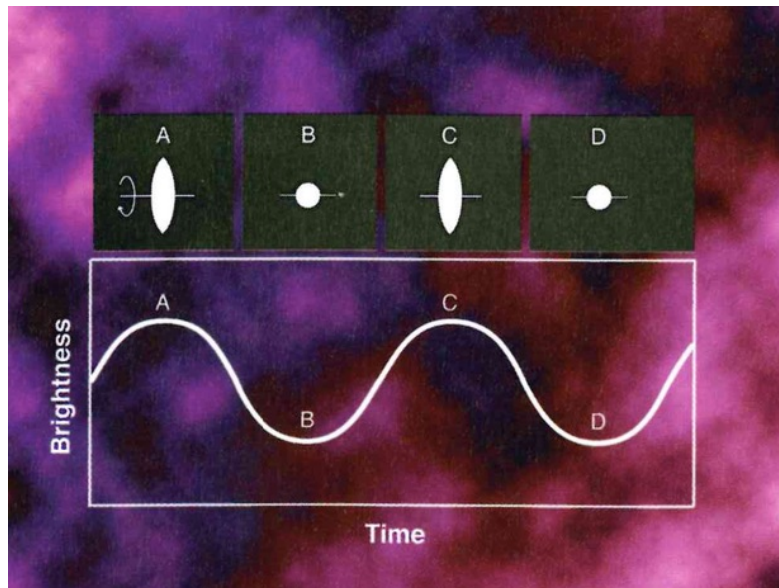
$$T_P = \frac{a_P}{a} + 2 \cdot \sqrt{\frac{a}{a_P} (1 - e^2) \cos i}$$



Characterization of Kuiper Belt and Centaur objects

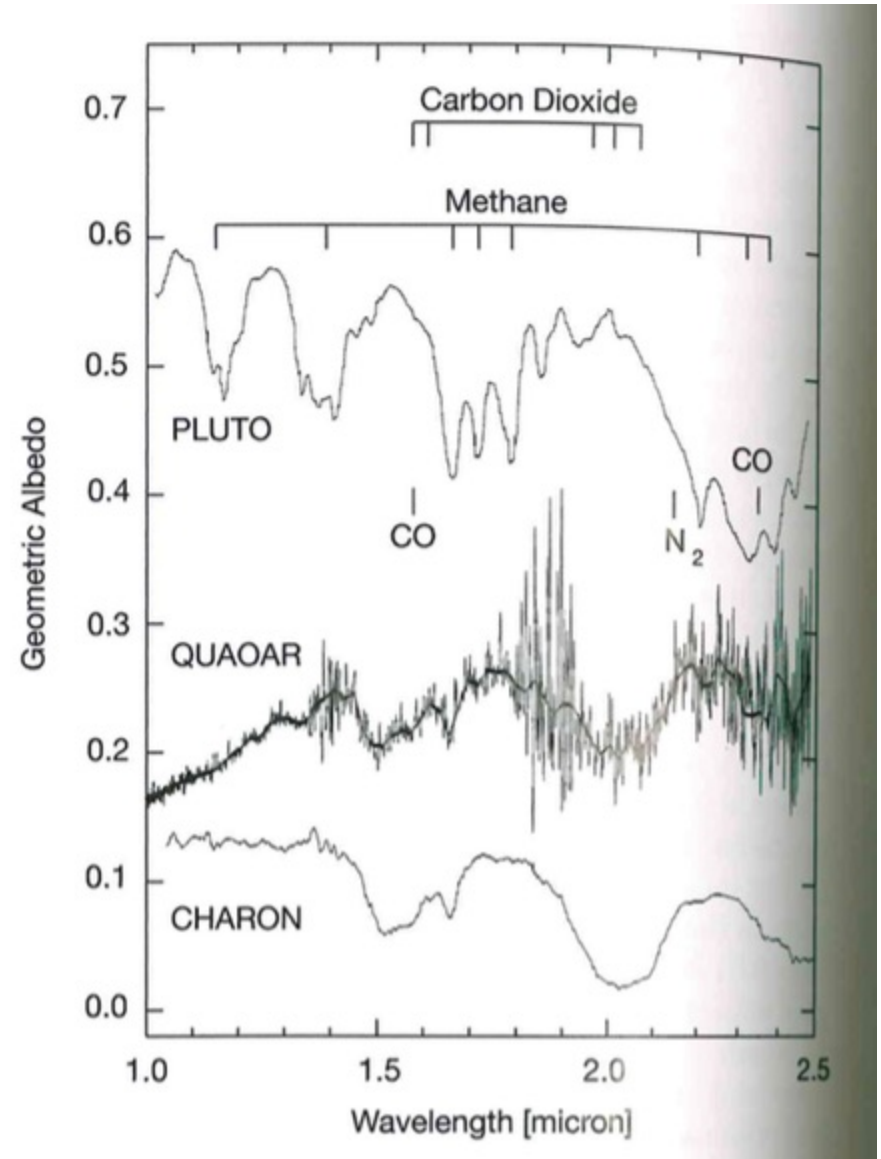
- **Rotation of KBOs**

- Left: rotation of a non-spherical KBO or Centaur object results in a periodic variation of the object's projected area on the plane (top) of the sky and hence a periodic variation in its brightness (bottom), i.e. a *lightcurve*
- Right: lightcurve for the Centaur Pholus



Characterization of Kuiper Belt objects

- Near infrared spectra of KBOs
 - The spectra of Pluto exhibits strong CH_4 ice bands
 - The spectra of Charon (Pluto's satellite) and Quaoar (a classical belt KBO) exhibit strong H_2O absorption bands at 1.5, 1.65 and 2.0 μm



Transneptunian dwarf planets

Name	region	M [M_{Moon}]	ρ [g/cm ³]	a [AU]	e	i [°]
Ceres	Asteroid belt	0.013	2.1	2.77	0.078	10.6
Pluto	Kuiper belt	0.178	2.0	39.5	0.249	17.1
Eris	Scattered disk	0.227	2.5	67.7	0.442	44.2

The difference in orbital properties suggest different origins

Orbits tend to be eccentric and tilted

Masses are small, even compared to Moon's mass

Mean densities are intermediate between the values typical of silicates and ices

Many other dwarf planets probably exist in the Kuiper belt

Pluto

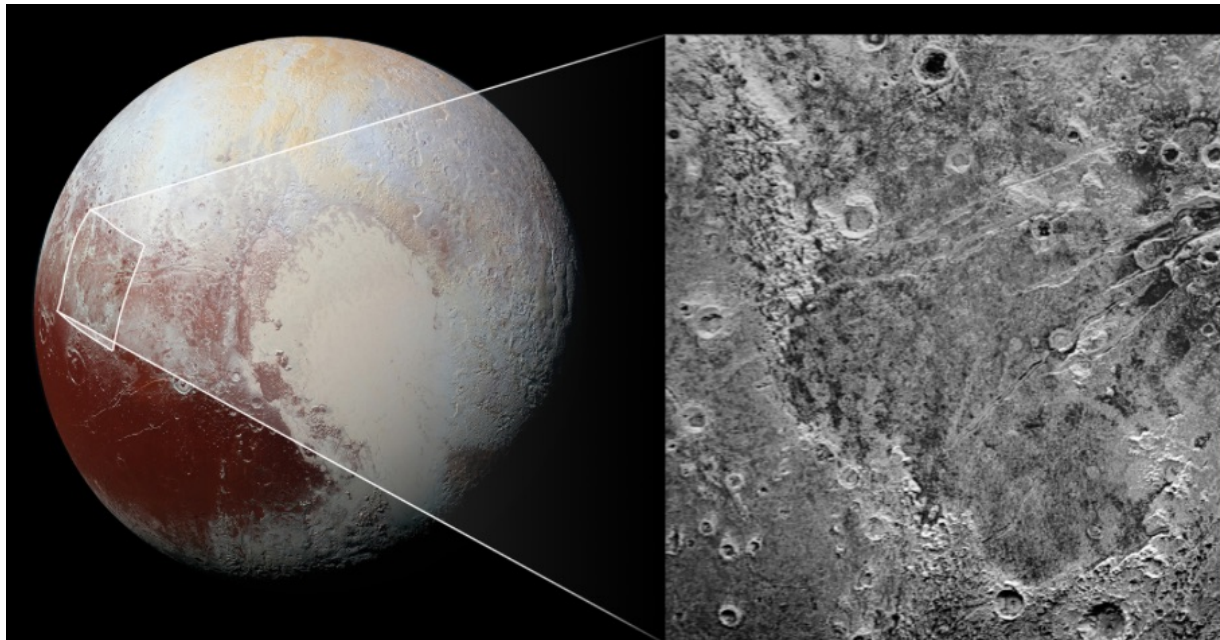
New Horizon observations

Launched: 2006 | Fly-by of Pluto-Charon: 2016 | Fly-by of other TNO: 2017-2023

Evidence for water-ice crust, geologically young surface units, surface ice convection, wind streaks, volatile transport, and glacial flow

Extended atmosphere with trace hydrocarbons and a surface pressure ~10 microbars; a global haze layer

The diverse surface geology and long-term activity raise fundamental questions about how small planets remain active many billions of years after formation



Comets

- Solid debris of the outermost regions of the Solar System
 - Believed to be more pristine (less processed) than asteroids/meteorites
 - Inhomogeneous population
 - Formed over a large interval of distances and temperatures
- Here we examine some characteristics:
 - Classification
 - Activity
 - Evolution
 - Chemical composition

Comet classification

- Based on the orbital period
 - Long period comets (LP)
 $P > 200$ yr
 - Short period comets (SP)
 $P < 200$ yr
 - If $P > 30$ yr \Rightarrow Halley type
 - If $P < 30$ yr \Rightarrow Jupiter type
- Based on their origin in the Solar System
 - For most the time, comets lie within two reservoirs:
the *Kuiper belt* and the *Oort Cloud*
- Cometary orbits can vary significantly, changing the location of a comet in the Solar System, due to dynamical instabilities driven by gravitational perturbations

The Oort Cloud

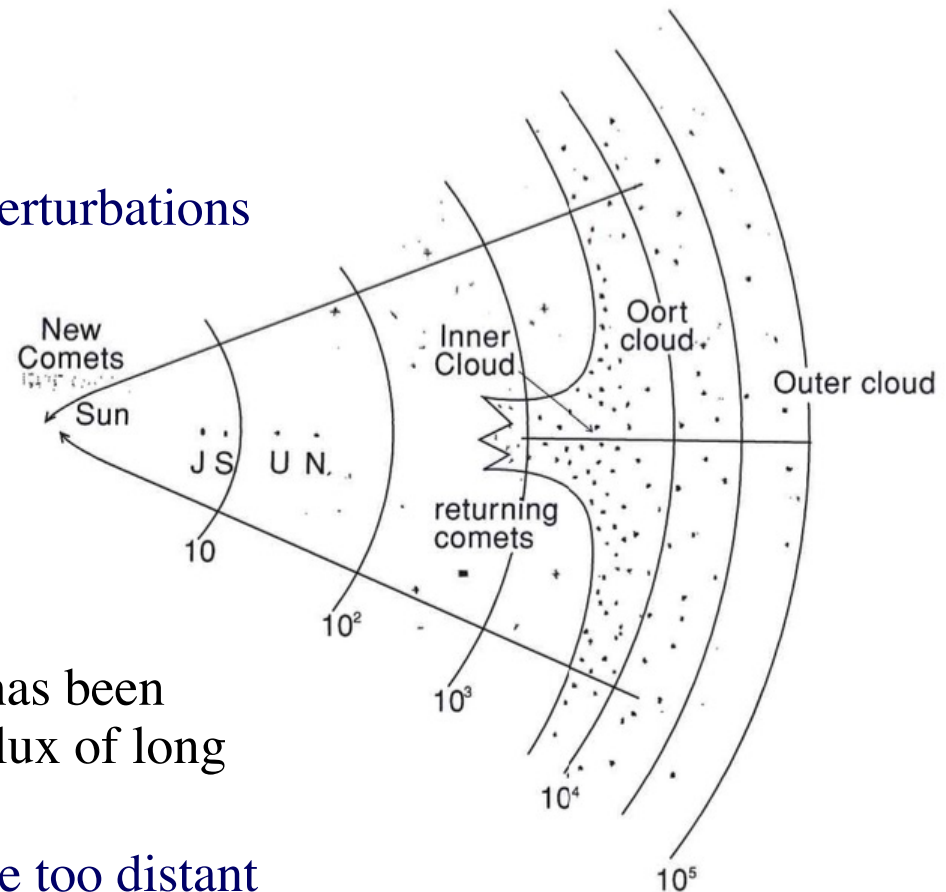
- Extended distribution of comets with random inclination of the orbits

Cloud with spherical symmetry

May comprise billions of comets

- Extends up to 5×10^4 AU

Up to the limit of gravitational perturbations from nearby stars

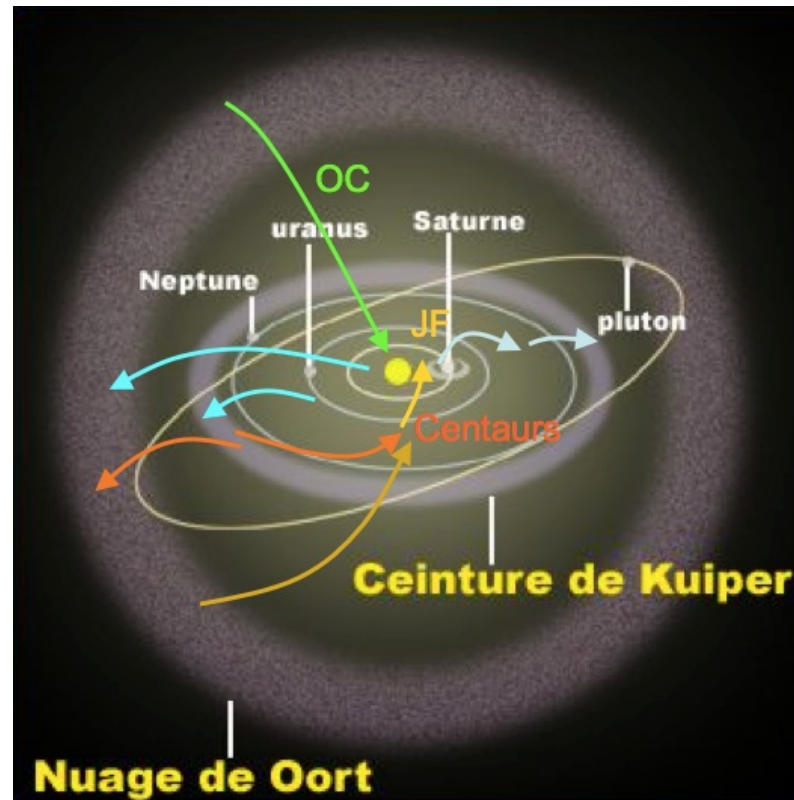


- The existence of the Oort Cloud has been invoked to explain the observed flux of long period comets

The comets of the Oort Cloud are too distant and inactive to be observable from Earth

Origin and dynamical evolution of comets

- It is believed that the comets of the Oort Cloud did not originate in situ, but instead they ended up in the Oort Cloud as a result of gravitational scattering in the region of giant planets
- Comets from the Kuiper Belt are instead believed to originate in situ, later becoming Centaurs and finally Jupiter-family comets



Cometary activity

- If a comet approaches the Sun, the rise of insolation triggers a release of gas, dust and rocks
- The outgoing material generates a rarified atmosphere, called “coma”
 - A spheroidal hydrogen coma, due Lyman alpha radiation, is visible in the ultraviolet spectral range
- The radiation pressure and the solar wind, by interacting with coma, create the characteristic cometary tails
 - Cometary tails can attain sizes larger than 10^6 km
 - Dust and ions form different types of cometary tails

- The dust tail is observable when it reflects the solar light
 - The dust tail is generated by the solar radiation pressure and can bend following the comet's trajectory
- The ejected gas becomes ionized, creating a plasma tail
 - Ionization takes place via:
 - (1) photoionization by UV solar radiation
 - (2) charge transfer with particles of the solar wind
 - The plasma tail is swept by the solar wind and is aligned with the Sun direction

Comet Hale-Bopp

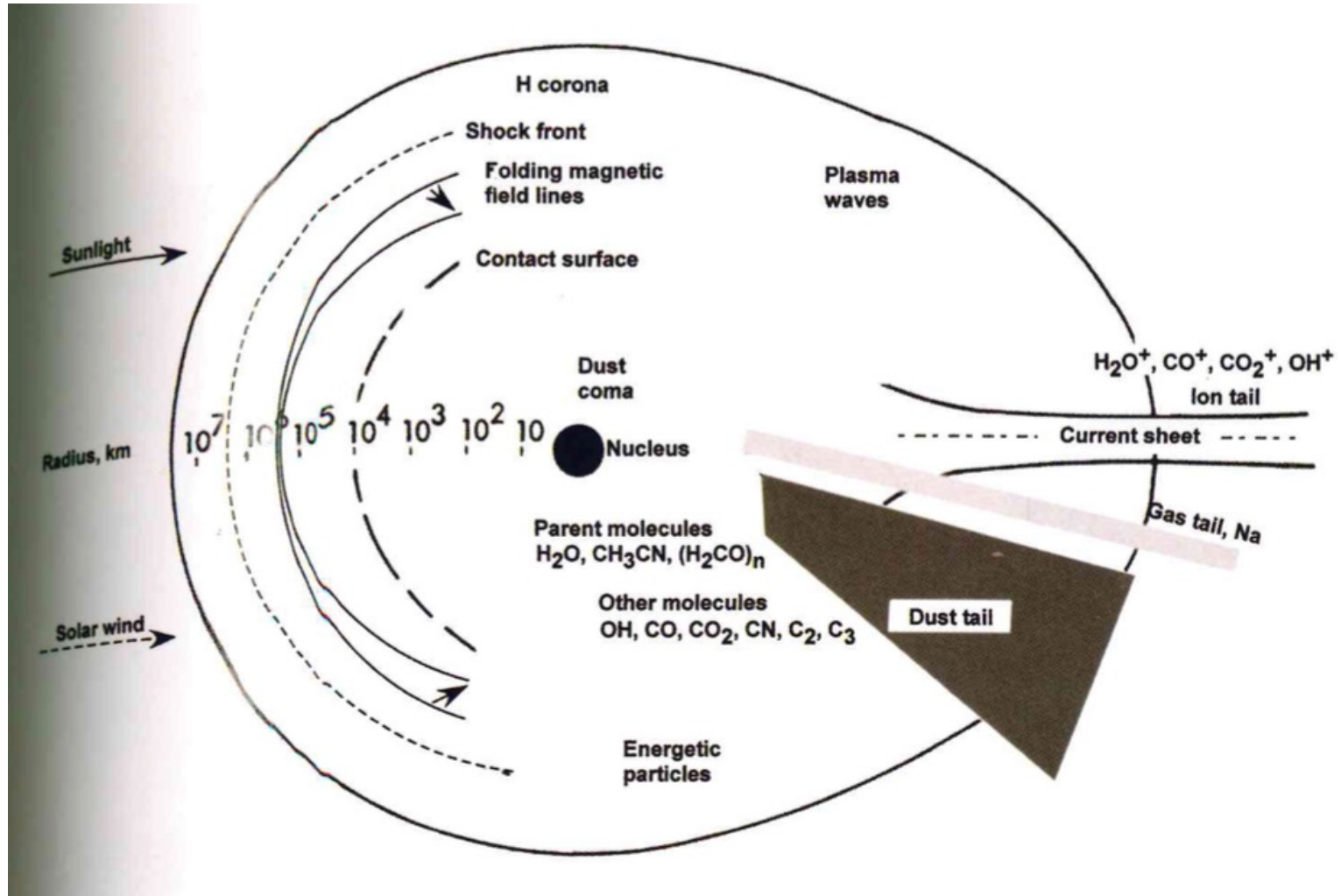
White: dust tail

Blue: plasma tail



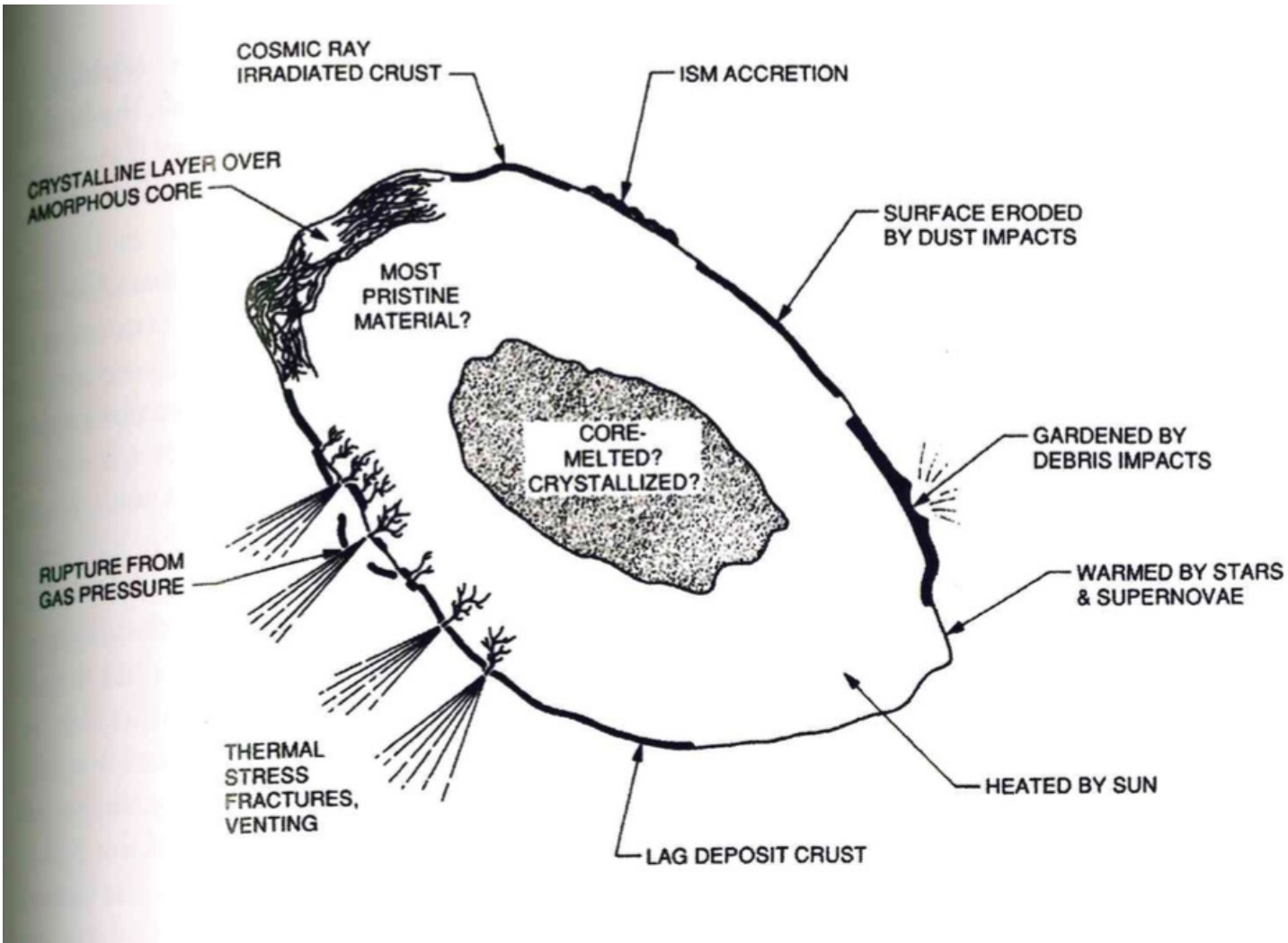
Schematic of cometary features and phenomena

[distances on a logarithmic scale]

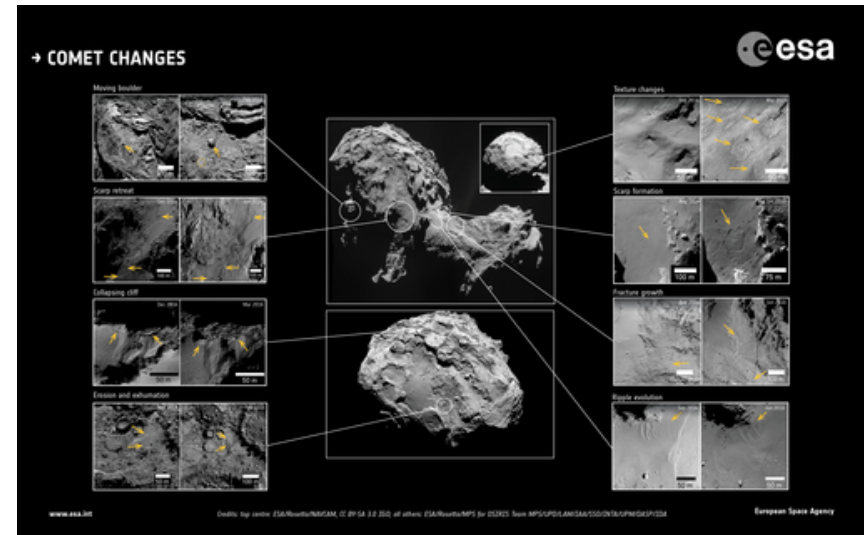
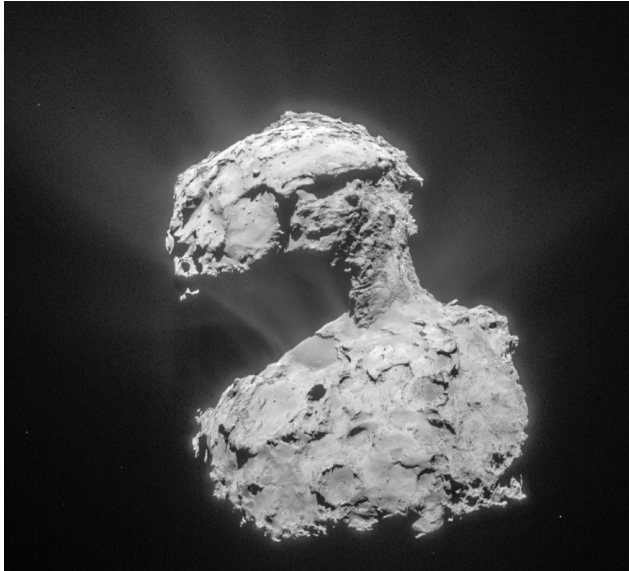


Cometary nucleus

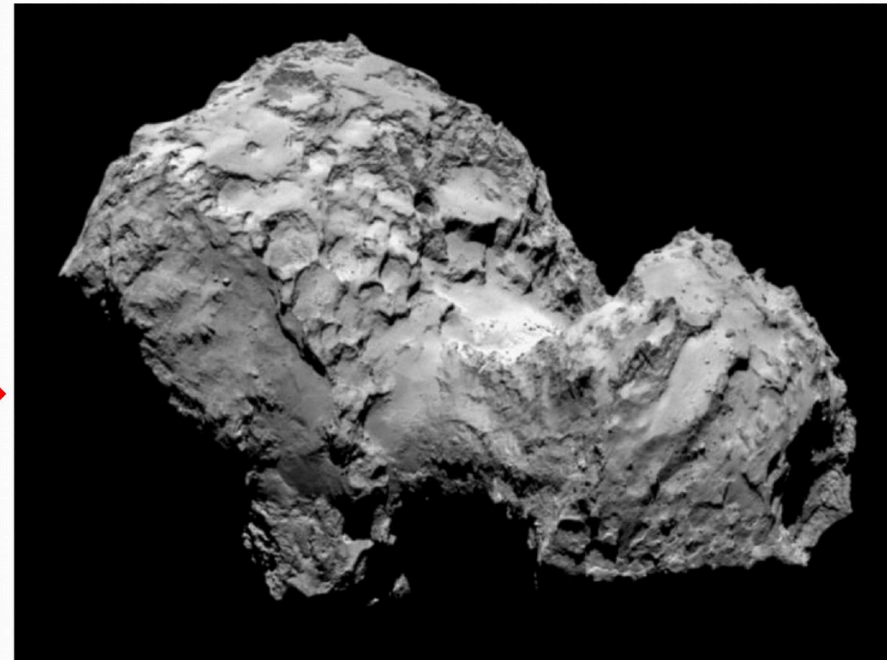
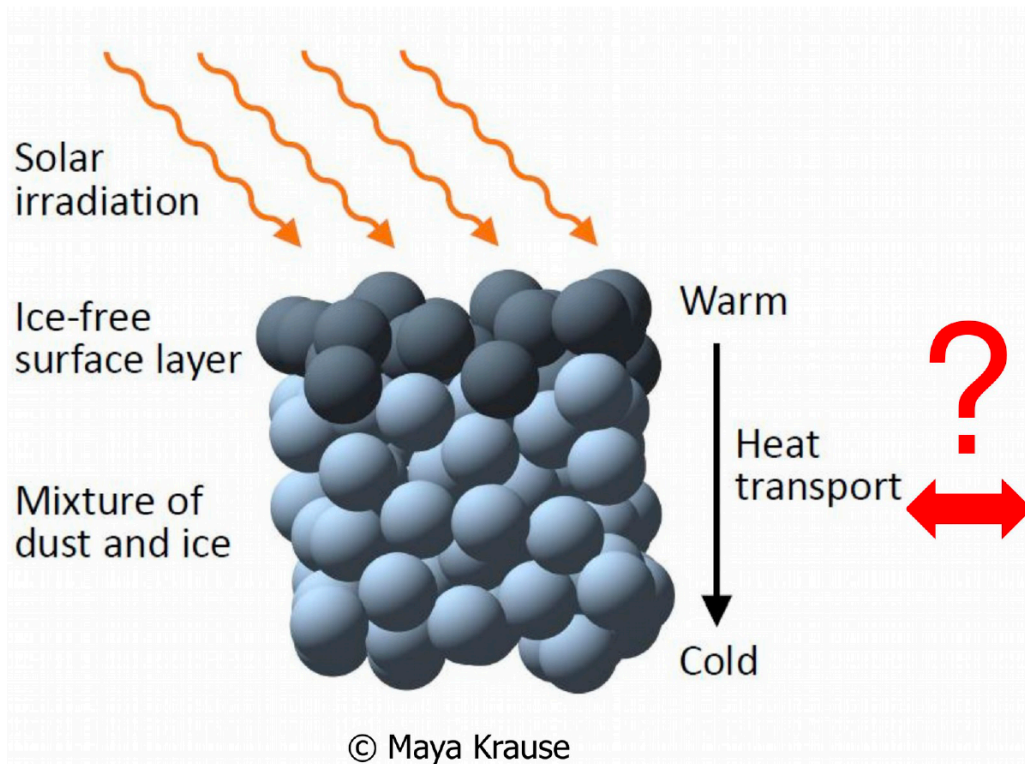
Schematic of the physical processes at work



Nucleus of comet P/67 Rosetta mission (ESA)



Are comets made of pebbles ?



© ESA/Rosetta/MPS für das OSIRIS-Team
MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Pebbles (if any) must be made of (icy) dust particles

Dust classification after IDPs, Rosetta, Stardust (Güttler et al 2019 AA 630, A24)

solid group

SOLID_1: ~ 100 nm

irregular grain



roundish monomer
(e.g., in computer models)



SOLID_2: dense aggregate of grains



< 1 mm

fluffy group

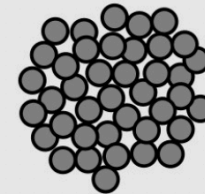
FLUFFY_1: fractal, dendritic agglomerate
(with $m \propto r^{D_f}$ and D_f typically 1.5 .. 2.5)



< 1 cm

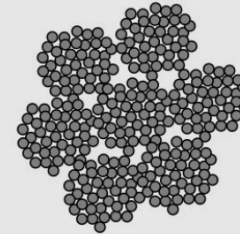
porous group

POROUS_1: porous agglomerate



"average"
dust particle
 < 1 cm

POROUS_2: cluster of agglomerates
(hierarchical)



"pebble"
 ~ 1 cm

Physical evolution of comets

- If comets get close to the Sun and exhibit activity, comets have relatively short life times due to several effects:
 - Orbital instability
 - Loss of volatiles
 - Fragmentation
- Eventually, they may transform into inactive bodies of asteroidal type



Fragmentation of comet
Shoemaker-Levy 9 after a
close approach with Jupiter

Comet composition

- Comets exhibit both volatile and refractory compounds
- Most volatiles are ices
 - Water ice is a main constituent that dominates the activity and the physical evolution of the comet
 - CO ice, more volatile than water ice, explains the cometary activity observed at large distances from the Sun
 - A large number of molecules have been found, especially organic ones, with abundances varying from comet to comet
- Most refractories are silicates
 - Non volatiles are studied through observations of the cometary dust
 - Dust observations: (1) astronomical observations in the infrared, (2) measurements *in situ* by space probes, (3) analysis of interplanetary dust particles collected on Earth

TABLE 2

Measured and Observed Species in Comets

Atoms + Molecules

H, C, O, S, Na, Fe, Ni, CO, CS, NH,
OH, C₂, ¹²C¹³C, CH, CN, ¹³CN, S₂, SO,
H₂, CO₂, HDO, CHO, HCN, DCN,
H¹³CN, OCS, SO₂, C₃, NH₂, H₂O, H₂S,
HCO, H₂CS, C₂H₂, HNCO, H₂CO,
CH₄, HC₃N, CH₃OH, CH₃CN,
NH₂CHO, C₂H₆

Ions

C⁺, N⁺, O⁺, Na⁺, CO⁺, CH⁺, CN⁺,
OH⁺, NH⁺, H₂O⁺, HCO⁺, CO₂⁺,
C₃⁺, CH₂⁺, H₂S⁺, NH₂⁺, HCN⁺,
DCN⁺, CH₃⁺, H₃O⁺, H₃S⁺, NH₃⁺,
C₃H⁺, CH₄⁺, H₃CO⁺, CH₅⁺, C₃H₃⁺

Organic molecules in 67/P

Results from the Rosina mass spectrometer on board of the *Rosetta* mission

Brown: new detections



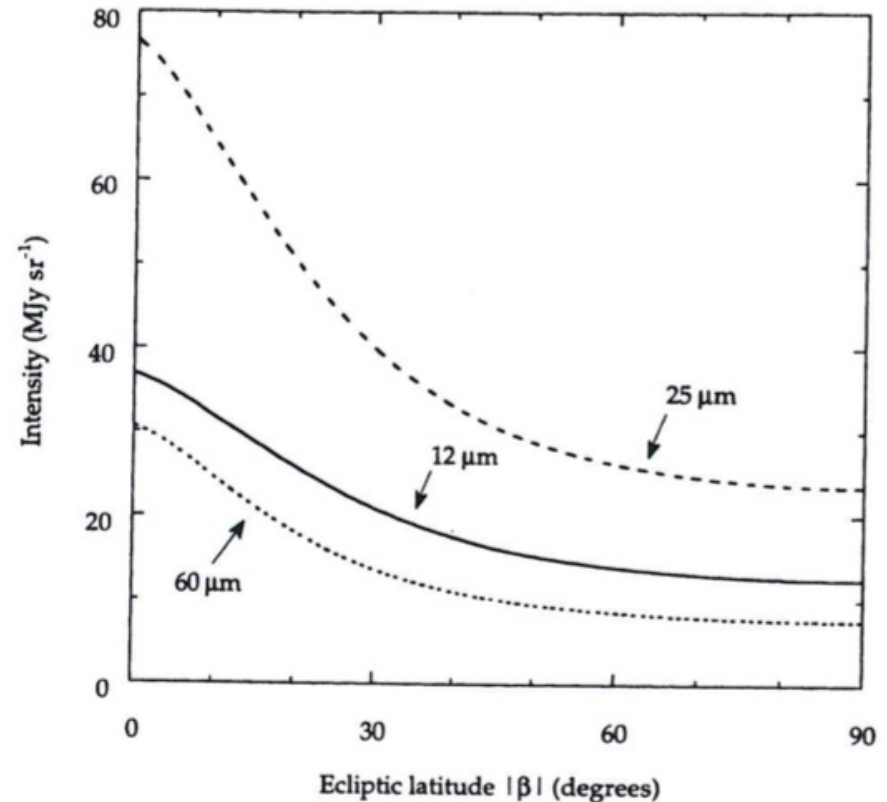
Interplanetary dust

- **Zodiacal light**

- Zodiacal light is due to sunlight scattered by a broad interplanetary dust cloud aligned with the ecliptic plane
- Zodiacal light brightness is a function of viewing direction, wavelength, heliocentric distance and position of the observer relative to the dust symmetry plane

- **Infrared zodiacal emission**

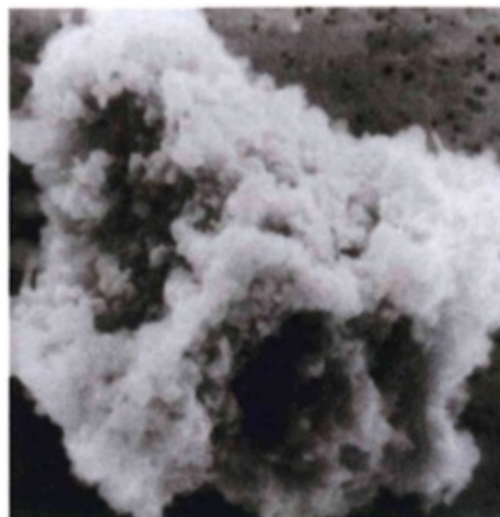
- At $\lambda \gtrsim 3 \mu\text{m}$, thermal emission from the interplanetary dust (zodiacal emission) dominates over scattered light
- The emission varies along the ecliptic plane and is a critical disturbing factor in extragalactic infrared astronomy



Interplanetary dust

Interplanetary dust particles
collected in the stratosphere by
NASA's cosmic dust program

Top:
grain of chondritic composition



Bottom:
Fe-S-Ni sphere

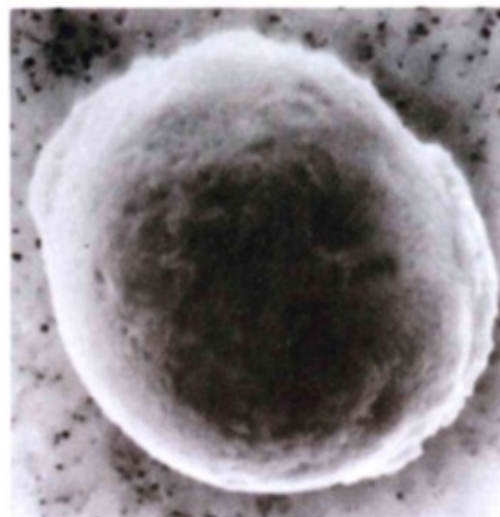


Image sizes:
30 μm