Minor Bodies in the Planetary System

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Some Basics

Ecliptic	plane of the Earth orbit around the sun projected into the solar system and sky
Astronomical Unit	mean distance Earth – Sun (149.6 10^6 km)
Inclination	angle of orbital plane to Ecliptic
Obliquity	angle of rotation axis and orbital plane
Elongation	angle between Sun and planet as seen from observer (Earth), greatest elongation (inner planets only)
Opposition	planet and Sun are seen with elongations close to 180 deg (outer planets only)
Conjunction	planet and Sun are seen with elongation close to 0 deg (upper/lower conjunction)

The Planetary System - Overview

- **Ingredients:**
  - Sun: central star
  - Planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune
  - Moons and rings: 6 planets with moons and moonlets, 4 planets with rings or ringlets
  - *Minor bodies: Dwarf planets, Asteroids, Transneptunian Objects, Comets*
  - The rest: *meteorites,* solar wind

Benchmarks

- **Dimensions:** solar system extension ~ 100000AU
  planetary system extension ~ 0.4-32/50/1000AU
- **Geometry:** flat disk close to Ecliptic and equator of the Sun
- **Masses:** 1+0.0015 solar masses (mostly concentrated in the Sun)
- **Angular momentum:** mostly in planets (due to large distances)
- **Barycenter:** close to photosphere of the Sun
  reflex motion of the Sun indicates presence of planet(s)
  ➔ detection of Jupiter around the Sun through radial velocity shift of photospheric lines of the Sun
  amplitude $\delta v = 2\pi R_o/U_{Jup}$
  R_o = Sun radius (700000km)
  U_{Jup} = orbit period of Jupiter (11.8y)

  ➔ $\delta v \sim 10$ m/s (over 11.8y)
  measurement accuracy ~ few m/s (HD spectrographs)
  problem is orbital period

Basic Physics

- Planck's law

  $B(\lambda) = (2hc^2/\lambda^5) / [\exp(hc/(2\pi\lambda kT) - 1]$

- Wien's law

  $\lambda_{max}\, T = 2880$ [μmK]

- Energy balance

  $F_o/r^2\, \pi R^2\, (1-A) = \sigma T^4\, 4\pi R^2$

- Surface temperature (atmosphereless)

  $T = (1-A)^{1/4}\, 273\, r^{1/2}$ (fast rotator)

  $T = (1-A)^{1/4}\, 324\, r^{1/2}$ (slow rotator)

➔ **snowline (T<273K): somewhere in asteroid belt**

λ = wavelength

Λ_{max} = wavelength of radiation maximum

T = temperature

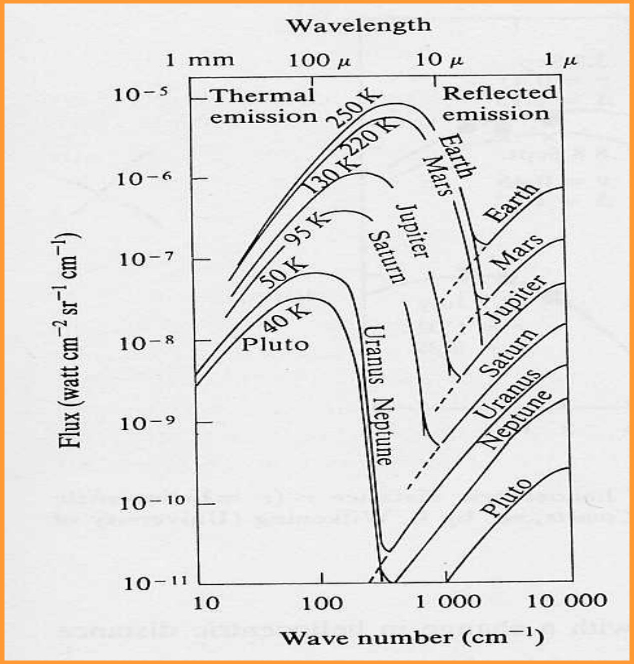
h, c, σ, k = Planck const, speed of light, Stefan const, Boltzmann const,

A = surface albedo

R = body radius

F_o = solar flux at 1 AU

r = distance from the Sun



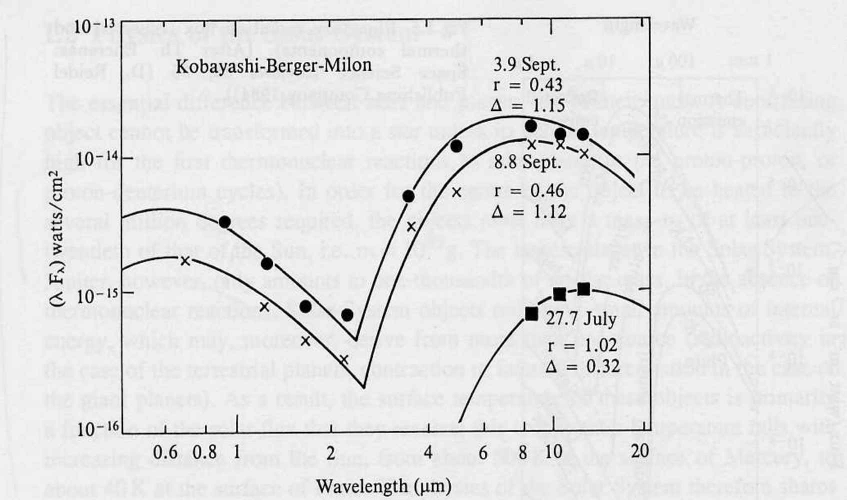


Fig. 1.6. The flux from a comet as a function of heliocentric distance r (r = heliocentric distance, Δ = geocentric distance. [After E. Ney: *Comets*, ed. by L. Wilkening (University of Arizona Press, Tucson 1982)]

Bodies with and without atmosphere

- **Criterium for possible stable atmosphere:**
  (1) $E_{kin}(gas) < E_{pot}(gas)$
  $v^2 < v^2_{escape} = 2\, \gamma\, m / R$
  (2) Mean velocity of gas
  $\underline{v}^2 = 2\, G\, T / \mu$

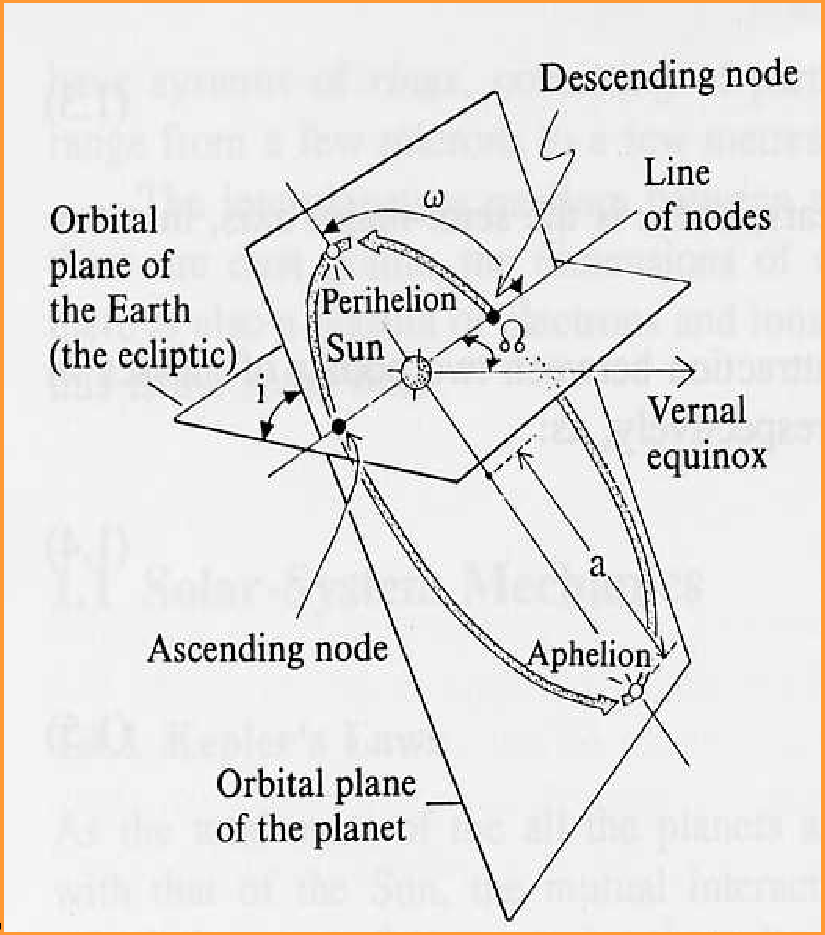
  ➔ $(m\, \mu) / (R\, T) < G / \gamma$

Sequence of stability of atmosphere: Jupiter – Saturn, Neptune, Uranus, Earth, Venus, Mars, Pluto, Triton, Titan ➔ other bodies without atmosphere

γ = gravity constant
m,R = body mass, radius
G = gas constant
T = gas temperature
μ = mean molecular weight

Orbits

- ***Ellipse***, parabola, hyperbola
- Newtonian 2-body solution ~ good approximation
  - Orbit plane defined by
    - I = inclination (to Ecliptic/equator)
    - Ω = argument of ascending node
  - Dynamics defined by
    - $r = a\,(1-e^2) / (1+e \cos v)$ (Ellipse)
    - r = length of radius vector
    - a = semi-major axis
    - e = eccentricity
    - v = true anomaly (angle between perihelion and actual orbit position as seen from central body)



Location of orbit in plane defined by

- ω = argument of perihelion (angle between Ω and perihelion measured in orbital plane as seen from central body)

- time dependance r = r(t)
  - $\cos v = (\cos E - e) / (1 - e \cos E)$
  - $E = M - e \sin E$
  - $M = n\,(t - T_p)$
  - E = excenrtic anomaly
  - M = mean anomaly
  - T_P = time of perihelion
  - n = mean motion rate
- Kepler's law 1+2+3
  - (1) Orbit = ellipse with the Sun in one focus
  - (2) $r^2\, dv/dt = G$

    $G^2 = a(1-e^2) / [\gamma\,(M_o+m)]$
  - (3) $P^2/a^3 = \gamma\,(M_o+m)/4\pi^2$

    P = orbital period

    M_o = solar mass

    m = planet's mass

    γ = gravity constant

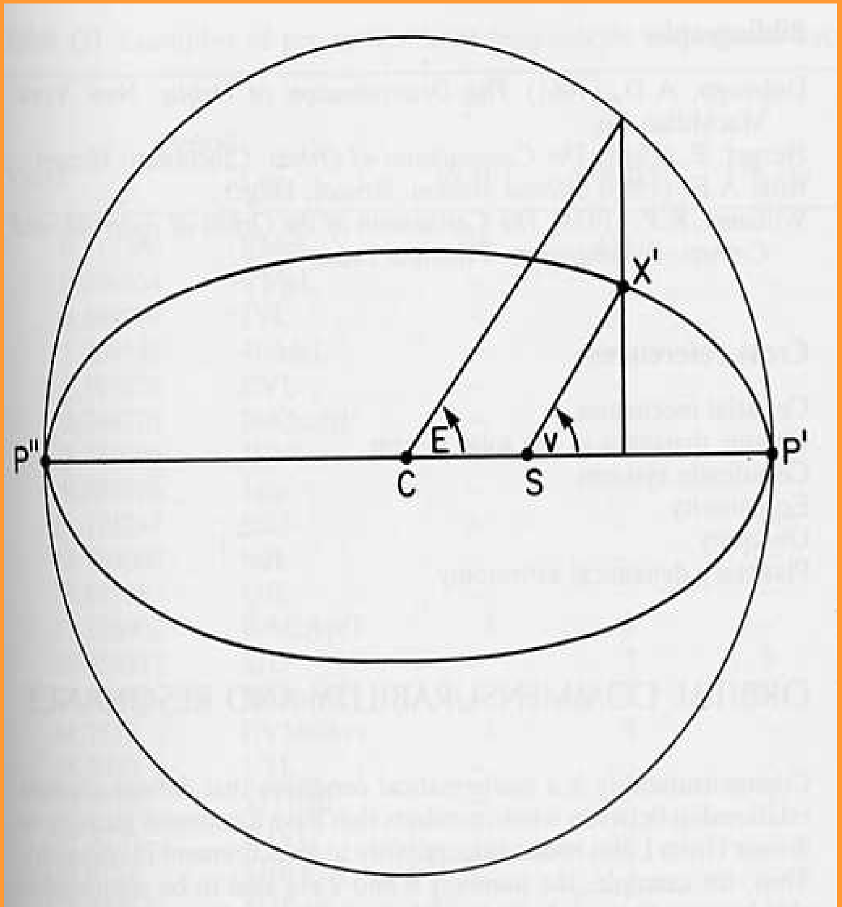


Figure O7 The true orbit seen face-on. The Sun S is at a focus. P' and P'' are the perihelion and aphelion points. The ratio CS/CP' is the eccentricity *e*. The perihelion distance SP' is $q = a(1 - e)$. The aphelion distance SP'' is $Q = a(1 + e)$. The circumscribing circle is the auxiliary circle. When the true planet is at X', its true anomaly is *v* and its eccentric anomaly is *E*.

Overview Tables of the Planets

TABLE I

Planetary Orbits[a]

Planet	Semimajor axis (AU)	Eccentricity	Inclination (°)	Period (years)	
Mercury	0.38710	0.205631	7.0048	0.2408	
Venus	0.72333	0.006773	3.3947	0.6152	
Earth	1.00000	0.016710	0.0000	1.0000	
Mars	1.52366	0.093412	1.8506	1.8807	
Jupiter	5.20336	0.048393	1.3053	11.856	
Saturn	9.53707	0.054151	2.4845	29.424	
Uranus	19.1913	0.047168	0.7699	83.747	
Neptune	30.0690	0.008586	1.7692	163.723	
Pluto	39.4817	0.248808	17.1417	248.02	← dwarf planet

[a] J2000, Epoch: January 1, 2000

TABLE III

Physical Parameters for the Sun and Planets

Name	Mass (kg)	Equatorial radius (km)	Density (g cm^{-3})	Rotation period	Obliquity (°)	Escape velocity (km sec^{-1})	
Sun	1.989×10^{30}	696,000	1.41	24.65–34 days	7.25[a]	617.7	
Mercury	3.302×10^{23}	2,439	5.43	58.646 days	0	4.43	
Venus	4.868×10^{24}	6,051	5.20	243.018 days	177.33	10.36	
Earth	5.974×10^{24}	6,378	5.52	23.934 hr	23.45	11.19	
Mars	6.418×10^{23}	3,396	3.93	24.623 hr	25.19	5.03	
Jupiter	1.899×10^{27}	71,492	1.33	9.925 hr	3.08	59.54	
Saturn	5.685×10^{26}	60,268	0.69	10.656 hr	26.73	35.49	
Uranus	8.683×10^{25}	25,559	1.32	17.24 hr	97.92	21.33	
Neptune	1.024×10^{26}	24,764	1.64	16.11 hr	28.80	23.61	
Pluto	1.32×10^{22}	1,170	2.1	6.387 days	119.6	1.25	← dwarf planet

[a] Solar obliquity relative to the ecliptic.

Asteroids

- **Summary**
  - Asteroids = remnants from formation disk between Mars and Jupiter
  - irregular shape except large ones
  - Did not make it to form a planet (Jupiter influence)
  - Continuous loss of asteroids from belt
  - Kirkwood gaps = gravitational scattering by Jupiter
  - Hirayama families = collision groups
  - Taxonomy classes = differentiated bodies
  - Solar distance distribution of taxonomic classes with signature from formation period

Orbits

- **Asteroid belt:**
  - largest concentration between Mars and Jupiter
  - much lower at other (larger&smaller) distances
  - within asteroid belts gaps with low number density

    ➔ Kirkwood gaps
  - Gaps are located at integer-ratio resonances between asteroid and Jupiter revolution periods

    Resonance effects: Jupiter increases eccentricity of asteroids when in resonance orbit, short life time of objects in resonance orbits

    ➔ asteroid becomes planet crossing and is at high risk to collide with terrestrial planets

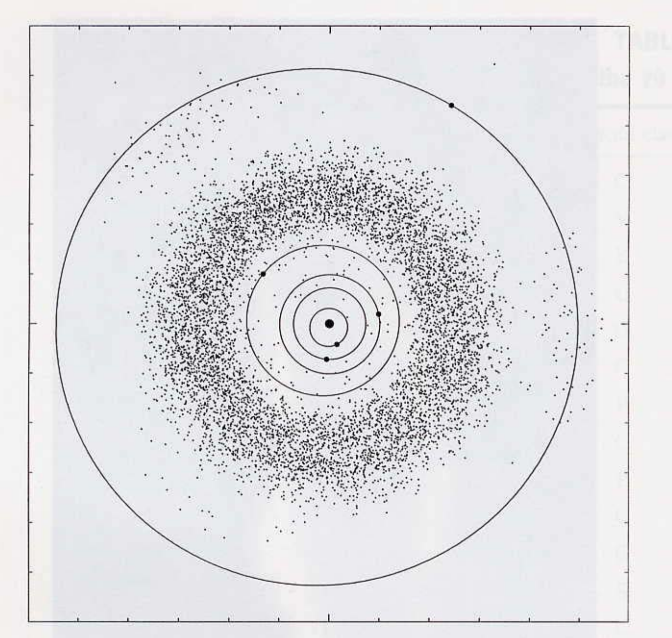
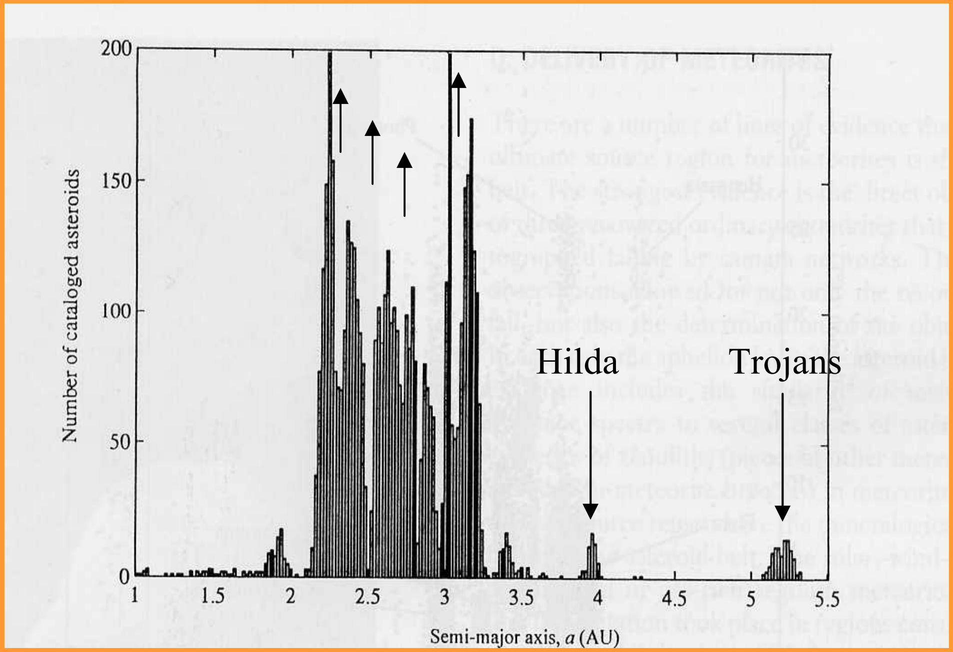


FIGURE 3 Positions projected onto the ecliptic plane for October 4, 2000 of the planets Mercury through Jupiter and 7722 numbered asteroids with accurately known orbits. (Copyright 1998 Institute for Remote Exploration.)



- Exception 1: Hilda group is in 3:2 resonance with Jupiter

  dynamically this resonance has a long lifetime, i.e. asteroids will be collected here
- Exception 2: Trojans are in 1:1 orbit with Jupiter and remain associated with the two stable Lagrangian points (~60^o ahead or behind Jupiter)

  ➔ solar system application of restricted three-body problem

  equal side triangle Sun-Jupiter-Trojan is a dynamically stable configuration

  Trojans at other planets: Mars & Neptune have Trojan-type asteroids
- Planet crossers: Amor group = Mars crossers

  Apollo group = Earth crossers with $a > 1$ AU

  Aten group= Earth crossers with $a < 1$ AU

  Planet crossers do not have very long lifetime due to the high probability to become
  - either scattered by planet in very different orbit or
  - to collide with the planet

- **Collision families:**
  - Clustering of asteroid orbits with certain orbital parameters

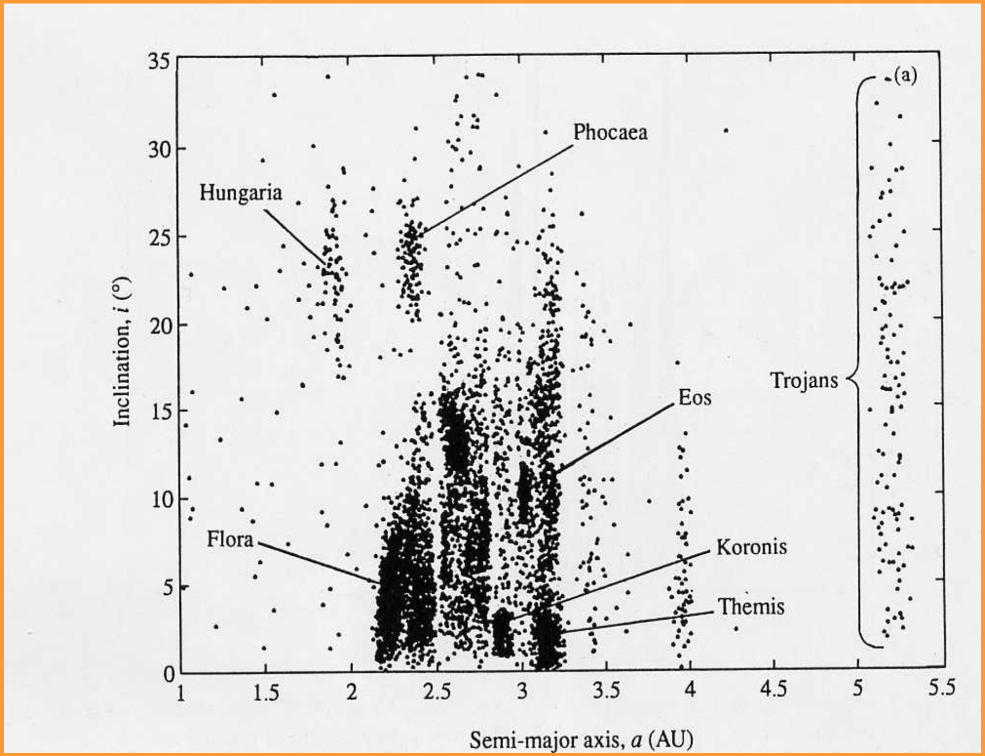
    (a,i) or (a,e) groups

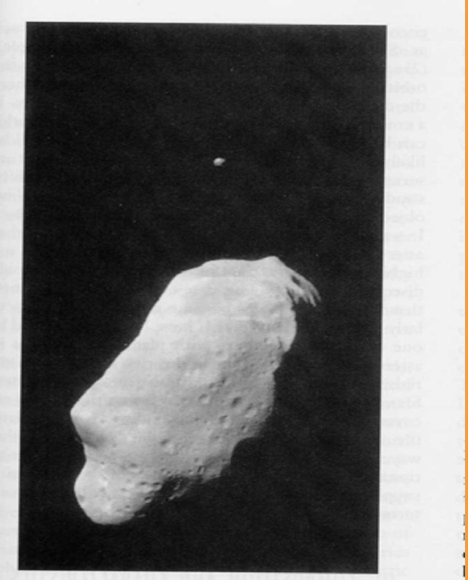
    ➔ Hirayama families
  - Collision families
  - Family members may have different taxonomic properties since they can originate from different part of possibly differentiated bodies by the collision event (for instance from the crust - S-type, from the core – M type)
- **Double asteroids:**
  - Double asteroids exist

    (first discovery: Ida+Dactyl discovered by GALILEO probe during flyby)
  - Formation through impact (?)

    through rotational break-up

    (small ones only)





JURE 6 243 Ida and its satellite, Dactyl. (Courtesy of NASA/ ./Caltech.)

Reflectance spectroscopy

Recipe:

- take object spectrum
- take solar analogue spectrum
- divide the two spectra

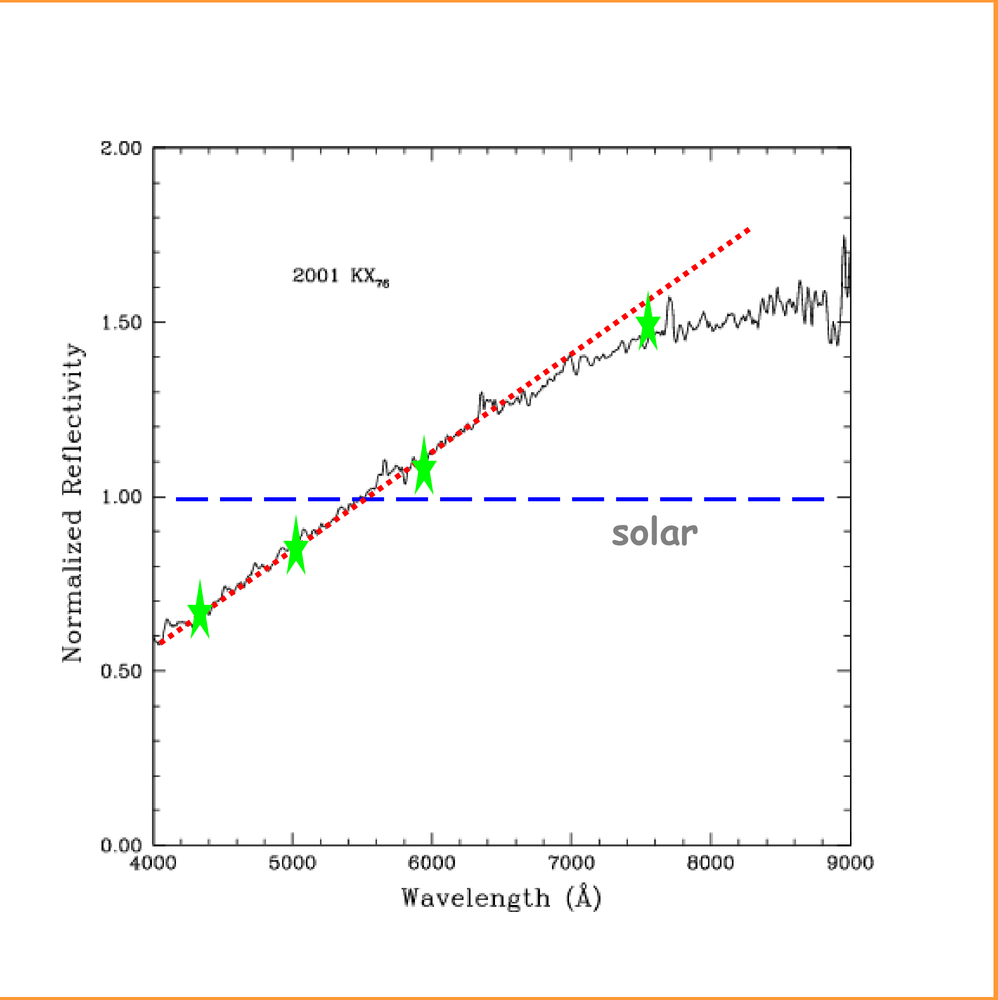
➔ intrinsic spectrum of the object

solar = flat without slope

gradient = diverse object continuum

absorption/emission = object specific materials

(works also for photometry)



Composition/Taxonomy

- Classification scheme based on telescopic (reflectance spectroscopy and/or photometry) and (few) flyby observations, no in-situ/lab analysis available (Hayabusa still to come)
- Main taxonomic classes (more classes exist, see table):
  - Indications/examples for differentiation of the internal structure of asteroids exists, however also for non-differentiation

    Note: similarities between asteroid and meteorite spectra are used for classification and identification of surface materials
  - A, S, V, R types: pyroxene and olivine absorptions

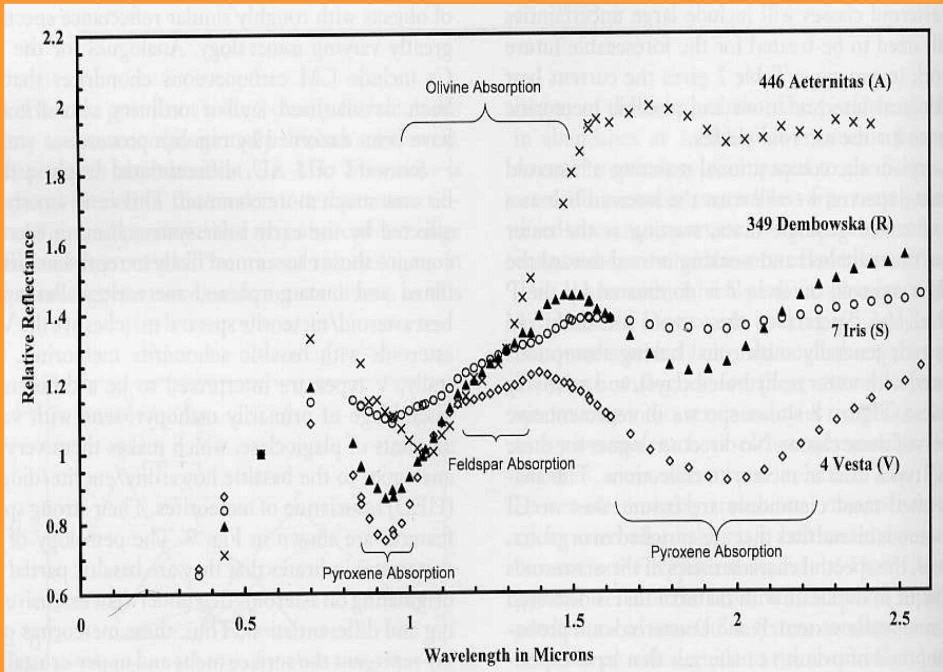
    ➔ silicate/basaltic bodies, heated material from early period of the Sun

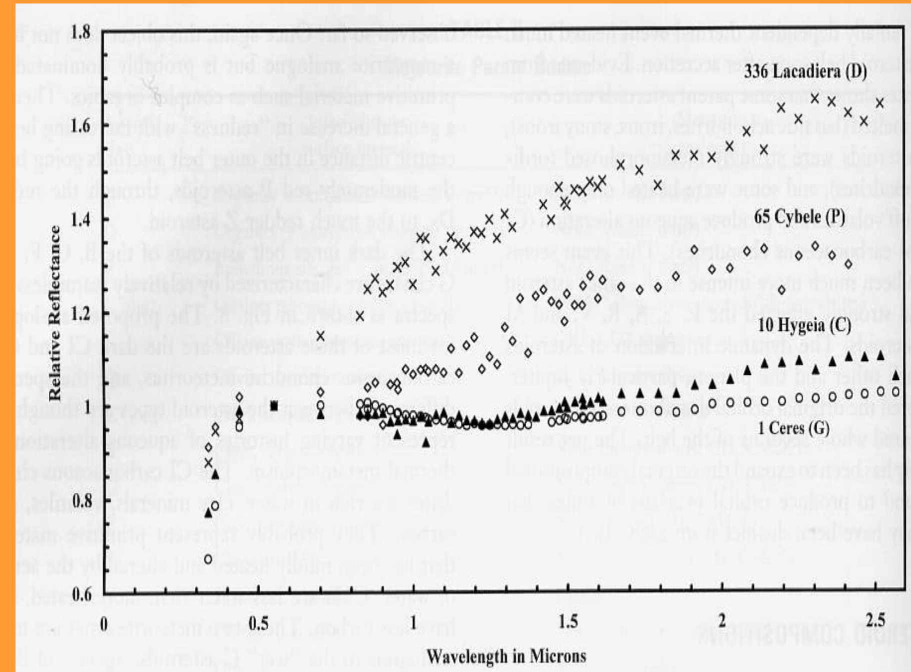
    could come from mantle of a differentiated body
  - E, M, T types: metal-rich absorptions

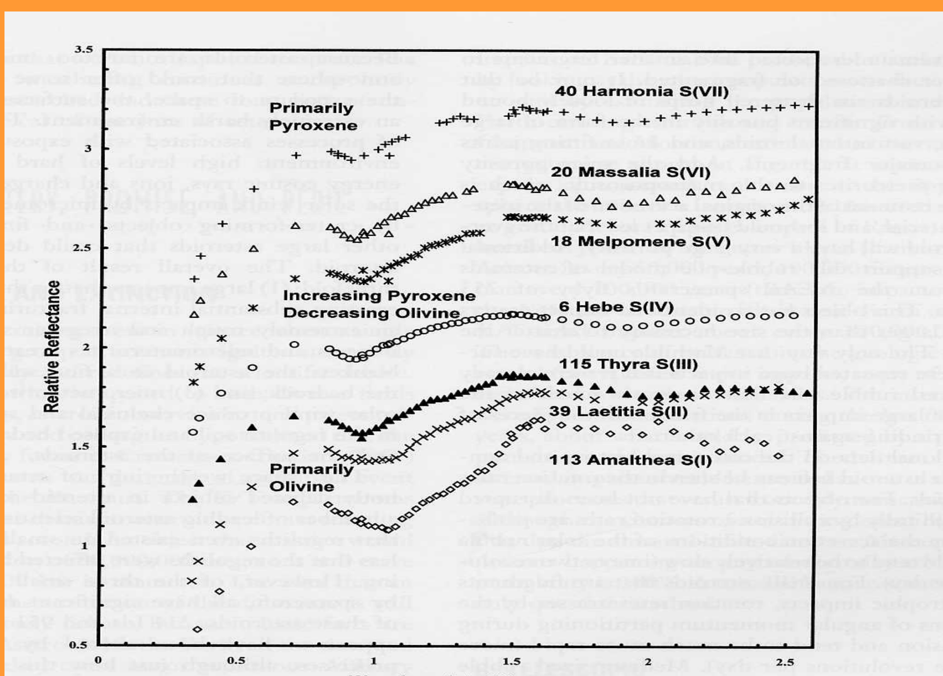
    ➔ from inner metal core or mantle of differentiated body (wet – hydrated, dry - anhydrous)
  - C, D, G, P types: carbon+organics, low albedo objects, mostly featureless

    ➔ primitive material in two forms:

    (wet – dry)
- Taxonomic class distribution in belt:
  - Non-uniform
    - Primitive classes in outer part
    - Silicate – metal-rich classes in center and inner belt







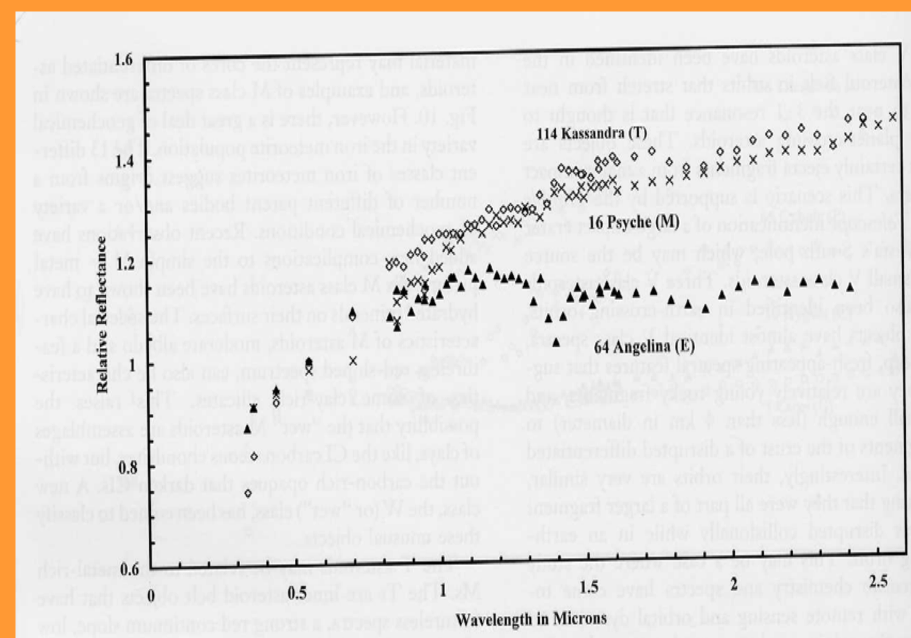


FIGURE 10 Red-sloped M, T, and E classes. These asteroids lack strong absorptions, but have large differences in albedo.

TABLE II
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

- **<u>Taxonomic class distribution in belt:</u>**
  - Non-uniform
    - Primitive classes in the outer part of the belt
    - Silicate – metal-rich classes in center and inner belt
  - Scenario: differentiation of object interior possible in inner belt due to heating by the early Sun (T-Tauri phase), some larger asteroids in central zone of the belt may have developed molten interiors due to gravitational/radioactive heating

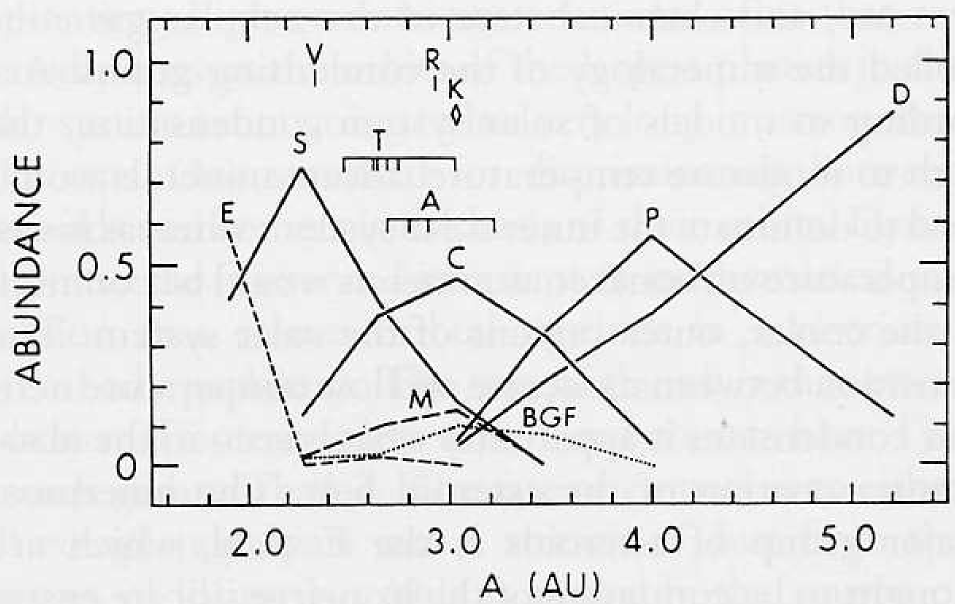


FIGURE 7 Distribution of taxonomic classes from Bell *et a*
(1989). (Courtesy of University of Arizona Press.)

Collision Effects

- Impact craters: exists in flyby images
  - Regolith surface
- Simulation conclusions:
  - Only large objects survive mostly ‚unaffected‘ from bombardment
  - Smaller objects (radius < 300km) experienced intense collisional evolution
    - Disruption
    - Re-accretion due to self gravity

      → loose rubble piles

      high porosity and low density
    - Higher rotation rates from impact events
    - Very small bodies (< 1km) suffer from rotational break-up due to YORP effect

Asteroids&other bodies

- Meteorite link:
  - Orbit similarity

    meteorites originate – in parts – from asteroids
  - Spectrum similarity

    → indirect evidences, but with very useful conclusions

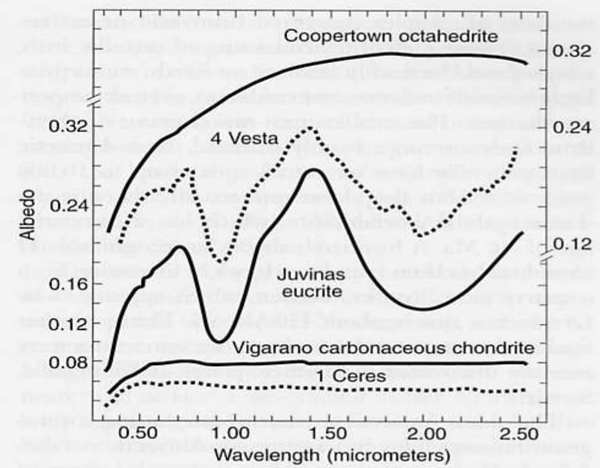


FIGURE 16 Spectral reflectances of the Coopertown IIIE coarse octahedrite, Juvinas eucrite and V-class asteroid 4 Vesta, and Vigarano C3V chondrite and G-class asteroid 1 Ceres. The albedo scale for all but Coopertown is on the left; that for Coopertown is on the right. Solid lines delineate meteorite spectra and dashed lines define asteroid spectra. (Courtesy of Dr. Lucy-Ann McFadden, University of Maryland.)

- Comet link:
  - –Orbit similarity
    - Tisserand constant of orbit as invariance parameter
    - $a_j/a + 2\,(a/a_j\,(1-e^{-2}))^{1/2} \cos i = C$

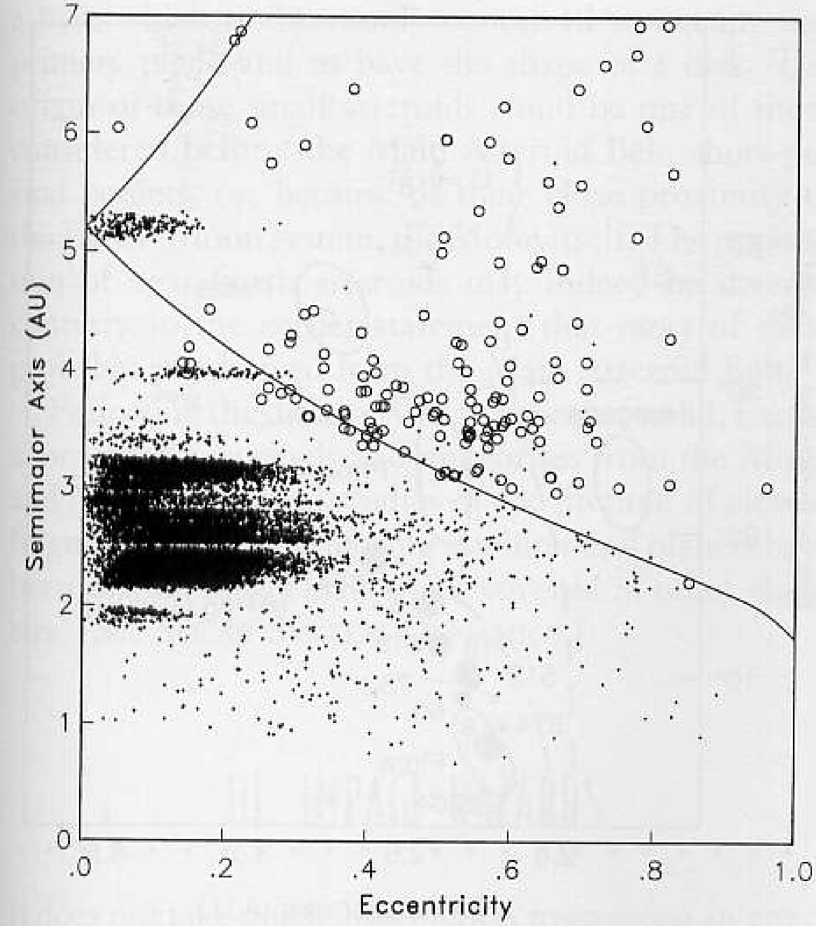
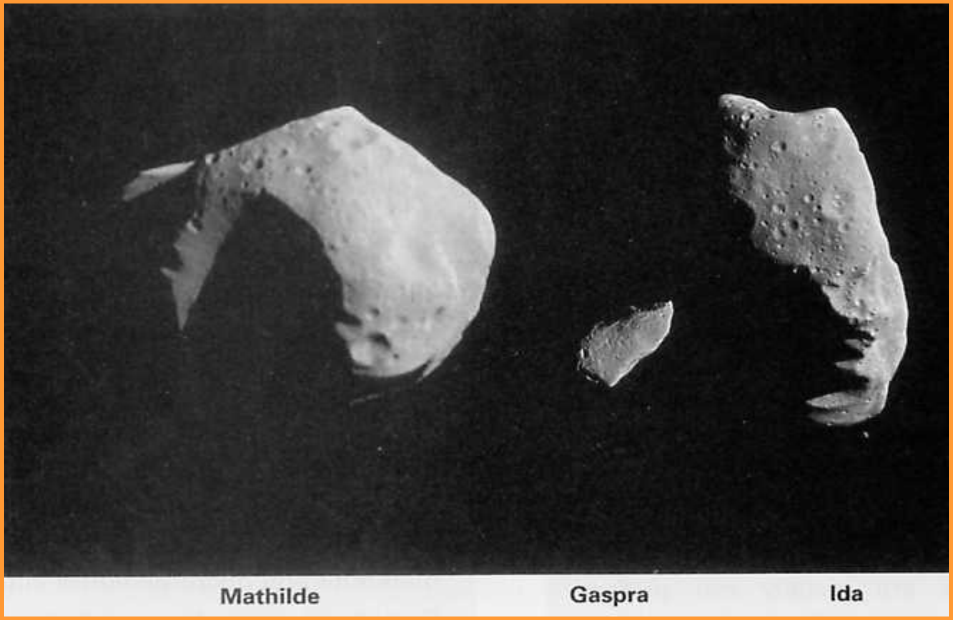


FIGURE 6 Graph of the Tisserand invariant. The solid line represents the Tisserand invariant with a value of 3. (Graph provided by Jeff Bytof, Jet Propulsion Laboratory, Pasadena, Calif.)

Radar image of 2000 PH5

Sizes, Shapes, Rotation

- Sizes:
  - 1000km → m → mm etc.
  - Only a few ones > 500km diameter
  - Size distribution N versus mass m: $N(m) \sim m^{-3}$
    → indicative for collision dominated size distribution
- Shapes:
  - Irregular except largest ones
    (spacecraft + radar + lightcurves)
  - Triaxial eelipsoids
- Rotation:
  - Fast rotators more frequent (irregular periodic lightcurves)
    → in agreement with collision scenario, but strong bias from observations (long periods need longer observing time)

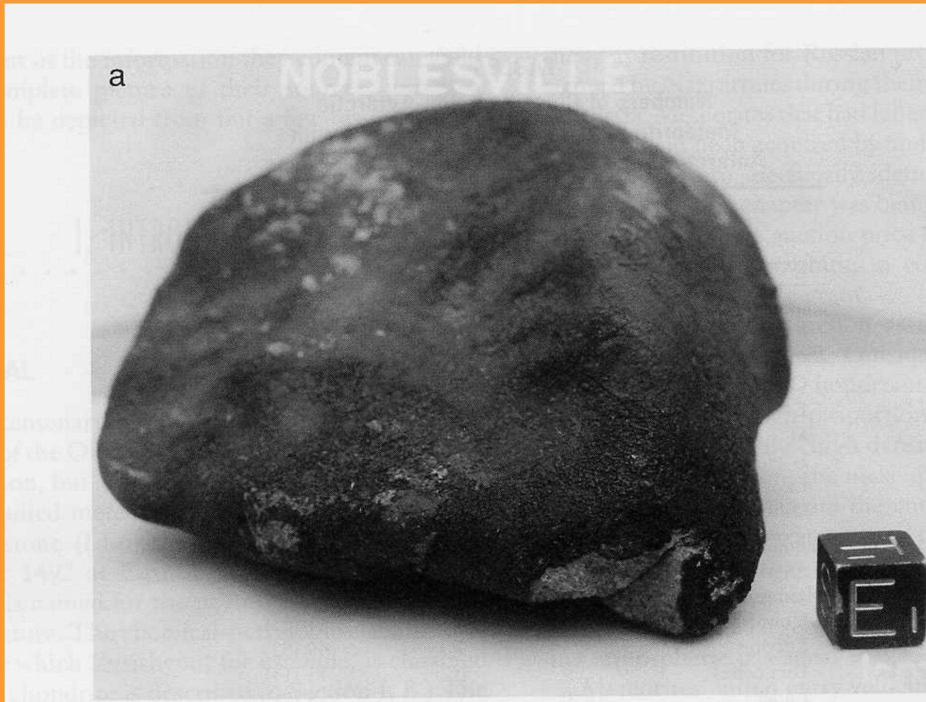


Eros by Shoemaker

1999 SF56 by Hayabusa

Meteorites

- **Summary**
  - Differentiated (associated with asteroids) and undifferentiated (primitive) meteorites
  - Chondrites: ‚uniform' age 4.6 10^9 y = age of the solar system
  - Solar composition (except volatile elements)
  - Organics found (L aminoacids)
  - Some isotopic peculiarities indicate non-uniform mixture of solar nebula

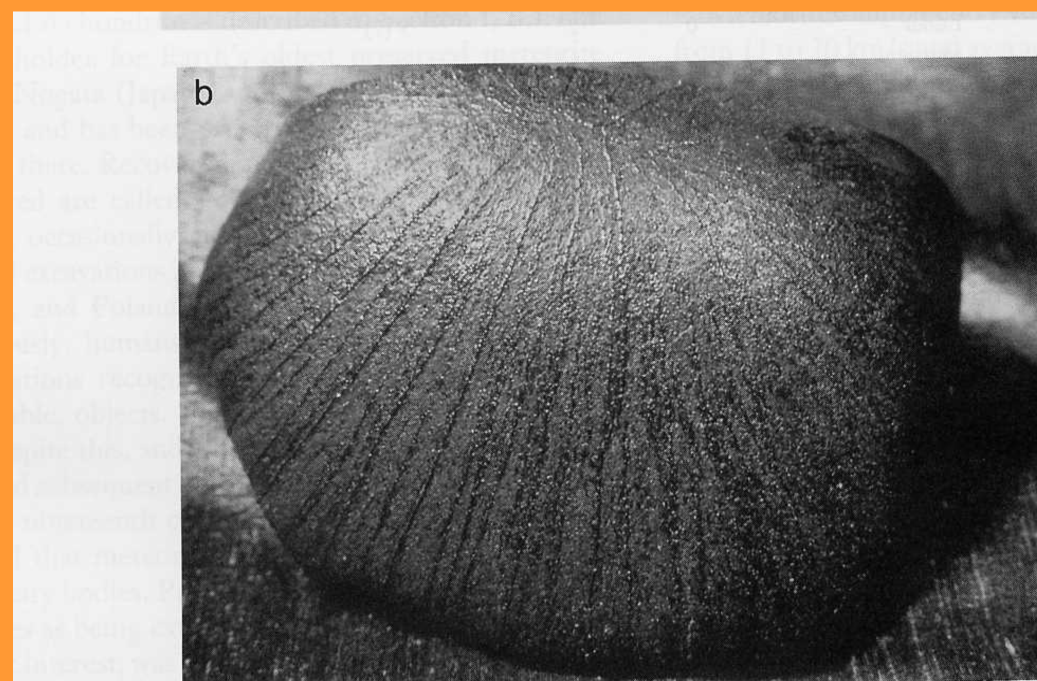


Meteorite with crust

Only the upper few cms are heated during entry in the atmosphere, the interior remains at deeply frozen temperature

Mars meteorite (SNC)

With signature of atmospheric ablations



Meteorites in the sky and hitting a car

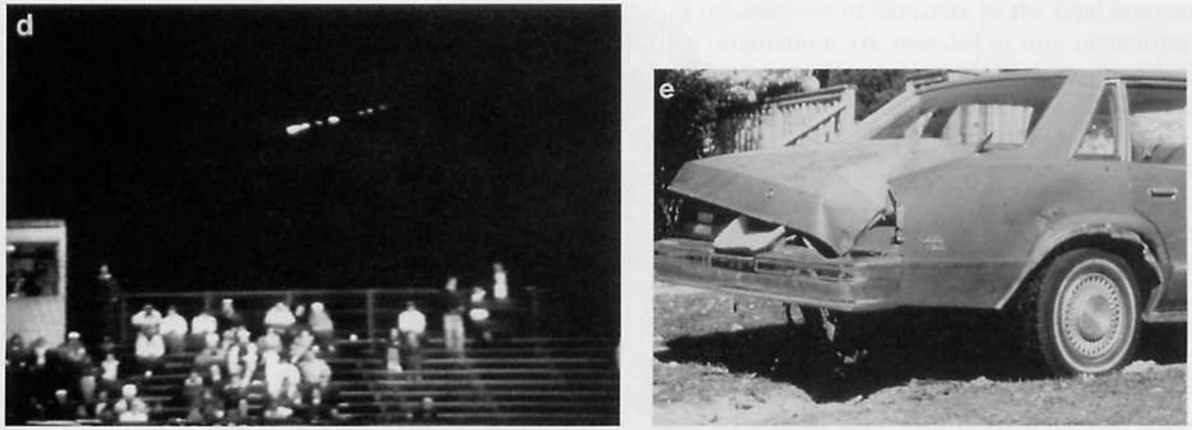
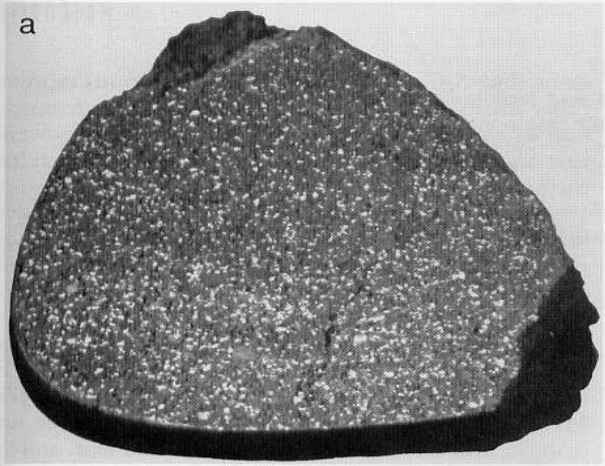


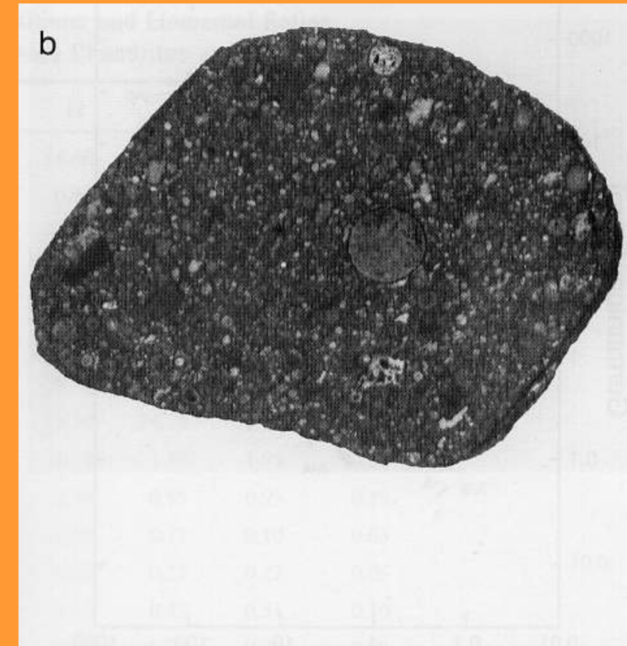
FIGURE 5 *(continued)*

Allende meteorite

Large meteoroids: Above, a fireball (shown by arrow) of an 80 m object with estimated mass of 1 MTonne, that apparently skipped out of the atmosphere, observed on August 10, 1972 moving left to right over Grand Teton National Park. (Photo courtesy of Dennis Milon) Below, the 1-km diameter Meteor Crater in Arizona formed by the explosive impact of the Canyon Diablo IA octahedrite meteoroid about 50 ka ago. (Photo courtesy of Allan E. Morton)

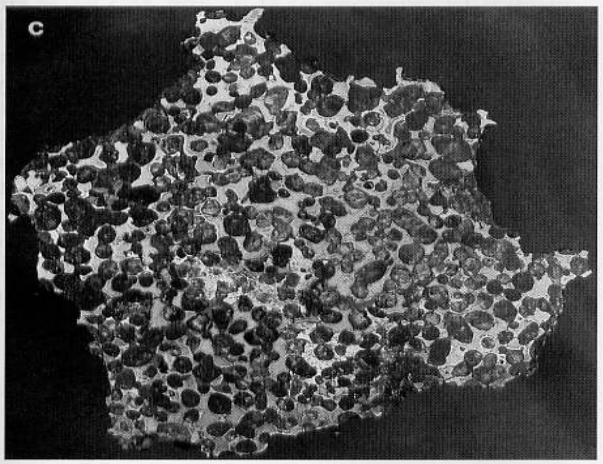
Meteorite - Types

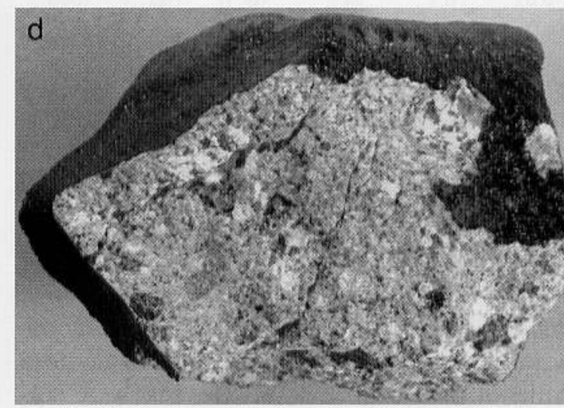




Chondrites (spherical chondrules are present)

undifferentiated





Achondrites

differentiated

Nickel-Iron

differentiated

Tectides

terrestrial molten impact ejecta

not considered

Classification

- **Differentiated meteorites:** contain processed material, i.e. were part of a larger differentiated body and became meteorite as a collision product

  Iron (4 %), Stony-Iron (1%), Achondrites (9%)

  molten core, mantle-crust, crust of asteroids

  ➔ differentiated meteorites have a clear link to asteroids

  – Widmanstätten pattern in iron meteorites: Ni content determines crystalisation

  → zones have different Ni content and crystallised at different times

- **Undifferentiated meteorites:** most original, unprocessed material from Solar System formation or before, chondrite types classified by iron content

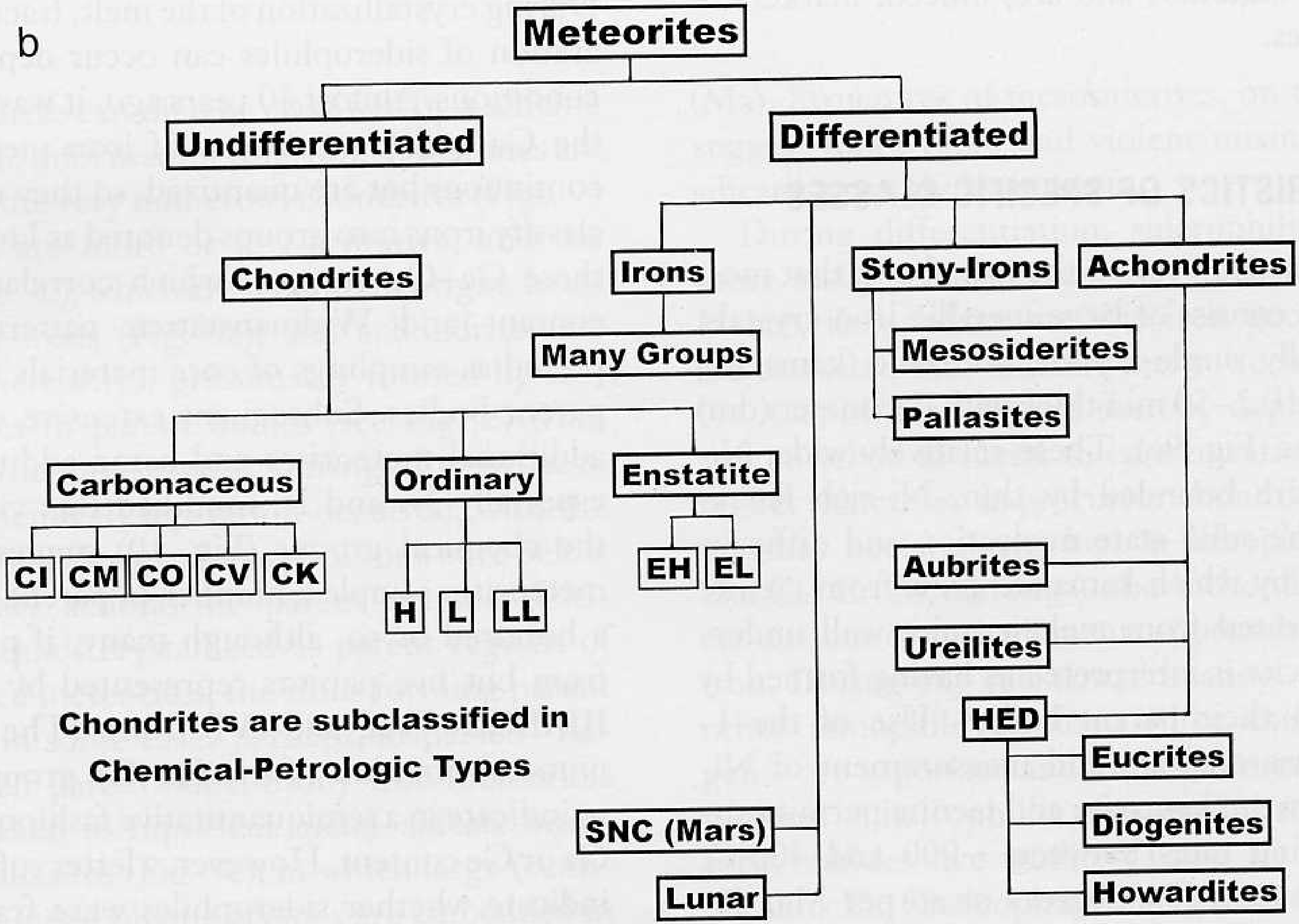
  normal Chondrites (81 %), carbonaceous Chondrites (5 %)

  chondrule: spherical inclusion of silicate (olivine etc.) in surrounding matrix, created by melting and rapid cooling (re-crystallisation at ~1600K) process at zero gravity

  ➔ either during early phase of the Sun or existent already before formation of the solar system (interstellar grains)

  matrix material is produced by gentle aggregation of molecules at surface in space (surface reactions in cold environment under high energy radiation

  → formation of complex - also organic - molecules) b


Meteorites
Undifferentiated
Differentiated
Chondrites
Irons
Many Groups
Stony-Irons
Achondrites
Mesosiderites
Pallasites
Carbonaceous
Ordinary
Enstatite
CI
CM
CO
CV
CK
H
L
LL
EH
EL
Aubrites
Ureilites
HED
Eucrites
Diogenites
Howardites
SNC (Mars)
Lunar
Chondrites are subclassified in
Chemical-Petrologic Types

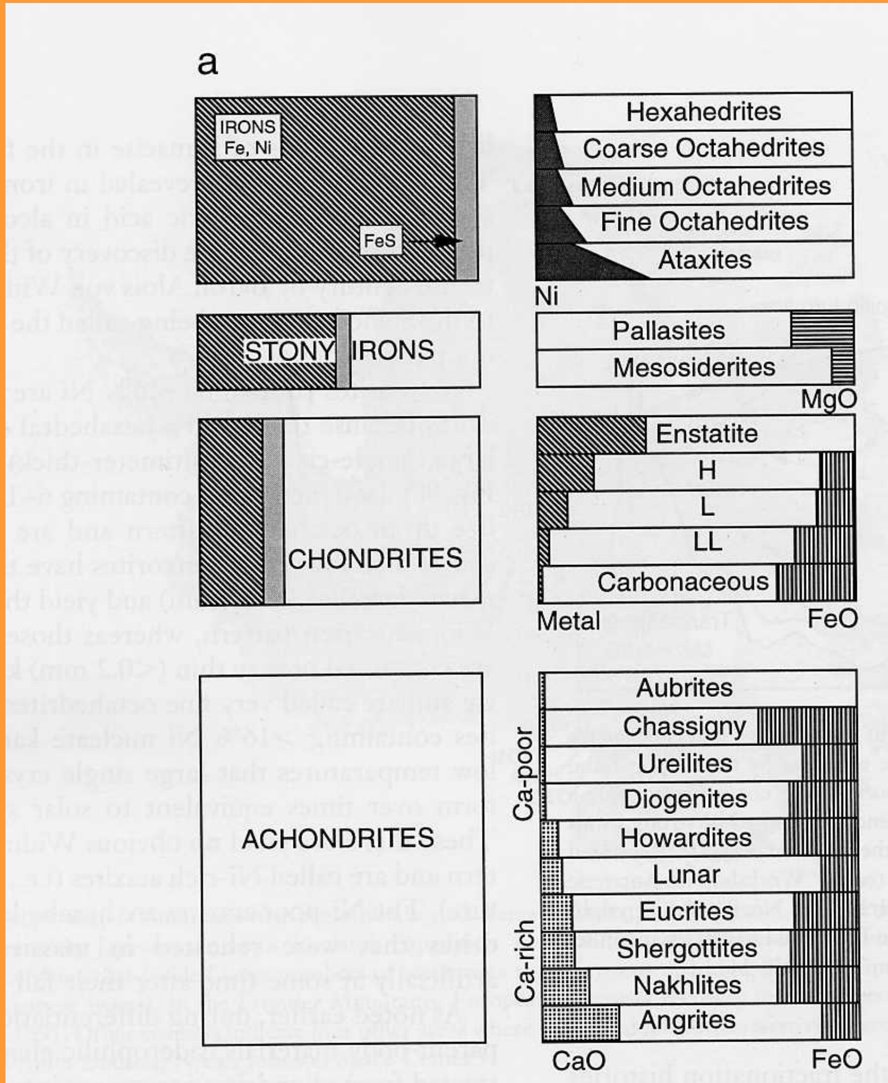


TABLE III
Average Chemical Compositions and Elemental Ratios of Carbonaceous and Ordinary Chondrites and Eucrites

Species[a]	C1	C2M	C3V	H	L	LL	EUC
SiO_2	22.69	28.97	34.00	36.60	39.72	40.60	48.56
TiO_2	0.07	0.13	0.16	0.12	0.12	0.13	0.74
Al_2O_3	1.70	2.17	3.22	2.14	2.25	2.24	12.45
Cr_2O_3	0.32	0.43	0.50	0.52	0.53	0.54	0.36
Fe_2O_3	13.55						
FeO	4.63	22.14	26.83	10.30	14.46	17.39	19.07
MnO	0.21	0.25	0.19	0.31	0.34	0.35	0.45
MgO	15.87	19.88	24.58	23.26	24.73	25.22	7.12
CaO	1.36	1.89	2.62	1.74	1.85	1.92	10.33
Na_2O	0.76	0.43	0.49	0.86	0.95	0.95	0.29
K_2O	0.06	0.06	0.05	0.09	0.11	0.10	0.03
P_2O_5	0.22	0.24	0.25	0.27	0.22	0.22	0.05
H_2O^+	10.80	8.73	0.15	0.32	0.37	0.51	0.30
H_2O^-	6.10	1.67	0.10	0.12	0.09	0.20	0.08
Fe^0		0.14	0.16	15.98	7.03	2.44	0.13
Ni			0.29	1.74	1.24	1.07	0.01
Co			0.01	0.08	0.06	0.05	0.00
FeS	9.08	5.76	4.05	5.43	5.76	5.79	0.14
C	2.80	1.82	0.43	0.11	0.12	0.22	0.00
S (elem)	0.10						
NiO	1.33	1.71					
CoO	0.08	0.08					
NiS			1.72				
CoS			0.08				
SO_3	5.63	1.59					
CO_2	1.50	0.78					
Total	98.86	99.82	99.84	99.99	99.99	99.92	100.07
ΣFe	18.85	21.64	23.60	27.45	21.93	19.63	15.04
Ca/Al	1.08	1.18	1.10	1.11	1.12	1.16	1.12
Mg/Si	0.90	0.89	0.93	0.82	0.80	0.80	0.19
Al/Si	0.085	0.085	0.107	0.066	0.064	0.062	0.290
Ca/Si	0.092	0.100	0.118	0.073	0.071	0.072	0.325
Ti/Si	0.004	0.006	0.006	0.004	0.004	0.004	0.0019
ΣFe/Si	1.78	1.60	1.48	1.60	1.18	1.03	0.66
ΣFe/Ni	18.12	16.15	16.85	15.84	17.73	18.64	
Fe^0/Ni			9.21	5.67	2.29		
Fe^0/ΣFe			0.58	0.32	0.12		

[a] ΣFe includes all iron in the meteorite whether existing in metal (Fe^0), FeS, iron silicates as Fe^{2+} (FeO), or Fe^{3+} (Fe_2O_3). The symbol H_2O^- indicates loosely bound (adsorbed?) water removable by heating up to 110°C; H_2O^+ indicates chemically bound water that can be lost only above this temperature. (Data courteously provided by Dr. E. Jarosewich, Smithsonian Institution.)

Note: almost all meteorites contain iron

First check: magnetism of probe

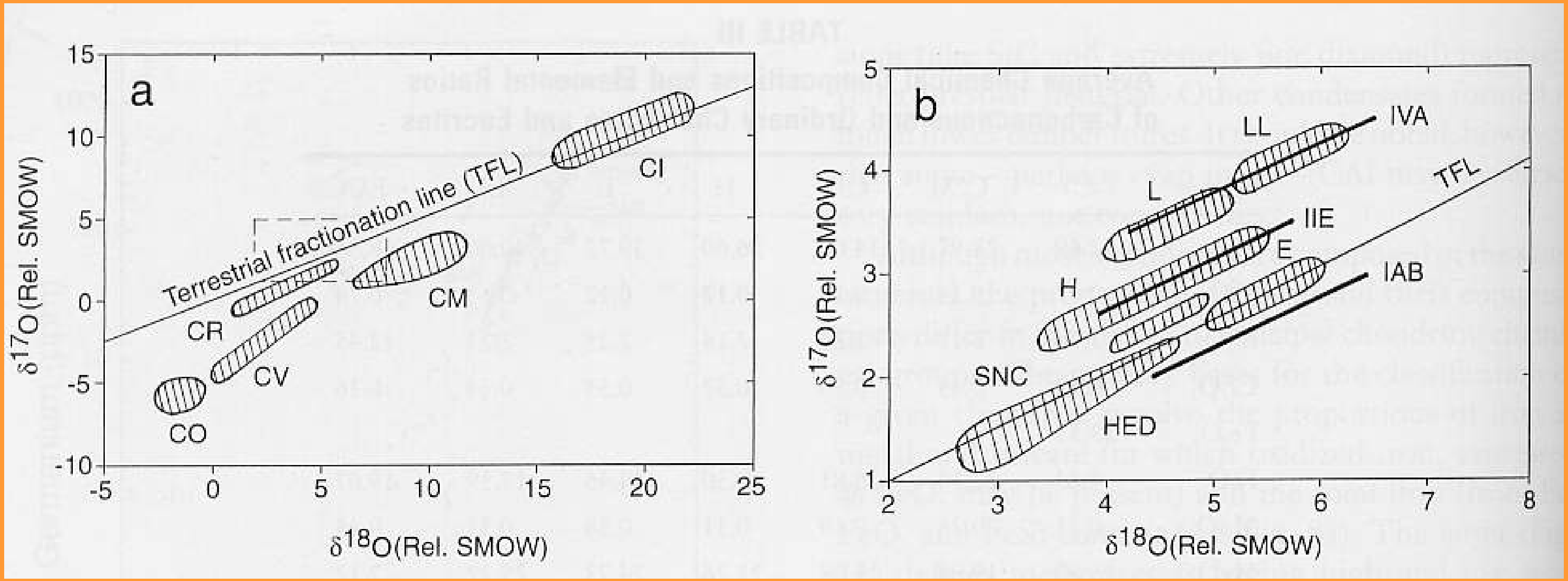
Verification: spallation isotope

Composition of chondrites is dominated by SiO_2, Fe_2O_3 and MgO

Oxygen Isotopics & Solar Chemistry

- Oxygen Isotopics
  - Concept: mass-dependent process involving O will create $^{17}O/^{18}O$ content with ratio ½ (mass-fractionation: slow process with minor but measurable effects)
  - Earth, moon, many chondrites and some achondrites on ½ fractionation line
  - Some other chondrites deviate

    ➔ solar system was created from a non-heterogenuous (O) isotopic mixture (most likely of pre-solar origin)



- <u>Isotopic composition CI to solar photosphere:</u>
  - Overall isotopic composition of CI chondrites is basically identical to solar photosphere (with some exceptions: gaseous and light elements, small deviations for mass-fractionation)

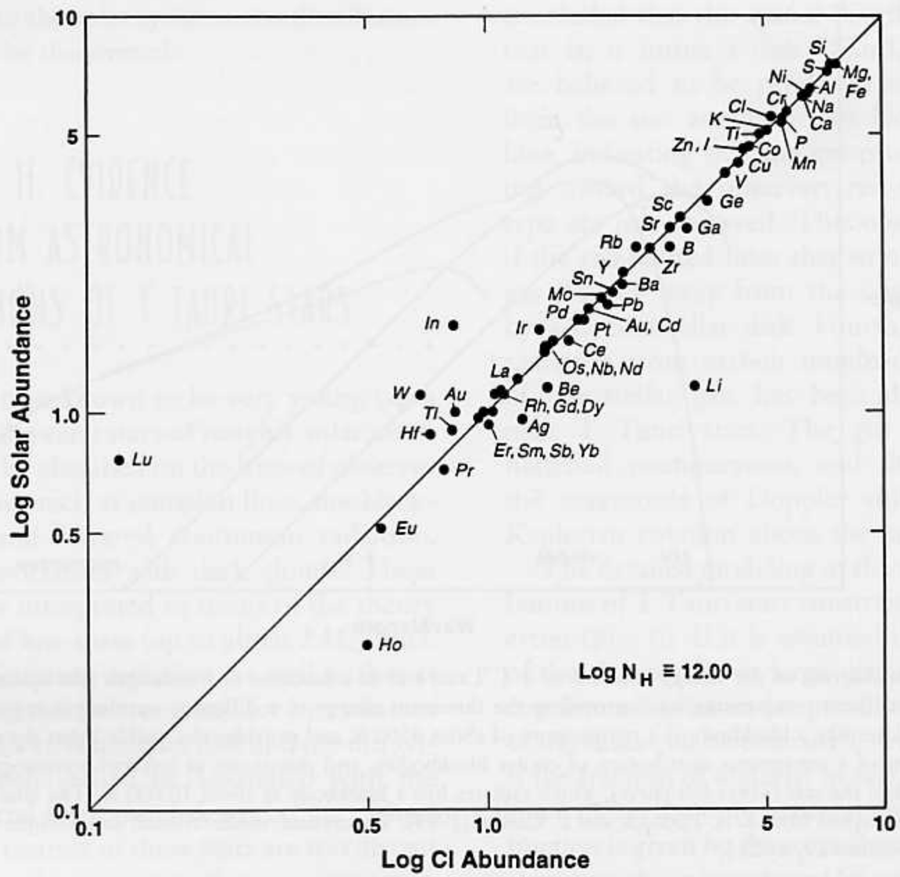
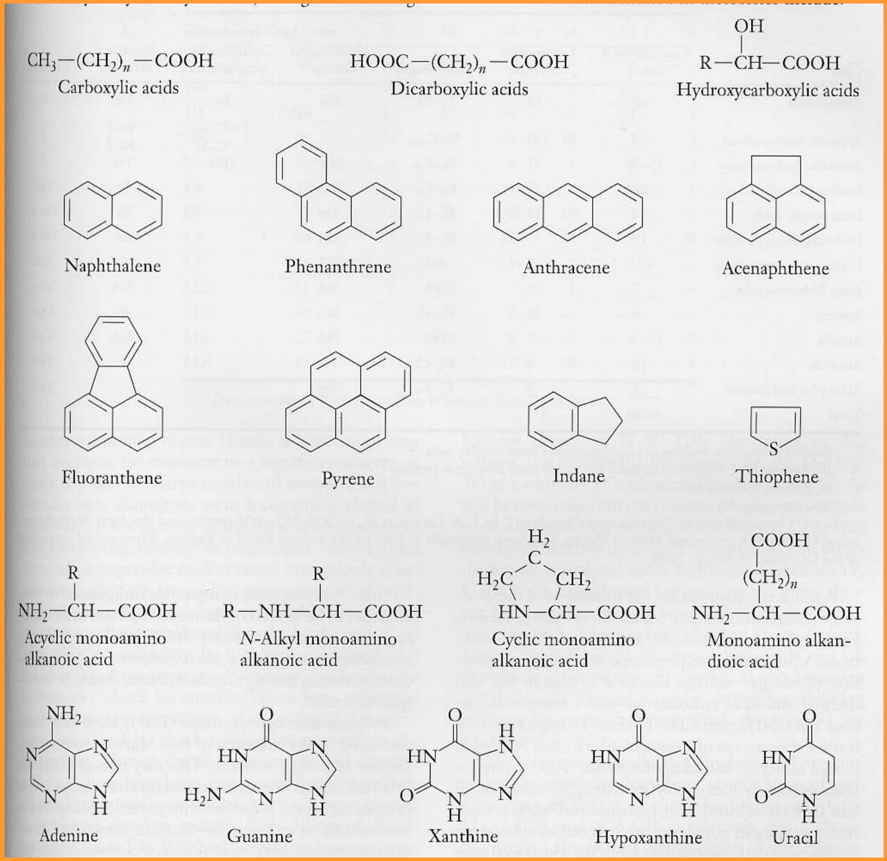


FIGURE 7 Elemental abundances in the solar photosphere are shown on a log–log plot versus those abundances measured in the CI carbonaceous chondrites. The abundances are normalized to 10^{12} hydrogen atoms: log N_H = 12.00. The remarkable 1 : 1 correspondence displayed for all but the most volatile elements is strong evidence for the creation of the CI meteorites out of unfractionated solar material, as well as for the essential homogeneity of the solar nebula. (Even some of the deviations are well understood. For instance, lithium in the Sun is low relative to CI abundances because lithium has been destroyed by nuclear reactions in the Sun.)

Organics & Hydration

- Organics:
  - More than 400 organics compounds identified in meteorites
  - All of non-biogenic, preterrestrial origin, but some with pre-biotic relevance

    (aminoacids of Murchinson & Orgueil L>D chirality)
  - many organics never hotter than 200-300K otherwise it would not exists in carbonaceous chondrites
- Hydration Effects:
  - Many chondrites contain signatures from hydration (chemistry modification due to presence of water – also in liquid form, inclusion of water molecules in mineral lattice)



Chronology with Meteorites

- Pre-requisite: state/phase transition locks isotopic ratio in meteorite radioactive and stable nuclides are measurable
  - Number of daughter nuclides D_t at time t

$$D_t = D_o + M_o - M_t = D_o + M_t\,(e^{\lambda t} - 1) \quad (1)$$

D_o, M_o = daughter (unknown), mother (measured) nuclides at ‚locking' time

D_t, M_t = daughter, mother nuclides measured in lab

λ = decay time of isotope

Trick: find/measure stable isotope D_x: $d D_x / dt = 0$

$$(D / D_x)_t = (D / D_x)_o + (M / D_x)_t\,(e^{\lambda t} - 1)$$

Linear relation: $y = I + x * m$ ➔ determine m, i.e. age t of the probe

$$t = 1 / \lambda \ \ln\left(1 + ((D / D_x)_t - (D / D_x)_o) / (M / D_x)_t \right)$$

Formation age = time of crystalisation

Radiation age = duration of high energy irradiation in space

Nuclides used:

$^{87}Rb \rightarrow {}^{87}Sr$, 4.9 10^{10} y

$^{187}Re \rightarrow {}^{187}Os$, 5 10^{10} y

$^{40}K \rightarrow {}^{40}Ar$, 1.25 10^{9} y

$^{129}I \rightarrow {}^{129}Xe$, 1.7 10^{7} y

Age determination of meteorites

Recipe:

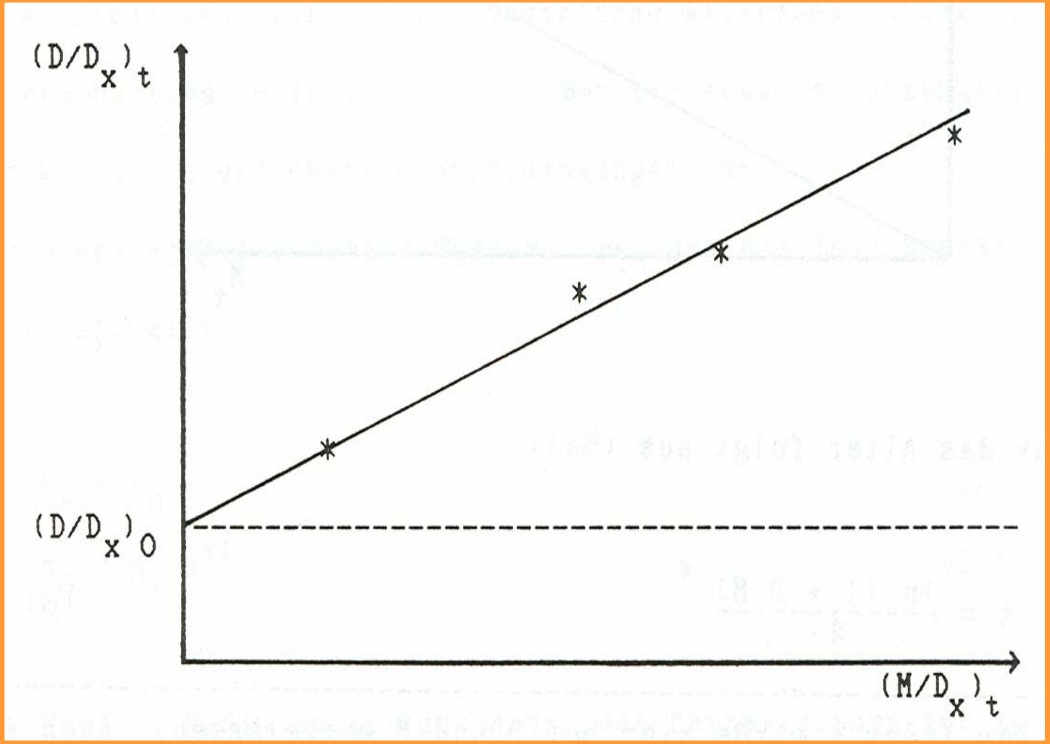
- measure radioactive isotopes “mother” & “daughter”

- plot linear relation

- determine slope $m = e\ \lambda t - 1$

- determine $y_o = (D / Dx)o$

- calculate age



Solidification age of chondrites

➔ 4.56 10^9 y +/-10^7 y (H-types)

➔ ingredients of solar system agglomerated quasi-simultaneously during a short time

➔ many L-types heated within last 10^9 y (shock-heating)

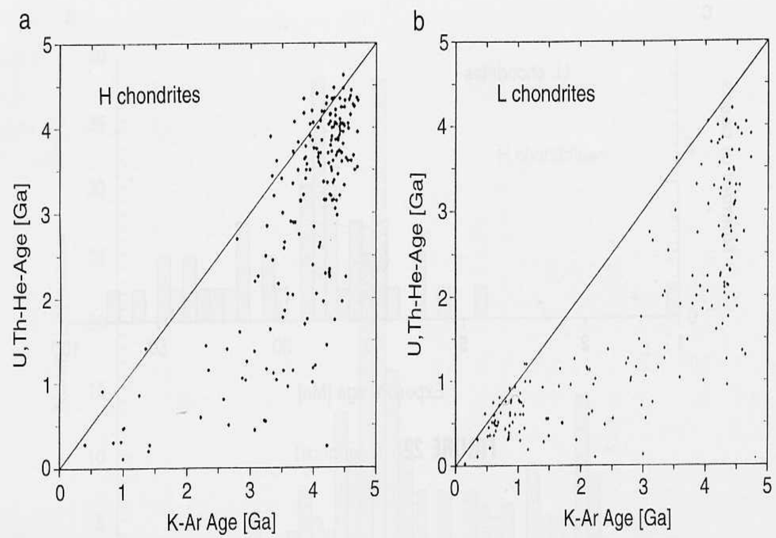


FIGURE 24 Gas retention ages of H and L chondrites. Data obtained from the U, Th–He and K–Ar methods are plotted against each other. The 45° line represents concordant ages. The very different trends indicate that the thermal histories of the two types of ordinary chondrites differ. The concordant long ages of H chondrites suggest that, in general, their parent body or bodies have remained thermally unaltered since they formed 4–4.5 Ga ago. The concordant short ages of L chondrites suggest that they were shock-heated in a major collision(s) 0.1–1.0 Ga ago. Nearly all discordant meteorites lie below the concordance lines because radiogenic ^{4}He is lost far more readily than is radiogenic ^{40}Ar.

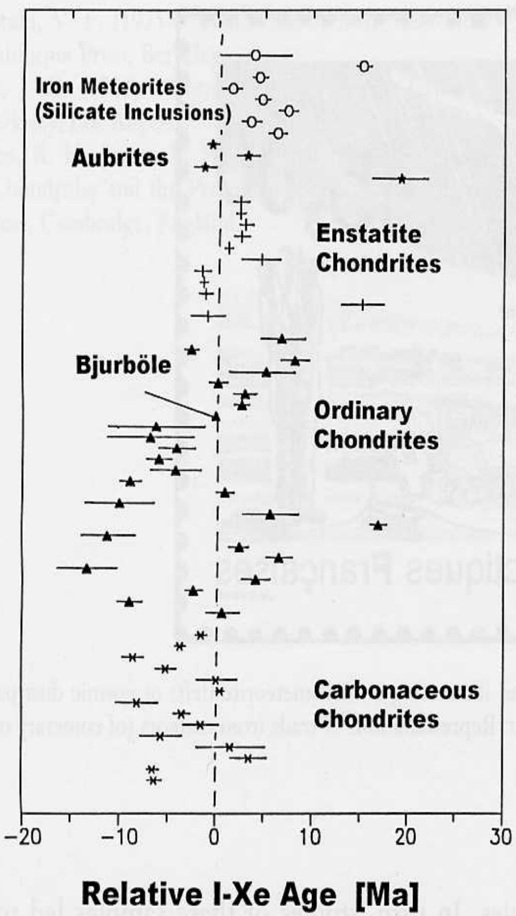


FIGURE 26 ^{129}I–^{129}Xe formation ages for various sorts of chondrites, aubrites, and silicate portions of iron meteorites, relative to that of Bjurböle (older ages to the left and more recent ones to the right).

Cosmic ray exposure age

Meteorite being exposed to cosmic rays in space

➔ ~100 million years (chondrites)

➔ before they were included in larger body

➔ iron meteorites last longer (IIIAB types may be produced by single massive impact event)

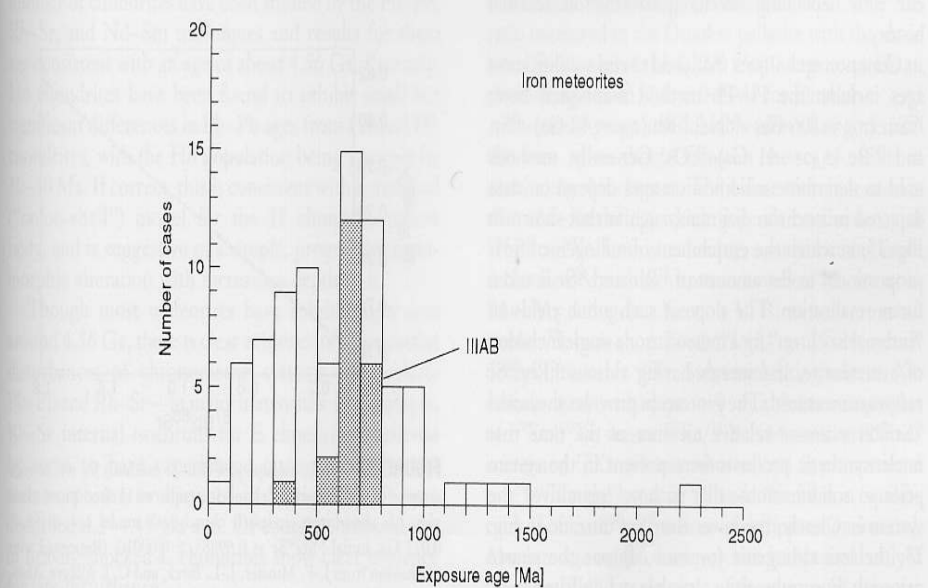


FIGURE 23 Cosmic ray exposure ages determined by the ^{40}K–^{41}K method for iron meteorites. The group IIIAB irons, nearly all of which were apparently produced by a single, massive collision of their parent body 650 ± 60 Ma ago, are depicted in the shaded region.

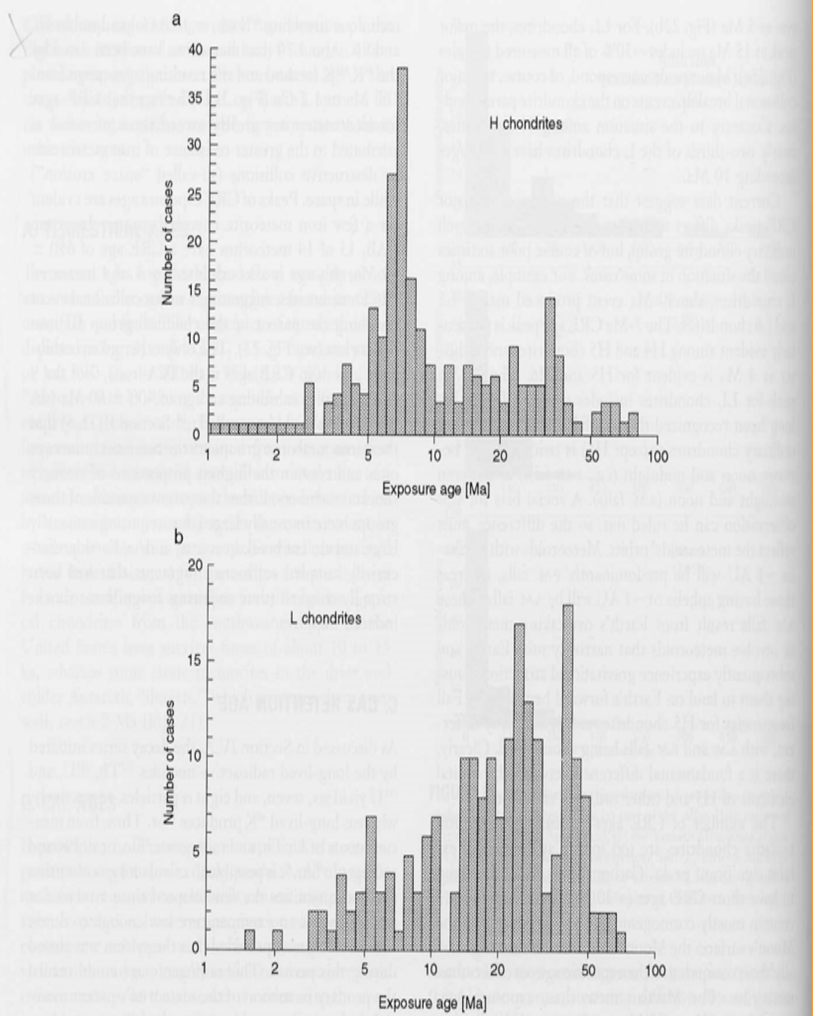
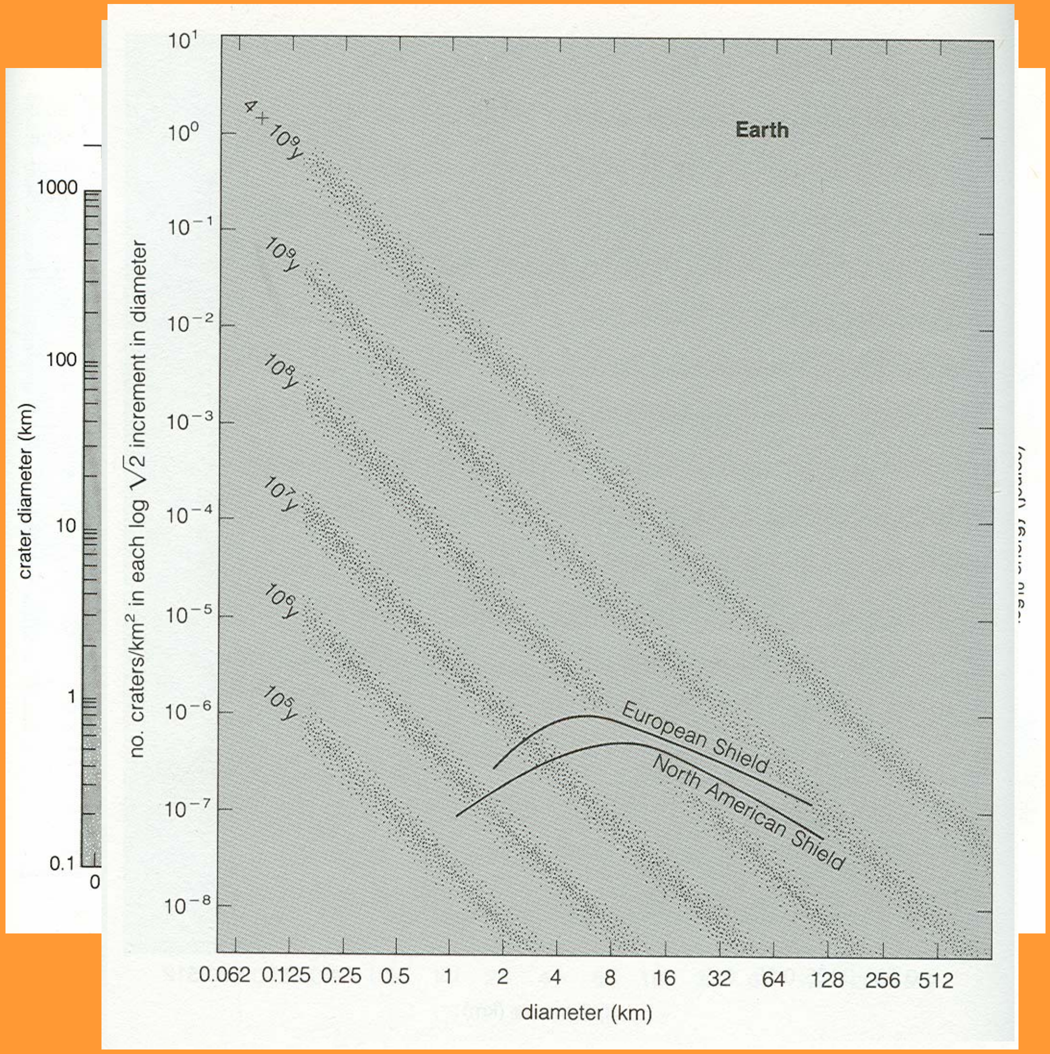


FIGURE 22 Cosmic ray exposure ages for ordinary (a) H, (b) L, and (c) LL chondrites. Peaks in the histograms indicate major collisional events on parent bodies that generated substantial proportions of meter-sized fragments (see Section V, B).

Dating of surface ages

Recipe:

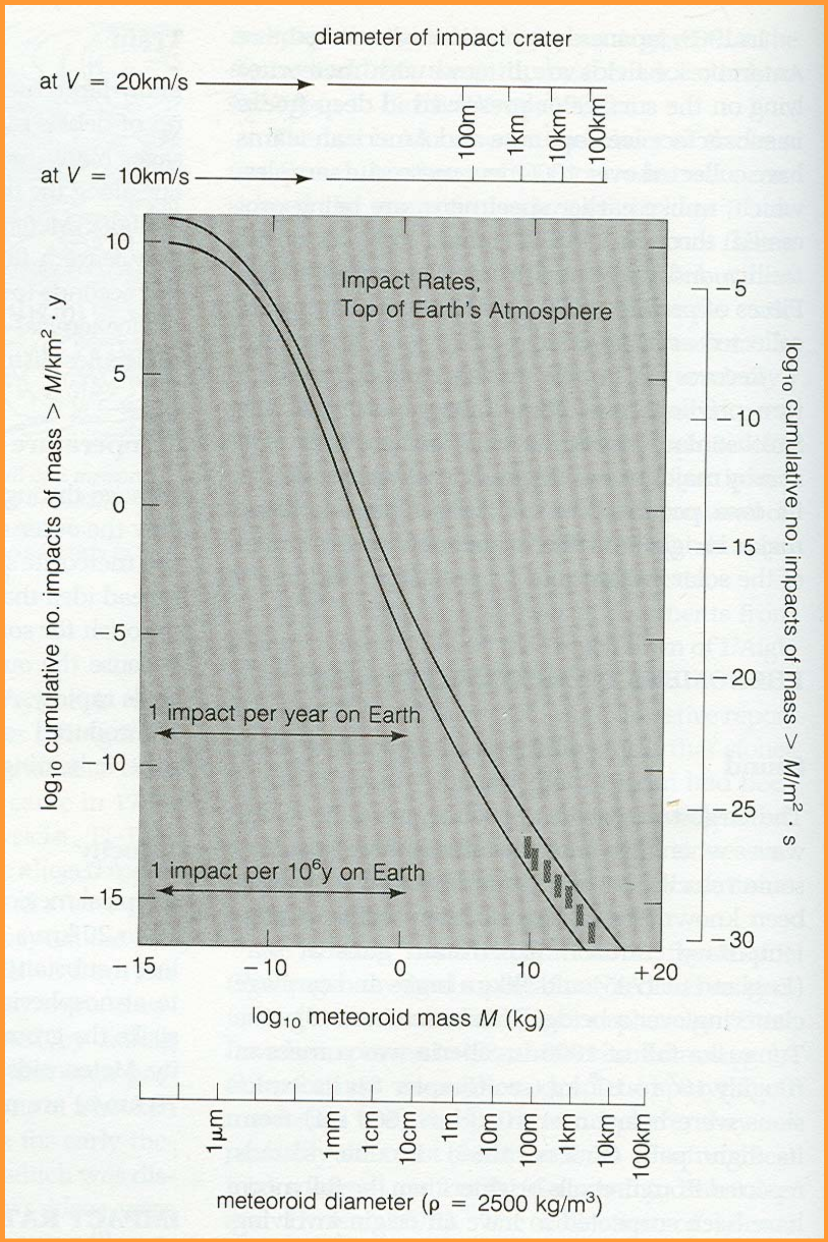
- count surface density of craters
- plot surface density versus diameter of craters
- compare with isochrone lines
- calibration of isochrone lines mostly from sample analysis of Apollo moon missions

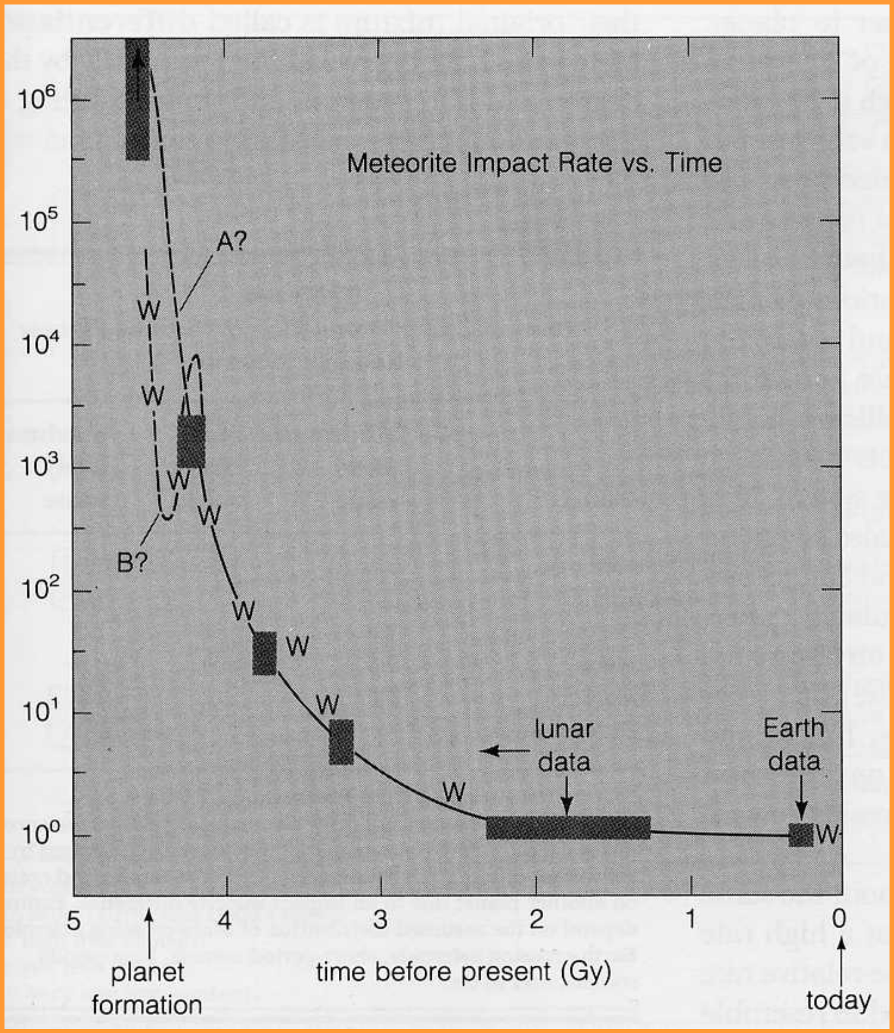


<u>Moon:</u> old surface modeled by early and late heavy bombardment

<u>Earth:</u> young surface due to tectonics, erosion, life

Cratering and planetary system formation





Comets

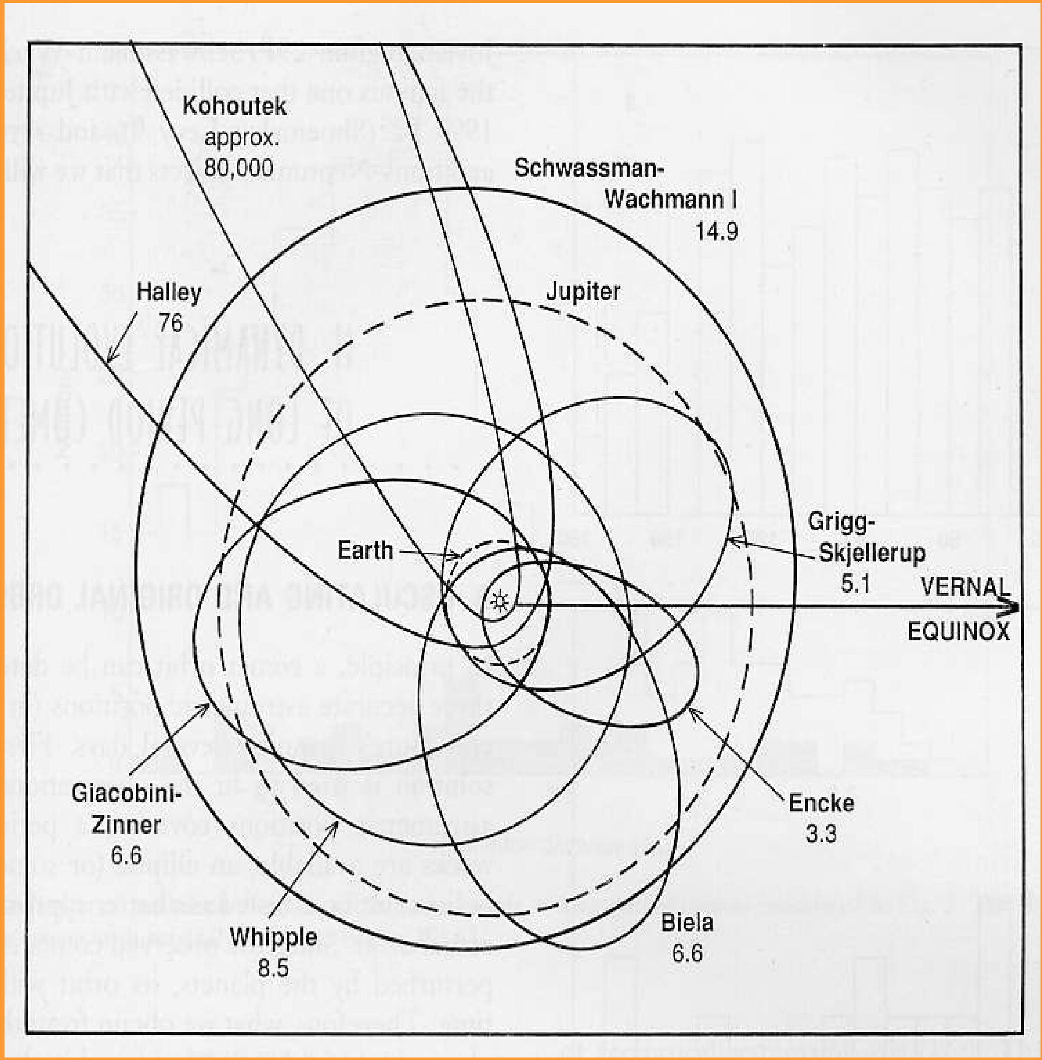
- **Summary**
  - Elliptical-hyperbolic orbits
  - Two reservoirs: short period comets & Oort cloud comets
  - Dirty snowball nucleus, km size
  - Main composition: water and silicates, some organics
  - Solar composition, possibly primordial (frozen)

Comet Hale-Bopp with dust and ion tail

Orbits

- Forms: ellipse+hyperbola
  (parabola easy fit of the other two)
  ➔ no extreme hyperbola found
  (e >> 1; max. 1.005)
  ➔ all observed comets belong to the solar system, hyperbolas caused by non-gravitational forces (reaction forces due to outgassing when active close to the Sun)

- Dynamical classes:
  – Short-period comets (P < 200 y)
    Ecliptic oriented
    captured and dominated by Jupiter gravity (Jupiter family comets)
    ‚old' comets (evolved)



– Long-period comets (P > 200 y)
  isotropic distribution, highly eccentric
  distribution of inverse semi-major axis peaks for large distances from the Sun
  ➔ Oort cloud of comets (10^{12})
    less evolved objects (new comets)
  perturbations by stars & molecular clouds of our galaxy cause Oort comet to enter into the planetary system

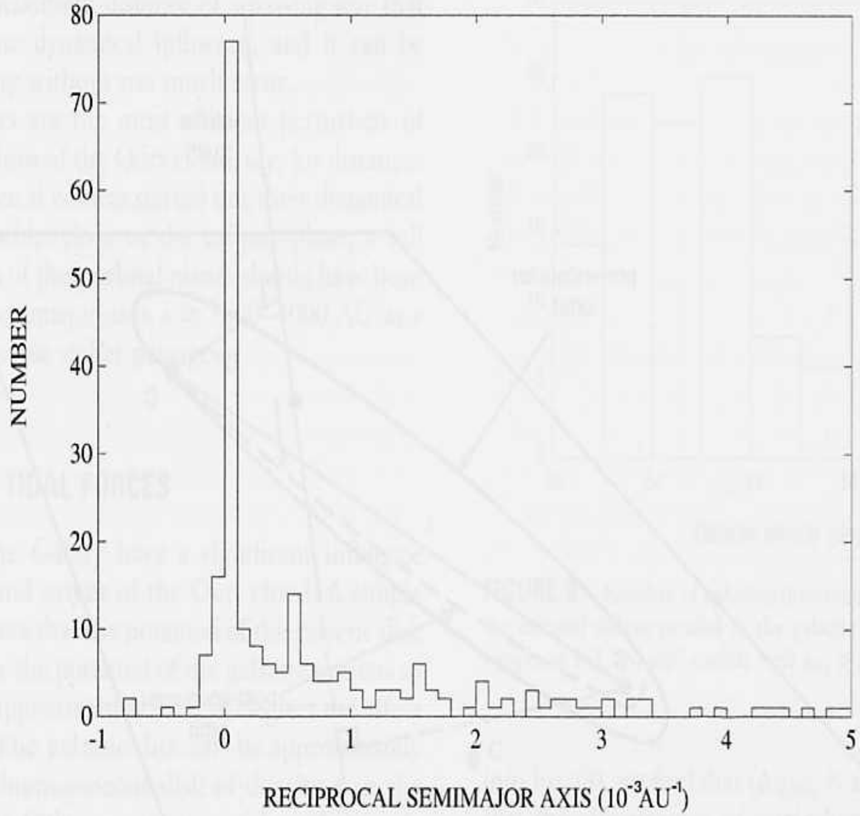


FIGURE 6 Distribution of the original inverse semimajor axes of observed long-period comets with $(1/a)_{orig} < 5 \times 10^{-3}$ AU^{-1}.

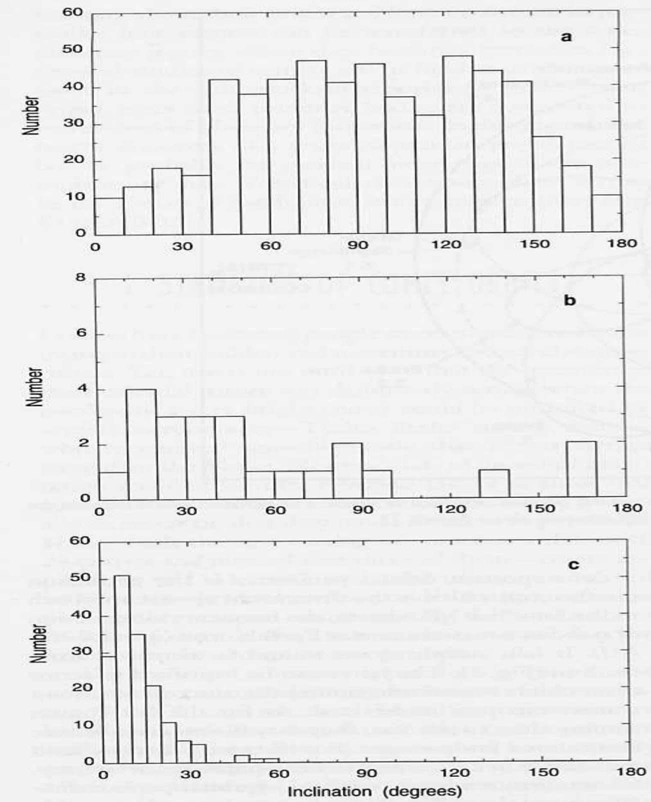


FIGURE 2 Inclination distributions of (a) long-period comets discovered after 1758 (the Kreutz family of sungrazing comets has been considered as a single comet, as well as C/1988F1 and C/1988J1, which move in similar orbits), (b) intermediate-period comets with 20 < P < 200 yr, and (c) short-period comets with $P \leq$ 20 yr.

<u>Nature</u>

- <u>Nucleus:</u> dirty snowball that becomes active when getting close (<5 AU) to the Sun
  - Sizes: a few 100 m – some 10 km
    (Wirtanen 600m) (Hale-Bopp 30km)
  - Shape: irregular with surface structures
  - Albedo: 1-5 %, darkest solar system objects
  - Rotation: a few hours (if measured)
  - Density: 0.1 – 1 g/cm^3 (uncertain)
    very weak structure (10^4 dyn/cm^2)
  - Different models for nuclei exist
    - Rubble pile (c)
    - Agglomerate with crust (d)

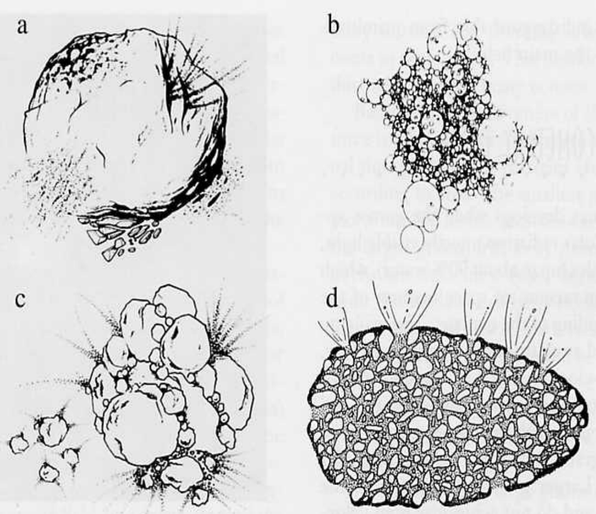


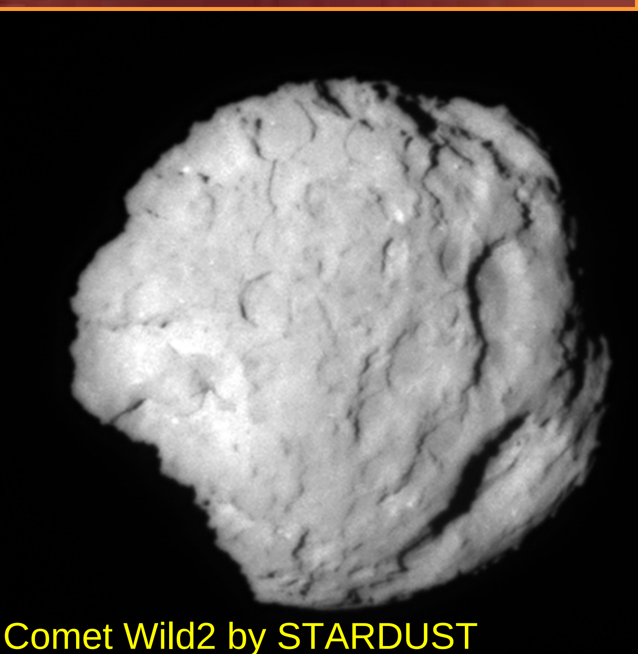
FIGURE 3 Four artist's concepts of suggested models for the structure of cometary nuclei: (a) the icy conglomerate model, (b) the fluffy aggregate model, (c) the primordial rubble pile, and (d) the icy-glue model. Evidence has continued to mount that the fluffy aggregate and the primordial rubble pile are the most likely representations of nucleus structure. All but model (d) were suggested prior to the Halley spacecraft encounters in 1986.

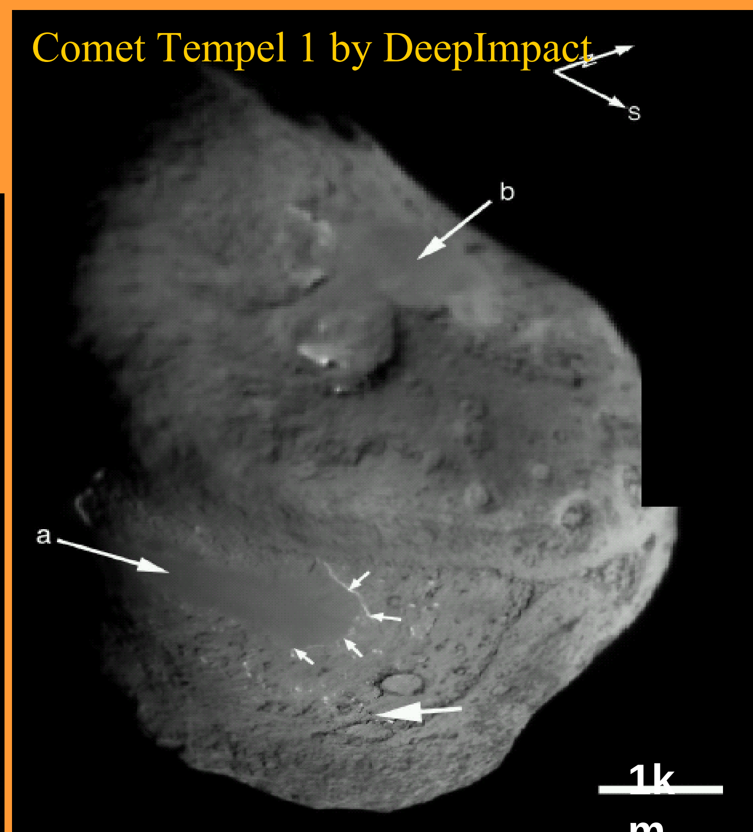
FIGURE 2 A composite image of the nucleus of Comet P/Halley as photographed by the camera onboard the *Giotto* spacecraft on March 14, 1986. The Sun is located toward the left, 29° above the horizontal. Note the elongated and irregular shape of the nucleus, which has dimensions of 16 × 8 × 7 km. The heterogeneity of the irregular surface is well illustrated; several surface features can be seen, including active regions and hills. The smallest features that can be resolved are about 100 m across. (Courtesy of H. U. Keller, Max-Planck-Institut für Aeronomie.)

How do they look like?


Comet Halley by GIOTTO


Comet Borrelly by DEEPSPACE 1


Comet Wild2 by STARDUST



Comet Tempel 1 by DeepImpact

Two movies:

upper: 1P/Halley

lower: 9P/Tempel 1

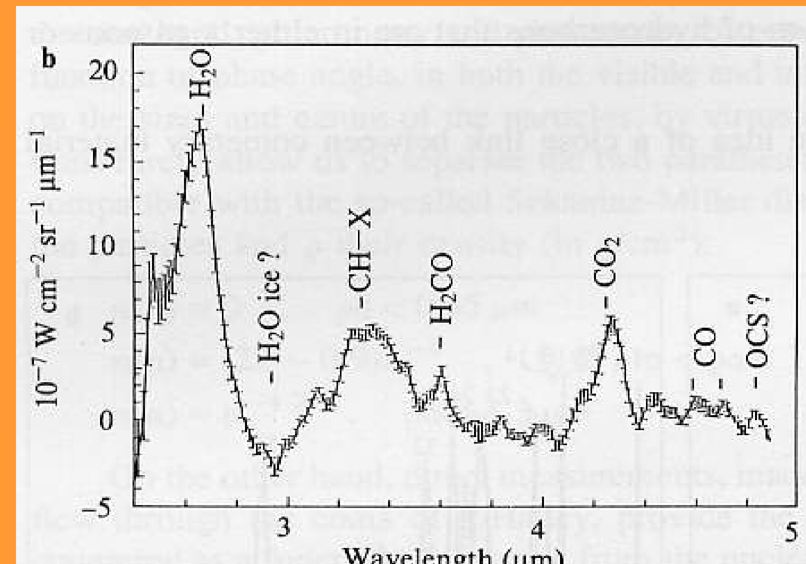
Coma: activity develops when nucleus is heated close to the Sun (on sunward side)

- Extension: $5\ 10^4 - 3\ 10^6$ km
- Frozen ice sublimates to gas
  - H_2O: ~80% ice
  - $CO+CO_2+H_2CO$: 4+3+2 (distant activity to several 10 AU)
  - Lots of organics identified
- Embeded dust is accelerated by gas
  - Mass ratio gas:dust 0.1-10
  - Silicate (fosterite), CHON, metallic
  - crystalline (hot) & amorphous (cold) silicates ➔ protosolar nebula got mixed up before comet formation
- Total production rates (gas, dust)
  - 10^{23}-10^{32} molecules/s (several 100 tons/s max)

    ➔ mass loss ~ 10000 revolutions life time in inner solar system

    ➔ continuous supply of comet required
- Crust formation: dust remains or falls back to surface
- Activity frequently localized

- Activity comes from upper few cm-m of the nucleus, nucleus core remains at low temperature 40-80K)



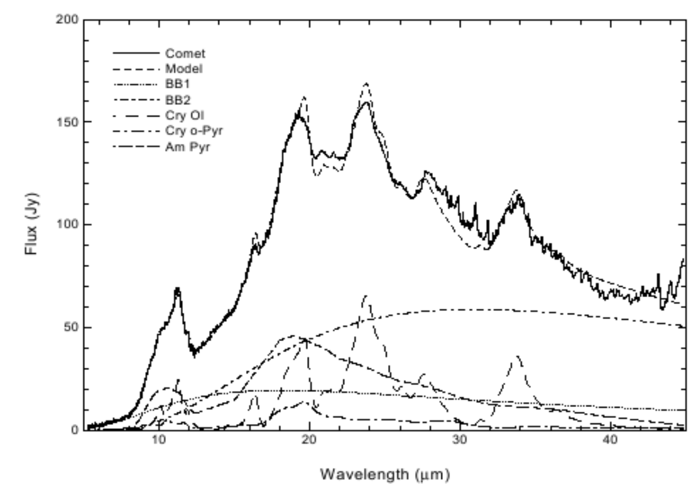


Fig. 2. ISO SWS spectrum of Comet Hale-Bopp at r = 2.8 AU, degraded to ℛ = 500, compared with a five-component dust model: 280 K blackbody (BB1); 165 K blackbody (BB2); forsterite (Cry Ol 22%); orthopyroxene (Cry o-Pyr 8%); and amorphous pyroxene (Am Pyr 70%). From *Crovisier et al.* (2000).

TABLE I
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		

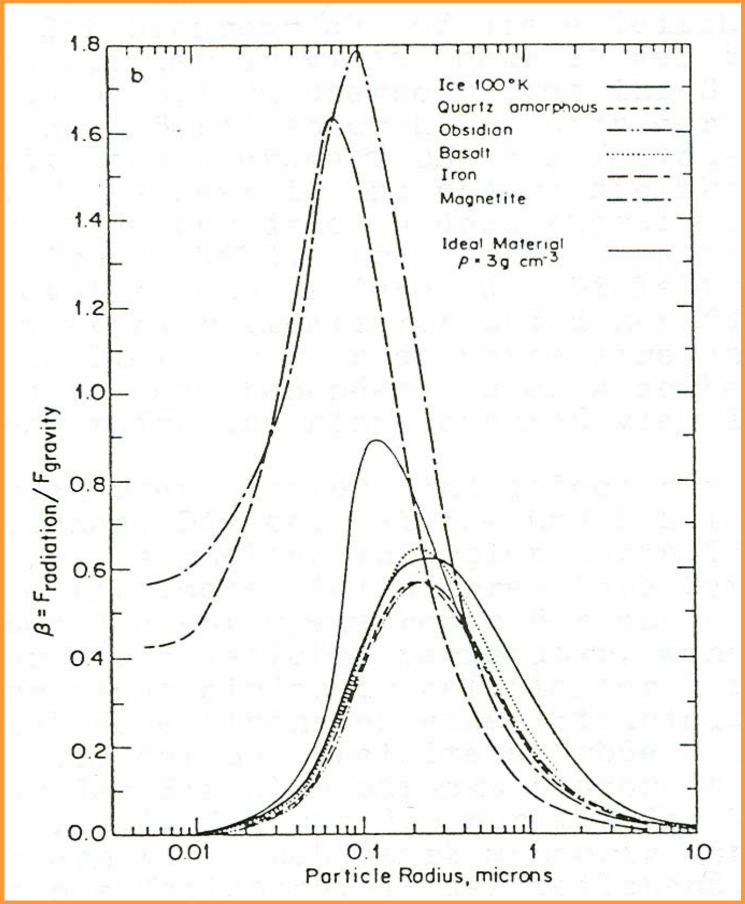
TABLE II
Identified Interstellar Molecules in the Gas Phase

H_2	C_2	CO	CS	$NaCl^a$	HCl	SiO	SiS
$AlCl^a$	KCl^a	PN	AlF^a	SiN^a	SiH^b	HF^b	
H_2O	SO_2	H_2S	OCS	HNO	C_3^a	HCN	C_2O
HNC	SiC_2^a	NH_2	N_2O	$MgNC^a$	$MgCN^a$	$NaCN^a$	
NH_3	HC_2H	C_3O	$HNCO$	$HNCS$	C_3S	H_2CO	H_2CS
$c\text{-}C_3H$	$l\text{-}C_3H$	$HCCN$	H_2CN				
CH_4	SiH_4^a	C_5^a	HC_3N	C_4Si^a	$OHCHO$	H_2CNH	CH_2CC
H_2NCN	CH_2CO	C_3H_2	$HCCNC$	$HNCCC$			
H_3CNC	CH_3CN	NH_2CHO	CHC_2HO	$H_2C_2H_2^a$	CH_3OH	CH_2C_3	CH_3SH
HC_5N	CH_3C_2H	CH_3CHO	CH_2CHCN	H_3CNH_2	$c\text{-}CH_3OCH_2$		
CH_3C_3N	CH_3OOCH	CH_3COOH	CH_3C_3N	C_7H^a	C_2H_6		
HC_7N	CH_3C_4H	CH_3CH_2CN	CH_3CH_2OH	CH_3OCH_3	C_3H^a		
$CH_3C_5N^b$	$(CH_3)_2CO$						
HC_9N							
$HC_{11}N$							
$(C_2H_5)_2O$							
CH^+	SO^+	CO^+					
HCO^+	HN_2^+	HOC^+	HCS^+	H_2D^{+b}	H_3^+		
$HCNH^+$	H_3O^+	$HOCO^+$					
CH_3NH^+							
OH	CH	CN	NO	NS	NH	SO	CP^a
SiC^a							
HCO	C_2S	C_2H	CH_2				
C_3N							
C_4H	CH_2CN						
C_5H							
C_6H							

[a] Detection only in the envelopes around evolved stars.
[b] Claimed but not yet confirmed.

- <u>Dust Tail:</u> dust particles removed from coma by solar radiation pressure
  - Dust sizes: 0.01-100 μm

    ➔ radiation pressure (strong hyperbolic orbits are possible)



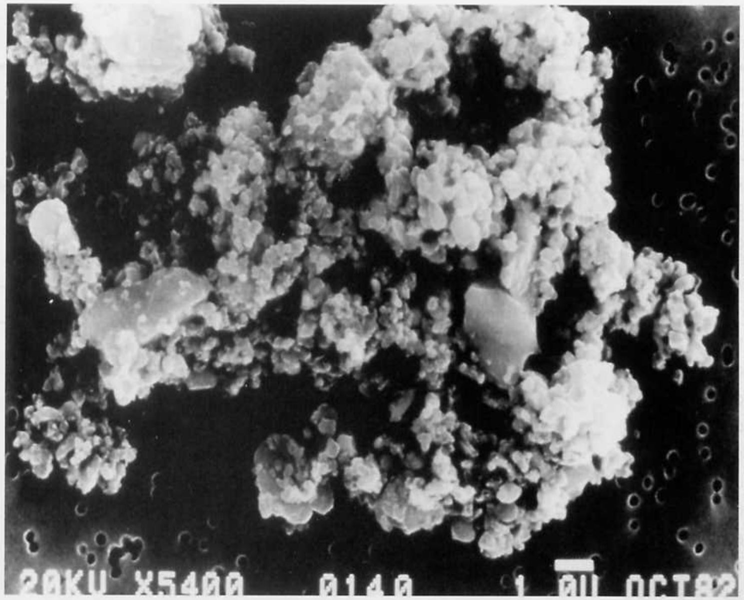


FIGURE 6 A suspected cometary interplanetary dust particle. The IDP is a highly porous, apparently random collection of submicron silicate grains embedded in a carbonaceous matrix. The voids in the IDP may have once been filled with cometary ices. (Courtesy of D. Brownlee, University of Washington.)

Dust particle motion

$$\underline{F}_{total} = \underline{F}_{grav} + \underline{F}_{rad} = ma\ \underline{e}_r$$

$$\underline{F}_{grav} = -\gamma mM/r^2\ \underline{e}_r$$

$$\underline{F}_{rad} = LA/4\pi cr^2\ \ Q\ \underline{e}_r$$

$$\Rightarrow\ \ \mathbf{ma\ \underline{e}_r = -\gamma mM/r^2\ \underline{e}_r + LA/4\pi cr^2\ \ Q\ \underline{e}_r}$$

$$\mathbf{= \underline{F}_{grav}\ (1 - ß)}$$

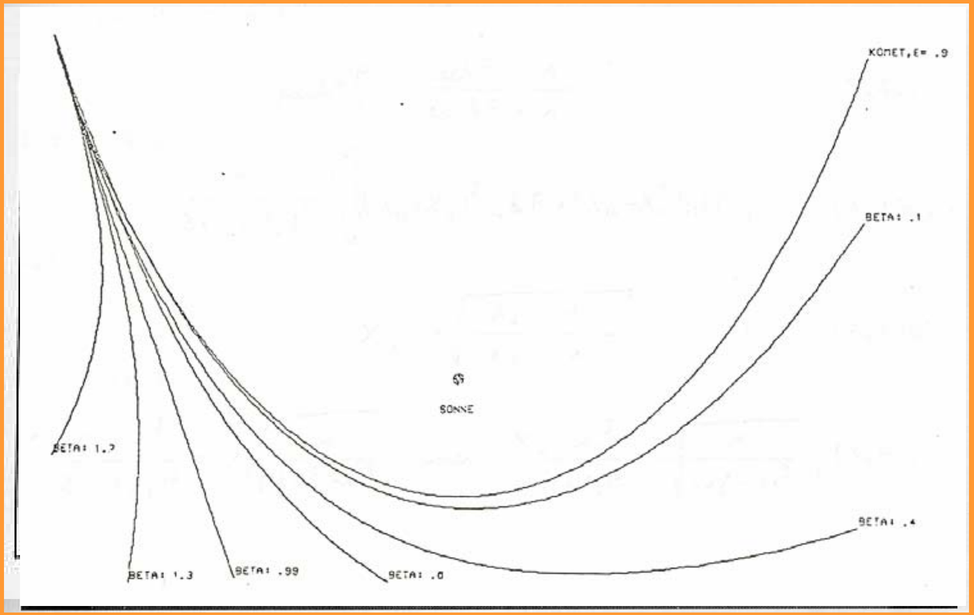
with

$ß = LA/4\pi cQ\gamma mM$
(radiation pressure coefficient)

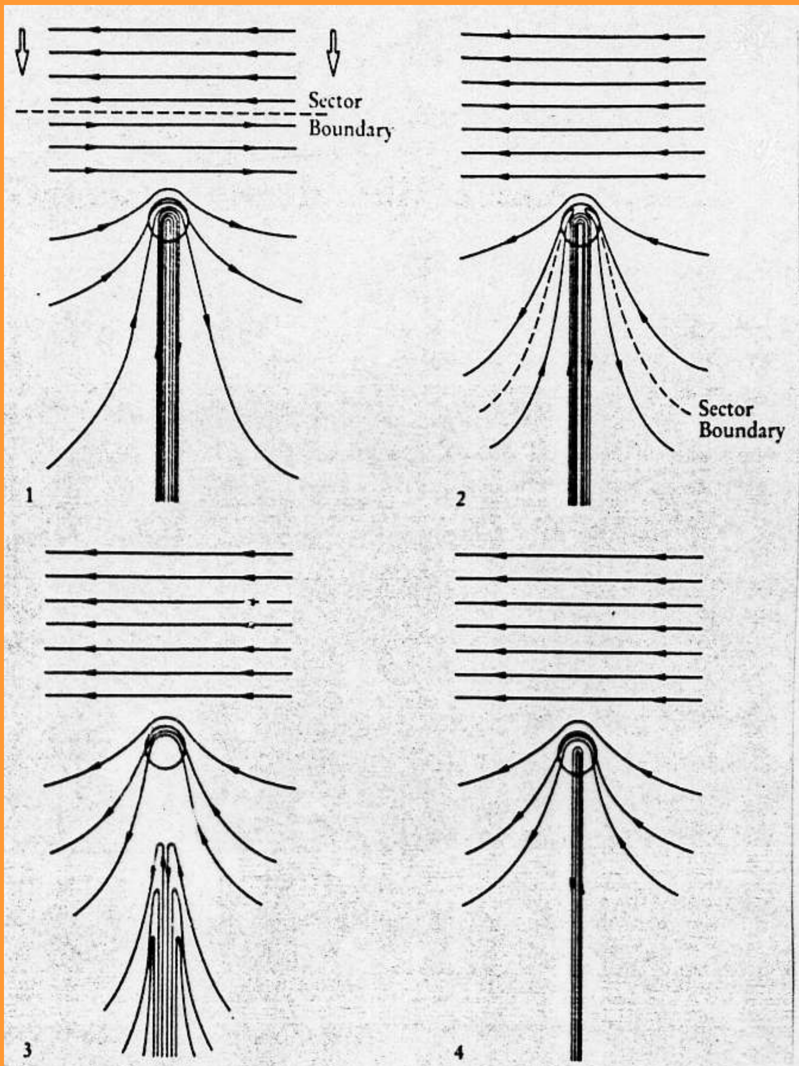
$\underline{F}_{grav}$ = gravity force
$\underline{F}_{rad}$ = radiation pressure force
a = total aceleration
m = mass of dust particle
M = mass of the Sun
γ = gravity constant
r = distance of the particle from the Sun
L = luminosity of the Sun
A = cross section of the particle
c = velocity of light
Q = radiation pressure efficiency

e_r = unit vector in radial direction to the particle

- equation of motion as for gravity
- reduced (even repulsive) effective force in radial direction (Kepler motion)
- recipe for calculating the dust tail geometry
  - calculate comet orbit
  - calculate dust particle orbit
  - calculate difference
  - ➔ synchrones & syndynes



- Ion Tail: ionized gas removed by magnetic field of solar wind



Composition

- Close to solar composition except for volatile elements
- Isotopic composition clearly solar

➔ comets are born in solar system

Table 15.3 Elemental Abundances in Comet Halley, CI-Chondrites, and the Solar Photosphere [a]

Element	Comet P/Halley		CI-	Solar
	Dust	Dust & Ice	Chondrites	Photosphere
H	2025	4062	520	2.63×10^6
C	814	1010	74	933
N	42	95	5.9	245
O	890	2040	748	1950
Na	10	10	5.61	5.62
Mg	100	100	100	100
Al	6.8	6.8	8.32	7.76
Si	185	185	97.7	93.3
S	72	72	43.7	42.7
K	0.2	0.2	0.363	0.347
Ca	6.3	6.3	6.31	6.03
Ti	0.4	0.4	0.234	0.288
Cr	0.9	0.9	1.32	1.23
Mn	0.5	0.5	0.912	0.646
Fe	52	52	83.2	85.1
Co	0.3	0.3	0.224	0.219
Ni	4.1	4.1	4.90	4.68

[a] atoms/100 Mg

Note: see also Table 3.5 for solar photospheric abundances and Tables 2.1 and 16.9 for abundances on CI-chondrites

Sources: Jessberger, E. K., & Kissel, J., 1991, in *Comets in the post-Halley era* (Newburn, R., Neugebauer, M., & Rahe, J., eds.), Kluwer Acad. Publ., Dortrecht, The Netherlands, Vol. 2, pp. 1075–1092. Mumma, M. J., Weissman, P. R., & Stern, S. A., in *Protostars & planets III* (Levy, E. H., & Lunine, J. I., eds.) Univ. of Arizona Press, Tucson, 1177–1252.

Table 15.4 Relative Abundances in P/Halley (by Number)

Molecule	Abundance	Molecule	Abundance	Molecule	Abundance
H_2O	100	H_2CO	0–5	N_2	~0.02
CH_4	0–2	CH_3OH	~1	NH_3	1–2
CO	7–8	OCS	<7	HCN	≤0.1
CO_2	3	CS_2	1	SO_2	<0.002

Isotopic ratios suggest that cometary material is home-made, i.e. typical for the solar system

TABLE V

Isotopic Ratios in Comets and Other Reservoirs

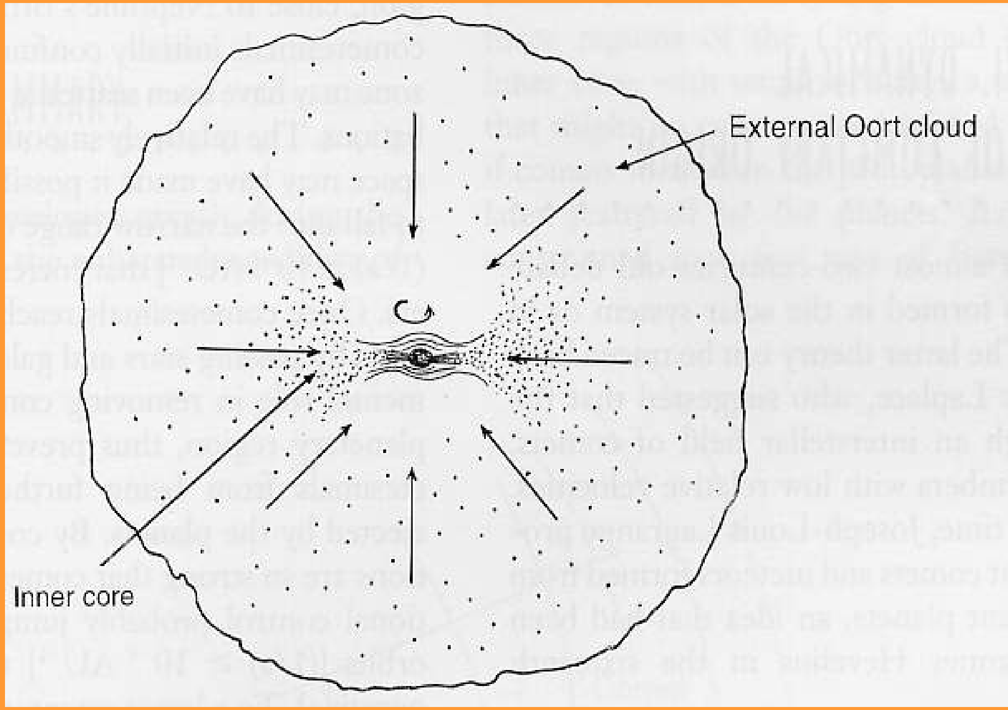
Species	Solar system	Interstellar matter	Comets
D/H	1 to 2×10^{-5}	1.5×10^{-5}	3.2×10^{-4}[a]
D/H		10^{-4} to 10^{-2}[b]	1.9 to 3.5×10^{-4}[c]
$^{12}C/^{13}C$	89	43 ± 4[d]	95 ± 12[e]
$^{12}C/^{13}C$		65 ± 20[f]	70 to 130[g]
$^{12}C/^{13}C$		12 to 110[b]	10 to 1,000[h]
$^{14}N/^{15}N$	272	≈400[f]	>200[e]
$^{16}O/^{18}O$	498	≈400[f]	493[a]
$^{24}Mg/^{25}Mg$	7.8		Variable[h]
$^{25}Mg/^{26}Mg$	0.9		<2[h]
$^{32}S/^{34}S$	22.6		22[h]
$^{56}Fe/^{54}Fe$	15.8		15[h]

[a] From *in situ* mass spectrometry of Comet Halley coma.
[b] Range of observed values in dense ISM clouds.
[c] From radio wavelength spectra of HDO in Comet Hyakutake.
[d] From visual spectra.

Origin

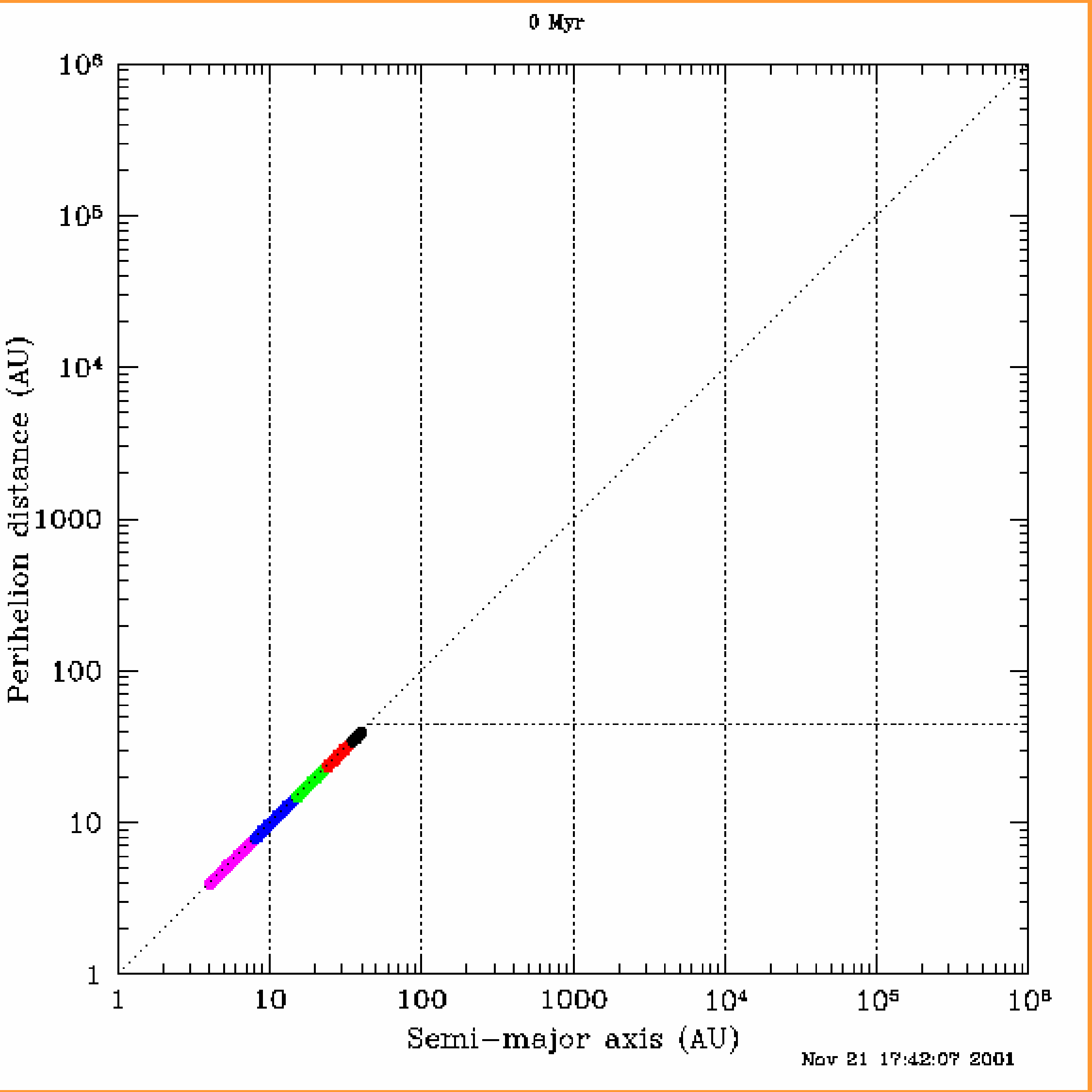
- Two sources:
  - Short-period comets: Kuiper Belt
  - Oort comets: Jupiter-Neptune region and scattered to outer/inner solar system during early phase of the solar system

    contributed to early bombardment



Oort Cloud formation – The movie

- **<u>Start:</u>** planetesimals in planetary disk between Jupiter and Neptune
- **<u>Clean-up:</u>** by gravitational scattering of gas gianst
- **<u>Thermalization:</u>** through galactic neighbourhood
- **<u>Return of Oort Cloud comet:</u>** through scattering by galactic neighbourhood



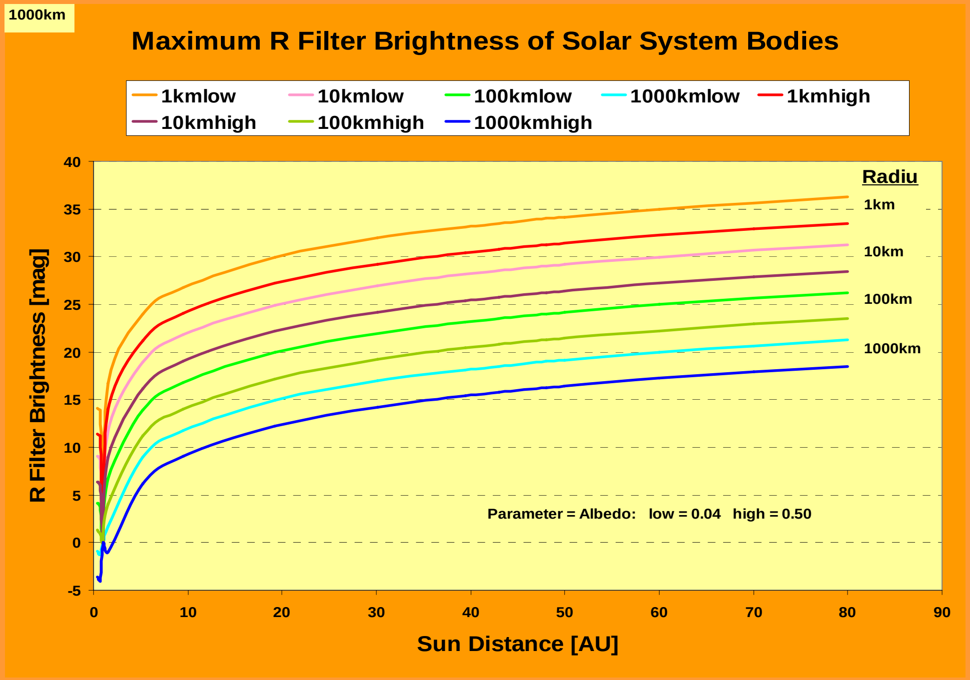
Edgeworth-Kuiper Belt

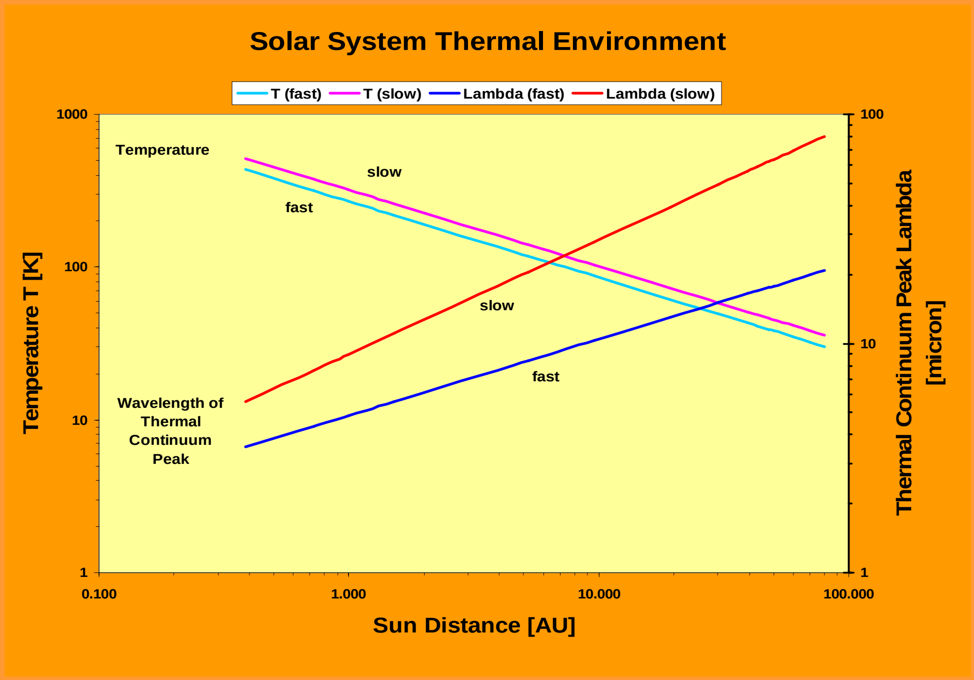
- **Summary**
  - Orbits mostly between 35-50 AU
  - Large population, with little total mass
  - Collision signatures (double objects, size distribution, collision family)
  - Icy objects (water, methane) with max radius of order 1000km
  - Processed surface: collision, high-energy radiation, activity
  - Reservoir for short-period comets

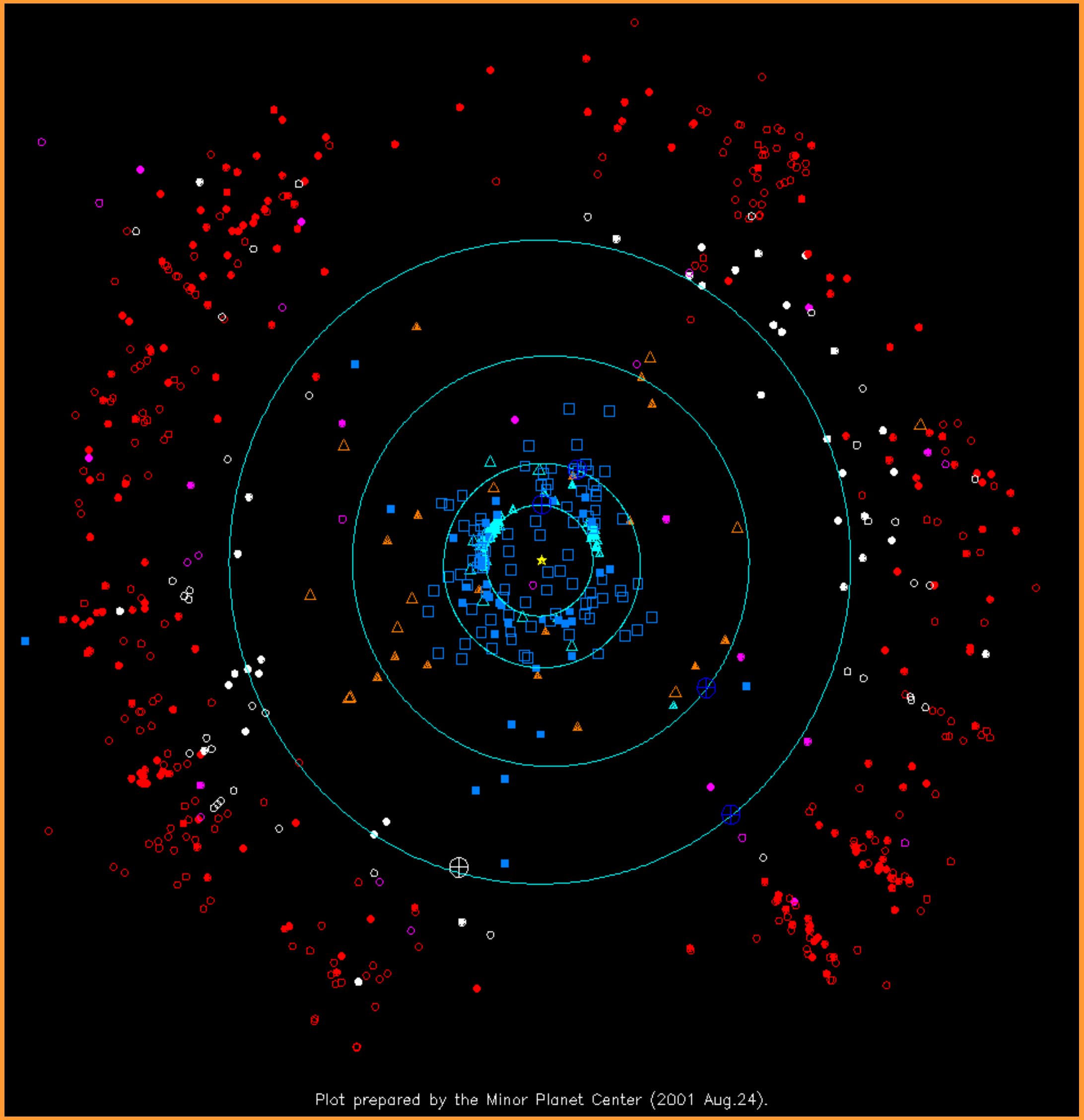
General

- Definition and history:
  - Orbits with semi-major axes larger than Neptune orbit

    Transneptunian Objects (TNOs = EKBOs)
  - Speculated 1938 (Edgeworth) and 1950 (Kuiper)
  - First object discovered in 1930 (Pluto), more in 1992 (1992 QB1)
  - ~1200 TNOs discovered so far
- Brightness:
  - 20-28mag and fainter
  - slow moving
  - Discovered in wide and deep survey
  - T ~ 40K ➔ thermal emision in submm radio range







Cubiwanos

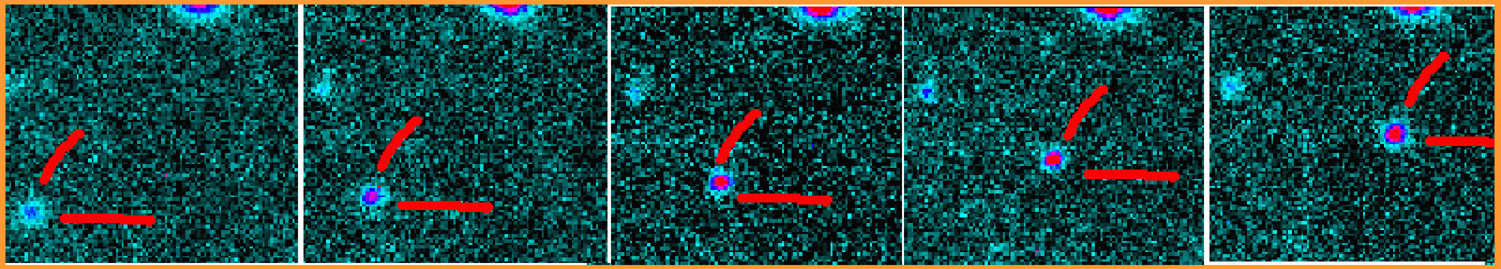
Plutinos

ShortP. Comets

Centaurs

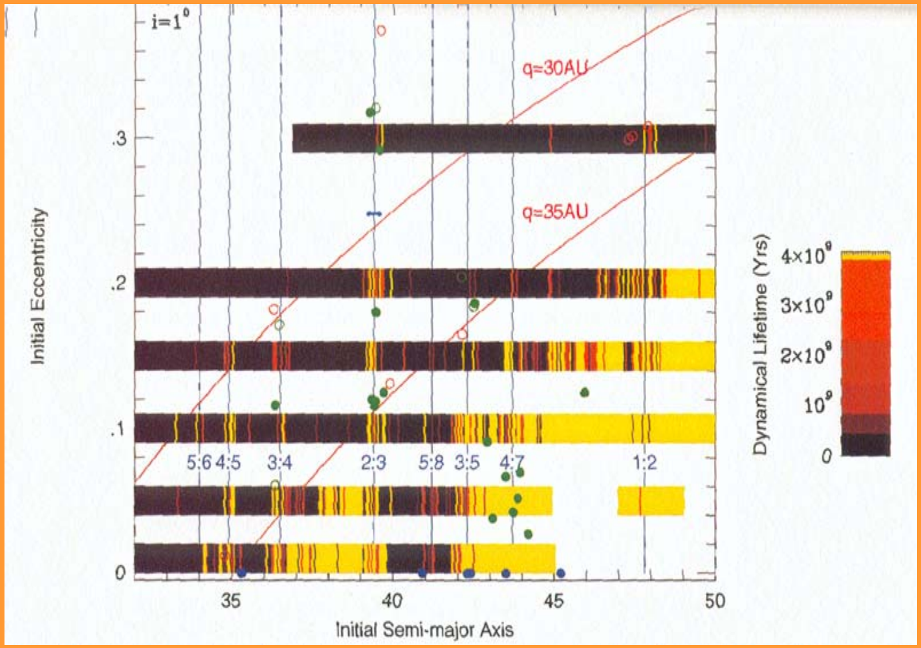
Scattered

The Transneptunian Region and ist dynamical Population



Dynamical Classification

– Plutinos: a ~ 39 AU
e ~ 0.1 - 0.3
➔2:3 resonance with Neptune
– Cubewanos: a ~ 40 - 46 AU
(classical disk) e < 0.1
➔ outside of planet resonance
– Scattered Disk:
a > 50 AU & e > 0.2
– Centaurs:
Jupiter …. Neptune
➔"eccentric" KB members
no resonance beyond 2:1 ~ 50 AU



- Plutinos, Cubewanos are in dynamically stable orbits

- Scattered disk will have encounters with planets (Neptune)

- Centaurs are transfered from EKB to inner solar system within ~10 10^6 y

➔ short-period comets

Population Density and Total Mass

- Population density: see table

  Size distribution = mixture from formation and evolution

  Slope change for smaller radii

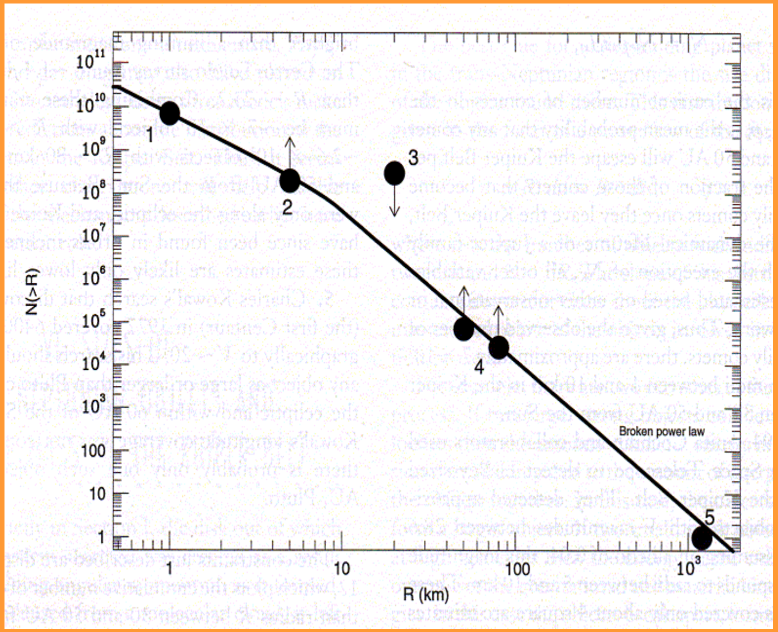
  ➔ Size distribution gets dominated by collision products

  more than 10 double TNOs found

  ➔ produced by large impacts

- Total mass: 0.15 Earth masses

  (with radius > 100km)

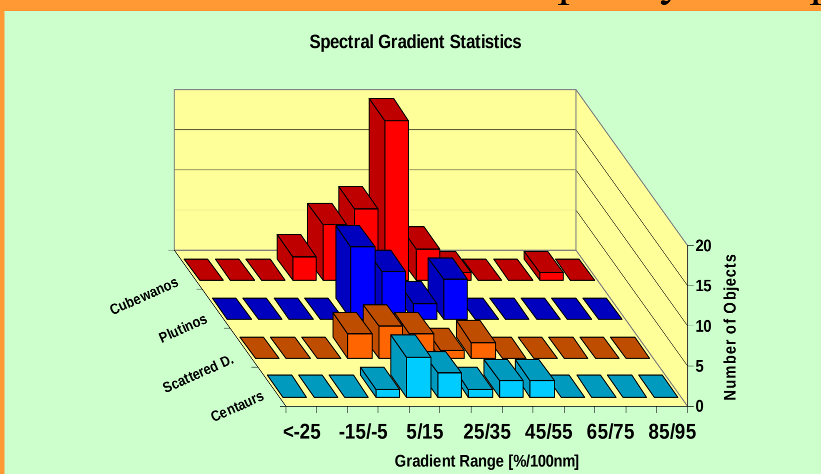


Limit. R Mag. [mag]	Surface Density [deg^{-2}]	TNOs In KB < 50 AU	Approx. Radius [km]
< 24	2.7	27000	110
< 26	33	330000	45
< 28	390	3900000	20

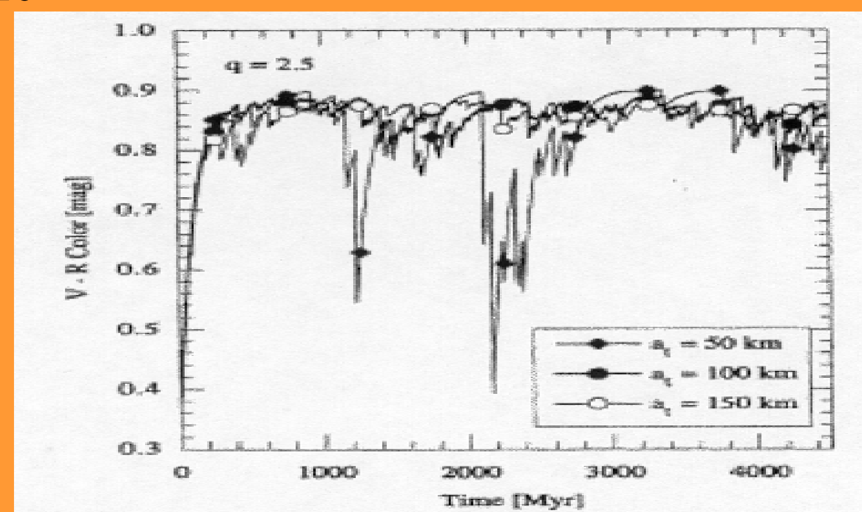
Physical Properties

- Size&Shape: 50-1200km radius
  Pluto = largest TNO
  large ones spherical, smaller ones asymmetric
- Albedo: dark (5%) – medium (15%)
  (except when active: >30%)
- Spectrum: some have strong reddening
  ➔ caused by high-energy radiation
  others are neutral compared to Sun
  ➔ due to impact resurfacing or recondensation of temporary atmosphere

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

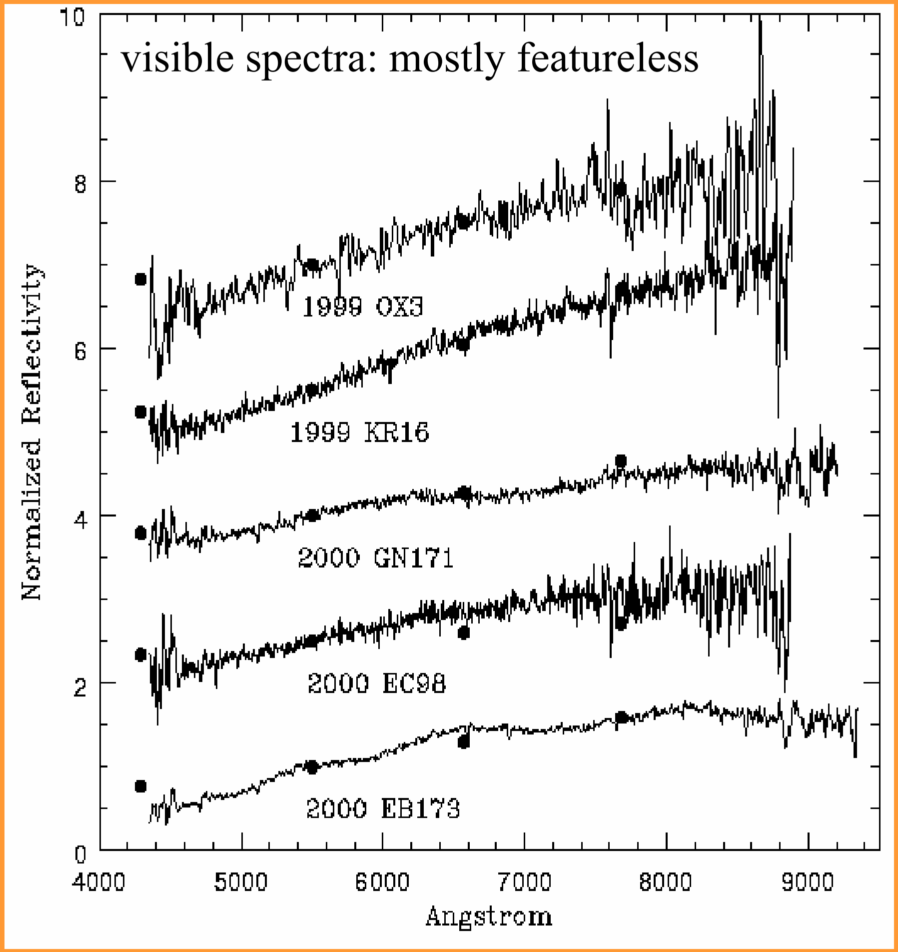


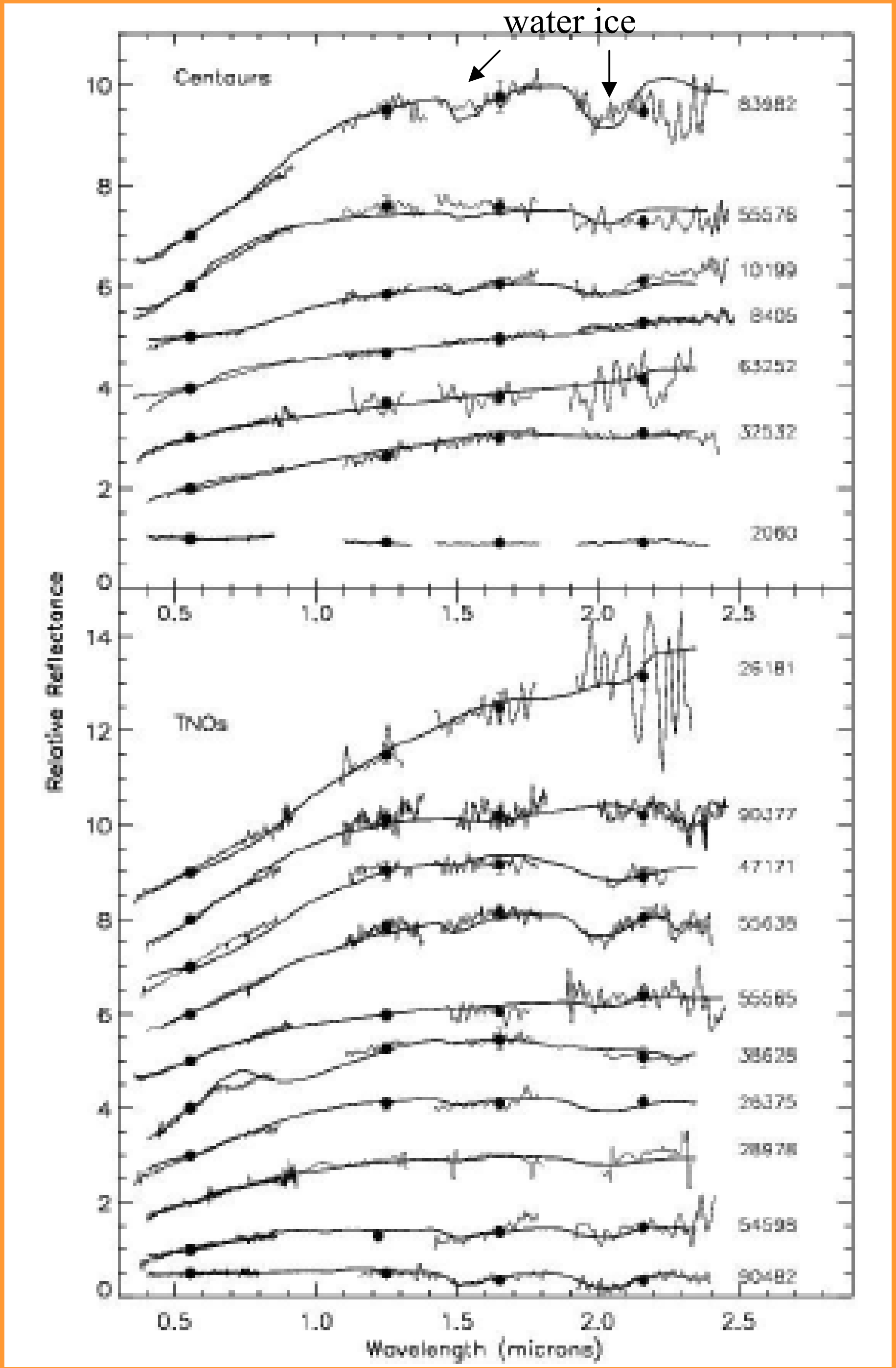
	<-25	-25/-15	-15/-5	-5/+5	5/15	15/25	25/35	35/45	45/55	55/65	65/75	75/85	85/95
Centaurs	0	0	0	1	5	3	1	2	2	0	0	0	0
Scattered D.	0	0	0	3	4	3	1	2	0	0	0	0	0
Plutinos	0	0	0	0	9	6	2	5	0	0	0	0	0
Cubewanos	0	0	0	3	7	9	20	4	1	0	0	1	0



Simulation of reddening changes

- Surface chemistry: some with water/methane ice absorption,
- One case of hydrated silicate dedected → surprise liquid water ?



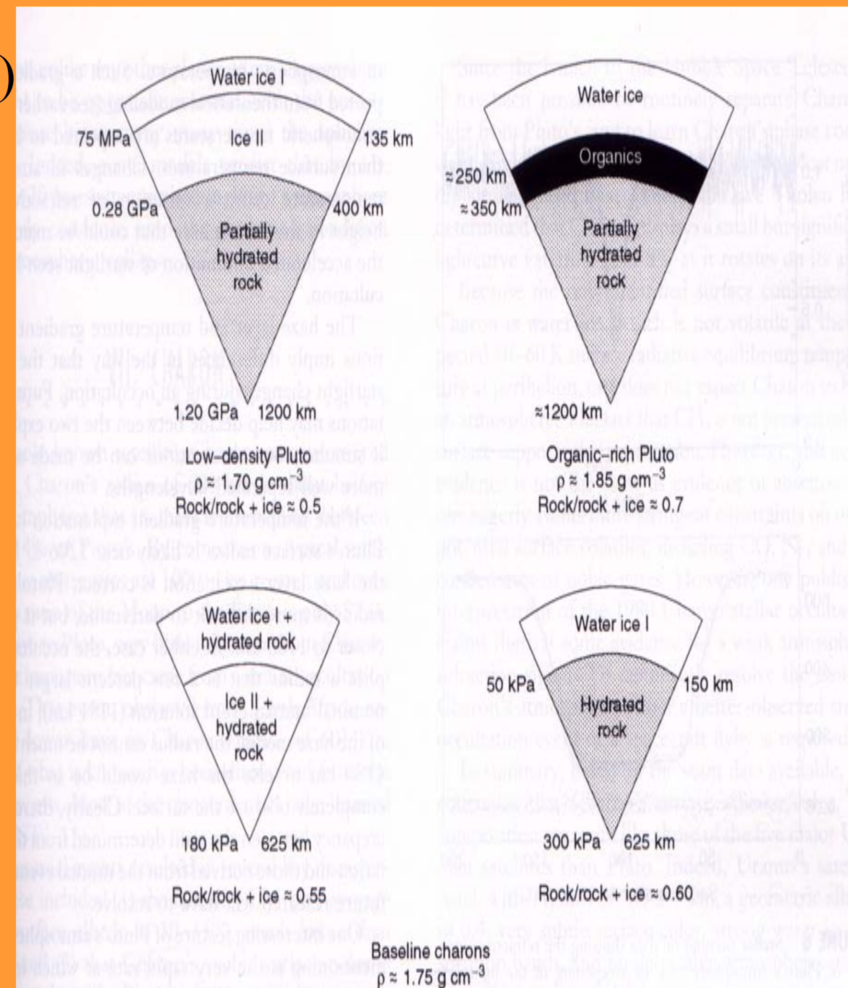


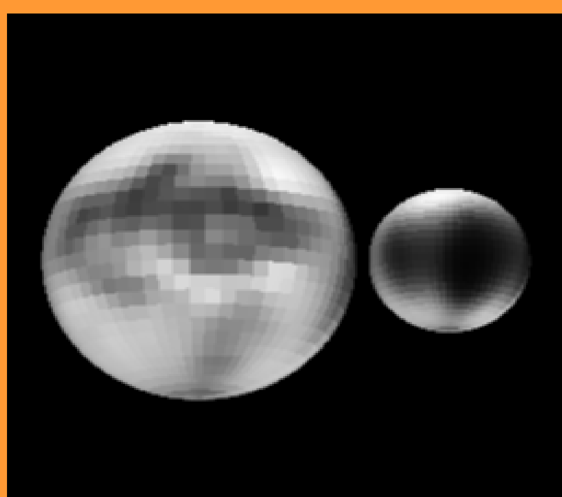
Pluto & Charon (since 1978)

- Orbit: stable in past, chaotic after ~ 2 10^7 y

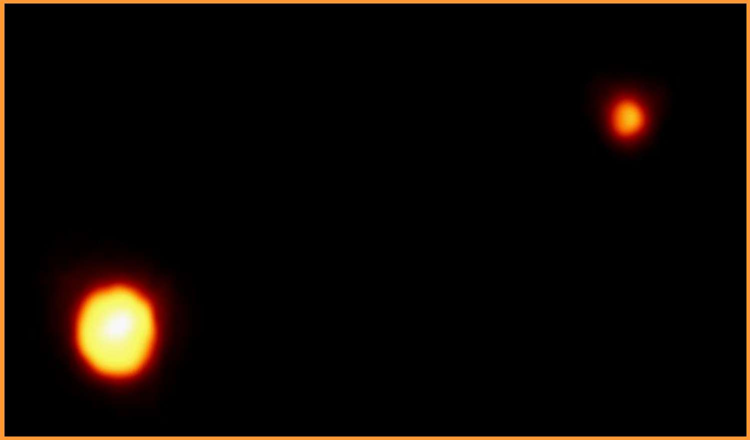
Size: 1200/600km radius, 2nd largest TNO

- Density: ~1.9 g/cm^3 (high! ➔ not only ices)
- Charon synchronous to Pluto orbit (6.4d)
- Albedo: P:0.4-0.6; C:0.3-0.35
- Colours: P = red, C = neutral
- Atmosphere: around perihelion for Pluto
  temporary nature ➔ resurfacing
- Surface: P: CH_4, N_2, CO T ~ 45-60K
  patchy
  C: H_2O, little CH_4 more uniform?

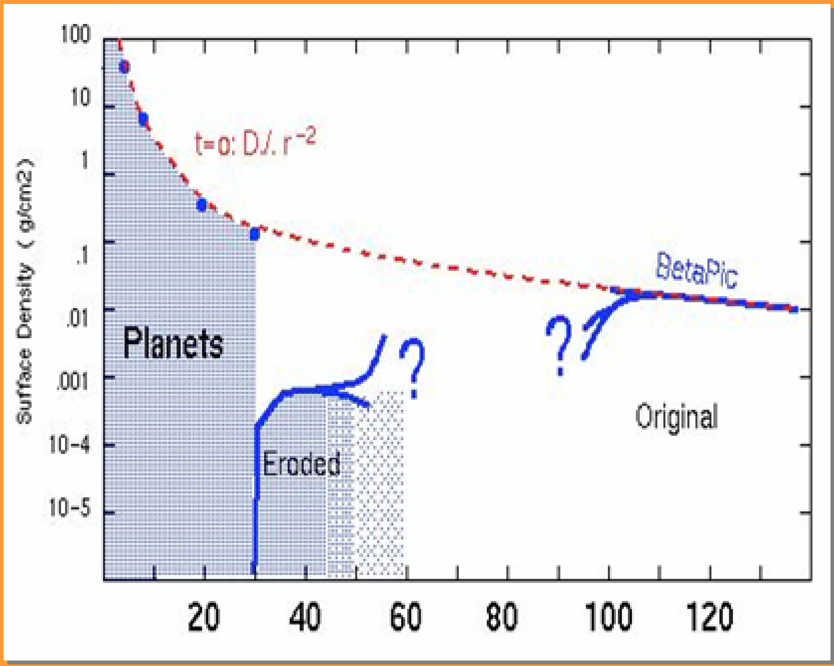




(1) Kuiper Belt formation:
- presence of Pluto puts modelling constraint
Try to make Pluto via accretion from 1m-1km size bodies at 40 AU distance
➔ more 1000-10000 Earth masses needed in Kuiper Belt region
➔ More than one Pluto is formed (Eris & Sedna & Triton)



(2) Missing mass problem:
mass surface density of outer planetary system $\sim r^{-2}$ in giant planet region
present Kuiper Belt drop by factor 10^2-10^3



(1)+(2) ➔ originally, the Kuiper Belt may have been massive and may have matched the extension of the mass surface density function

Interplanetary Dust

- **Summary**
  - Interplanetary dust cloud in inner solar system
  - Sources: cometary dust and collision in asteroid belts
  - Short lifetimes ➔ continuous replenishing

Appearance & Detection

- <u>Zodiacal light:</u> visible close to the horizon as diffuse light before/after sunrise/set
  - dust disk around the Sun, ecliptic oriented
  - Sun illuminated micron-size dust
- <u>Meteors:</u> trails of excited mostly atmospheric molecules in entry channel of mm-cm size dust, 120-60km height
- <u>Other detection techniques:</u> see schematics

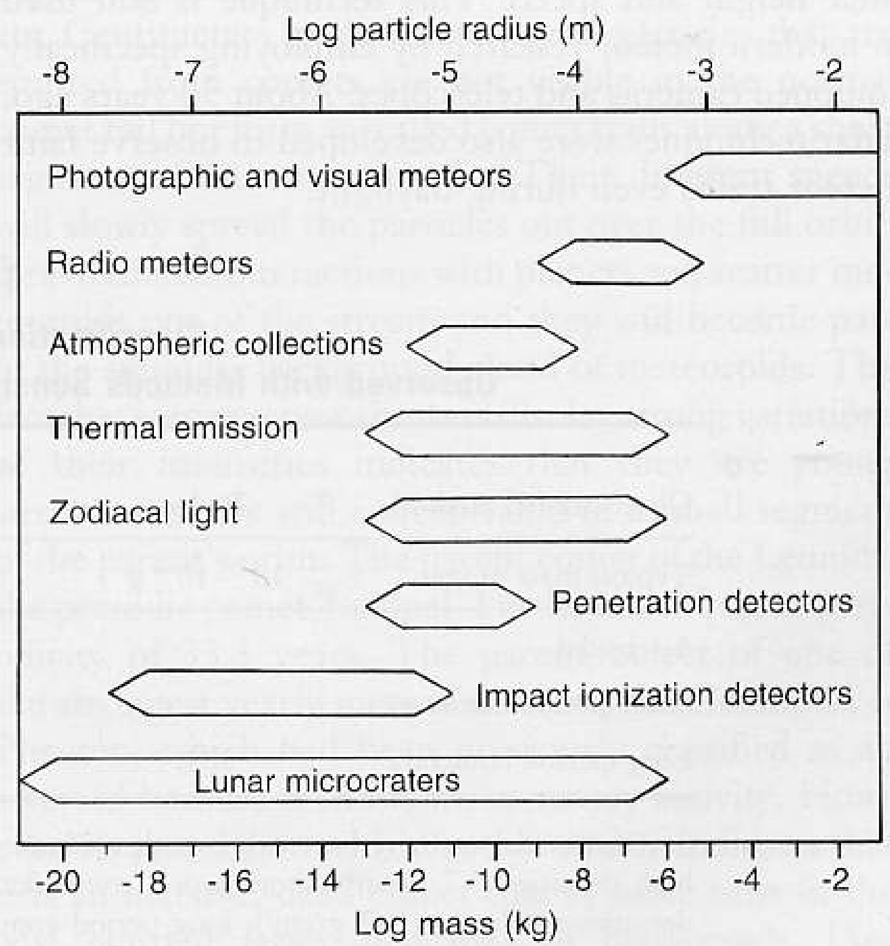


FIGURE 3 Comparison of meteoroid sizes and masses covered by different observational methods.

FIGURE 4 An unusually strong meteor shower (Leonid) was observed on 17 November 1966. The meteor trails seem to radiate from the constellation Leo.

FIGURE 1 Cone of zodiacal light seen in the west one hour after sunset. The ecliptic plane is delineated by Venus at the top of the cone and the crescent moon just above the horizon. (Courtesy of C. Leinert.)

Zodiacal light

Leonid meteor stream

- Meteor streams: enhanced meteor activity with trails converging to the same apparent point in the sky (radiant, meteor streams are named after radiants)
  - Orbits of meteors in stream similar to comets
  - Trails of dust along cometary orbits
    - ➔ Dust particles from comets
    - ➔ Earth passage through trails causes meteor streams

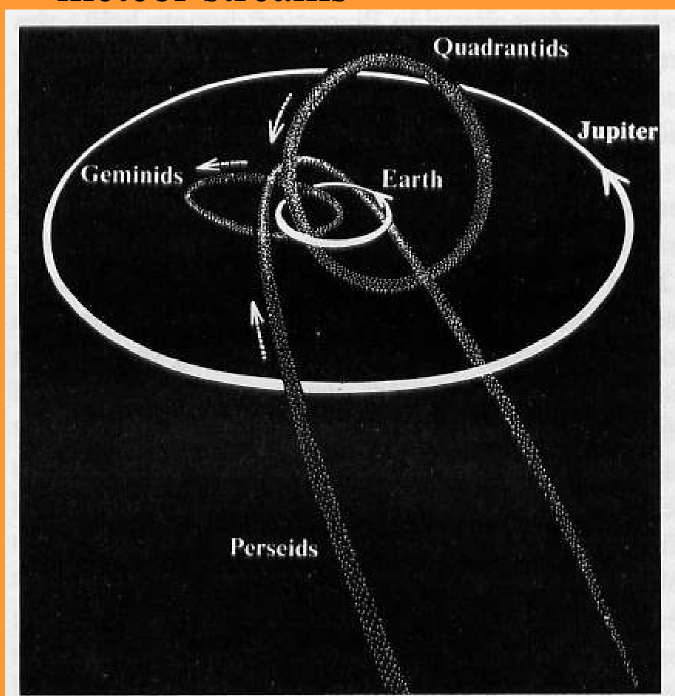


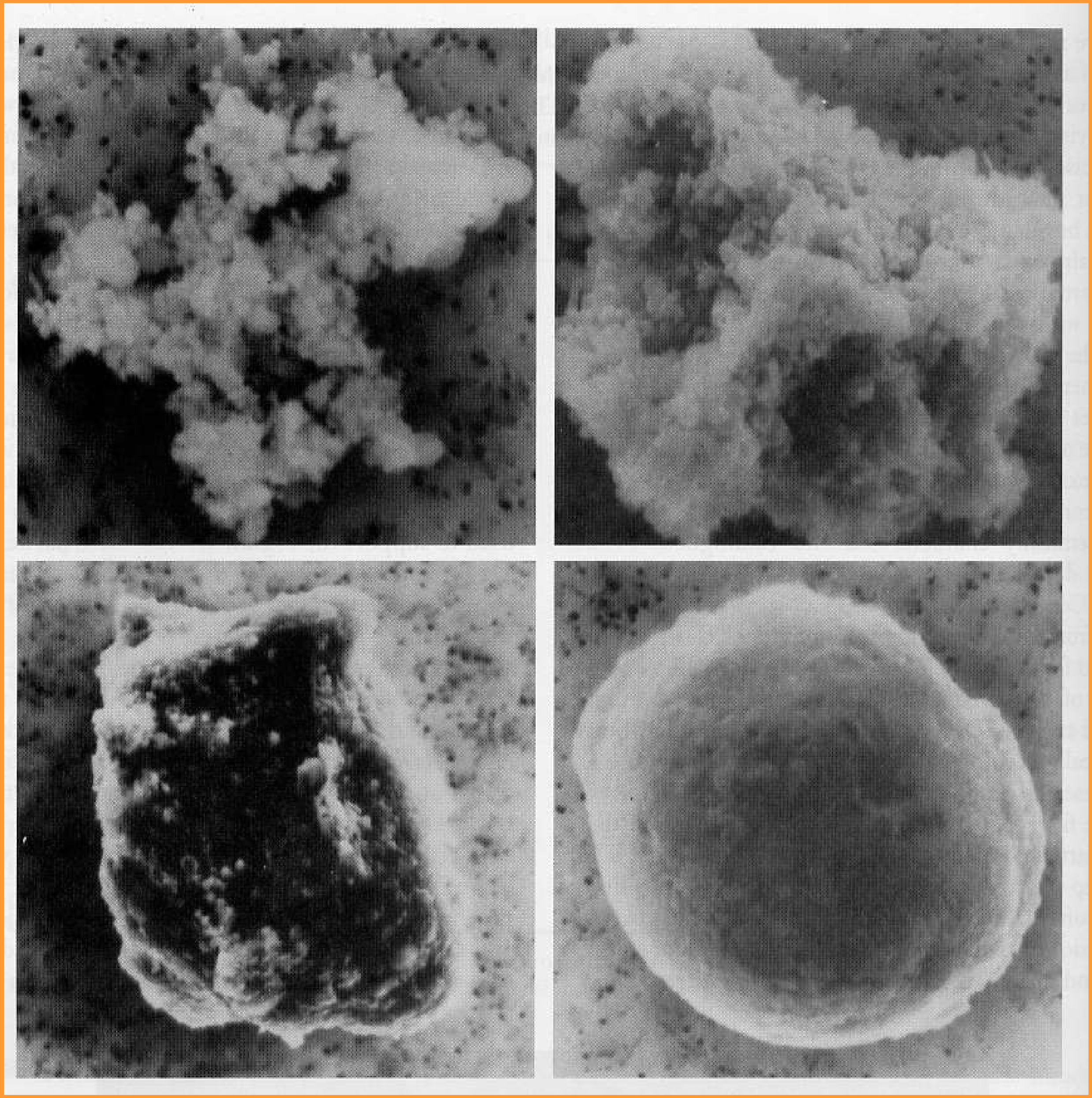
TABLE II

Major Meteor Showers, Date of Shower Maximum, Radiant in Celestial Coordinates (Right Ascension, RA, and Declination, DEC, in Degrees), Geocentric Speed (km/s), Maximum Hourly Rate, and Parent Objects (If Known, Short-Period Comets Are Indicated by P/)[a]

		Radiant				
Name	Date	RA	DEC	Speed	Rate	Parent object
Quadrantids	Jan. 3	230	+49	42	140	
April Lyrids	Apr. 22	271	+34	48	10	Comet 1861 I Thatcher
Eta Aquarids	May 3	336	−2	66	30	P/Halley
June Lyrids	June 16	278	+35	31	10	
S. Delta Aquarids	July 29	333	−17	41	30	
Alpha Capricornids	July 30	307	−10	23	30	P/Honda-Mrkos-Pajdusakova
S. Iota Aquarids	Aug. 5	333	−15	34	15	
N. Delta Aquarids	Aug. 12	339	−5	42	20	
Perseids	Aug. 12	46	+57	59	400 (1993)	P/Swift-Tuttle
N. Iota Aquarids	Aug. 20	327	−6	31	15	
Aurigids	Sept. 1	84	+42	66	30	Comet 1911 II Kiess
Giacobinids	Oct. 9	262	+54	20	10	P/Giacobini-Zinner
Orionids	Oct. 21	95	+16	66	30	P/Halley
Taurids	Nov. 3	51	+14	27	10	P/Encke
Taurids	Nov. 13	58	+22	29	10	P/Encke
Leonids	Nov. 17	152	+22	71	3000 (1966)	P/Tempel-Tuttle
Geminids	Dec. 14	112	+33	34	70	Phaeton
Ursids	Dec. 22	217	+76	33	20	P/Tuttle

After A. F. Cook (1973). *In* "Evolutionary and Physical Properties of Meteoroids" (C. L. Hemenway, P. M. Millman, and A. F. Cook, eds.), pp. 183–192. NASA SP-319, National Aeronautics and Space Administration, Washington, D.C.

Airborne collected interplanetary dust particles (IDPs)



Physico-chemical properties

- Composition: IDPs similar to chondrites for lighter stony elements, but enriched in rare earth elements
- Sizes: power laws with similar exponent
- Radial distribution: double peak distribution
  - Core population peaks at Sun
  - Distant population peaks in asteroid belt

  ➔ two sources for IPDs:
    - Comets (dust release by nucleus)
    - Asteroids (collisions)

TABLE III
Average Elemental Composition (All Major and Selected Minor and Trace Elements) of Several Chondritic IDPs Is Compared with C1 Chondrite Composition[a]

Element	C1	IDP	Variation	T_c
Mg	1,071,000	0.9	0.6–1.1	1067
Si	1,000,000	1.2	0.8–1.7	1311
Fe	900,000	1	1	1336
S	515,000	0.8	0.6–1.1	648
Al	84,900	1.4	0.8–2.3	1650
Ca	61,100	0.4	0.3–0.6	1518
Ni	49,300	1.3	1.0–1.7	1354
Cr	13,500	1.1	0.9–1.4	1277
Mn	9,550	1.1	0.8–1.6	1190
Cl	5,240	3.6	2.8–4.6	863
K	3,770	2.2	2.0–2.5	1000
Ti	2,400	1.5	1.3–1.7	1549
Co	2,250	1.9	1.2–2.9	1351
Zn	1,260	1.4	1.1–1.8	660
Cu	522	2.8	1.9–4.2	1037
Ge	119	2.3	1.6–3.4	825
Se	62	2.2	1.6–3.0	684
Ga	38	2.9	2.1–3.9	918
Br	12	34	23–50	690

[a] The IDP abundances are normalized to iron (Fe) and to C1. C1 abundance is normalized to Si = 1,000,000 condensation temperatures T_c (°C). From E. K. Jessberger *et al.* (1992). *Earth Planet. Sci. Lett.* **112**, 91–99.

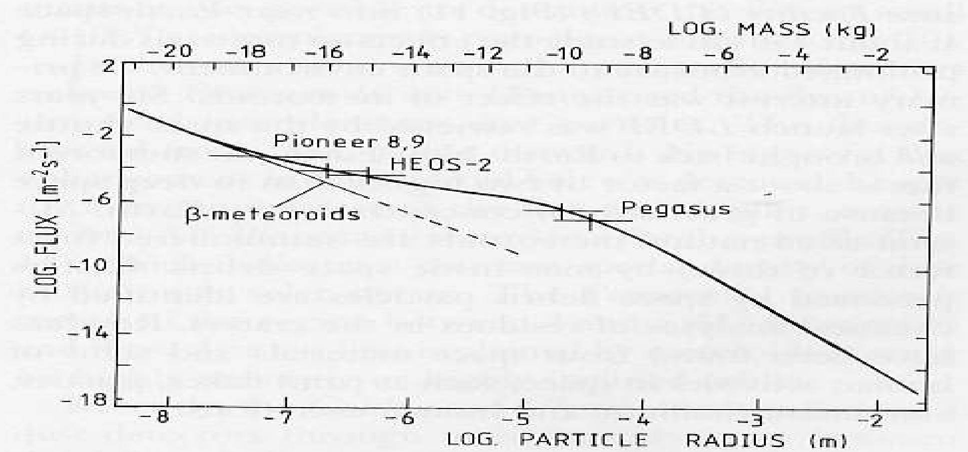


FIGURE 10 Cumulative flux of interplanetary meteoroids on a spinning flat plate at 1 AU from the Sun. The solid line has been derived from lunar microcrater statistics and it is compared with satellite and spaceprobe measurements.

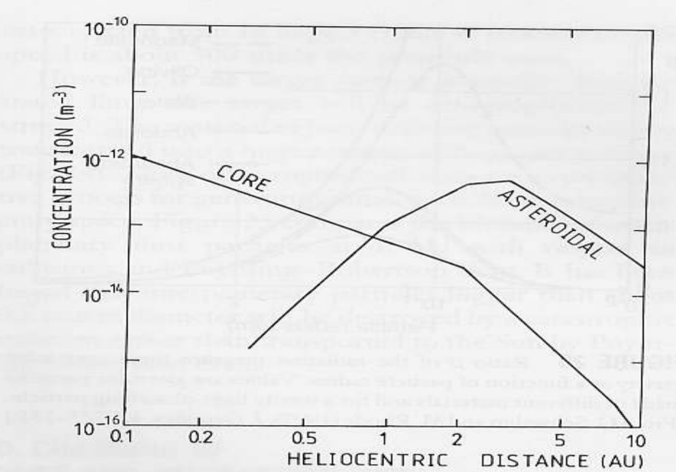


FIGURE 19 Radial dependence of meteoroid concentrations for two main populations in interplanetary space according to Divine (1993). The values given refer to particles with masses $> 10^{-4}$ g. The zodiacal core population comprises particles of all sizes, whereas the asteroidal population comprises only big ($>10^{-6}$ g) particles.

- <u>Lifetime of dust:</u> short lifetime ~ 1000-100000 y
  - Removal effects
    - Poynting-Robertson effect

      (IPDs either blown out of the solar system or spiraling into the Sun
  - Destruction effects
    - Collisions
    - Electrostatic disruption
    - Heating &evaporation
  - Continuous supply necessary!

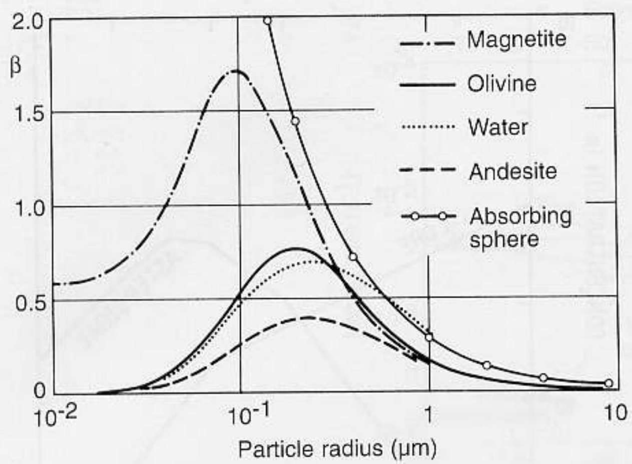


FIGURE 20 Ratio β of the radiation pressure force over solar gravity as a function of particle radius. Values are given for particles made of different materials and for a totally light-absorbing particle. [From G. Schwehm and M. Rhode (1997). *J. Geophys.* **42**, 727–735.]

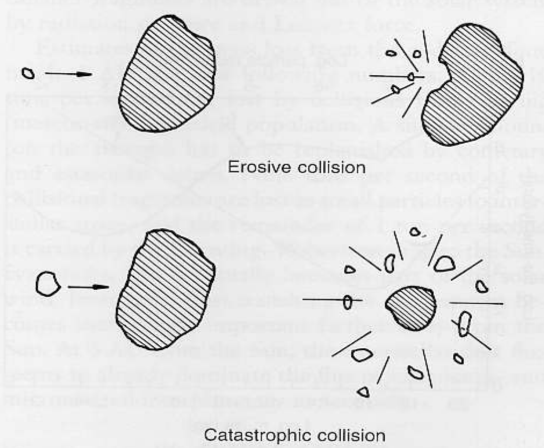


FIGURE 23 Schematics of meteoroid collisions in space. If the projectile is very small compared to the target particle, only a crater is formed in the bigger one. If the projectile exceeds a certain size limit the bigger particle is also shattered into many fragments. The transition from one type to the other is abrupt.

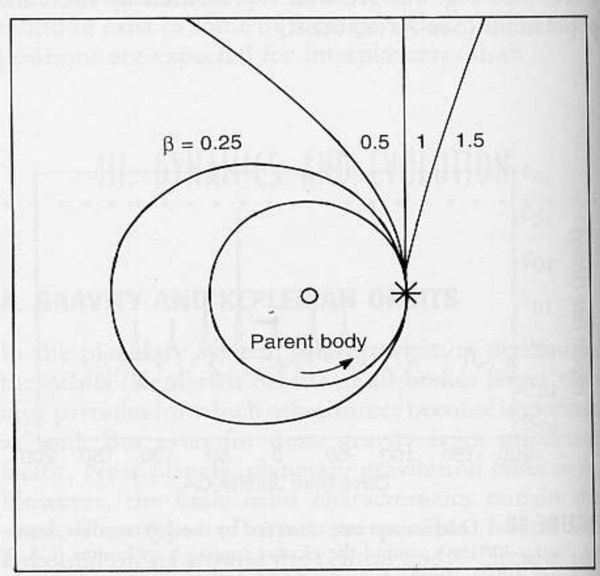


FIGURE 21 Orbits of beta-meteoroids that were generated from a parent body at the position indicated by the asterisk. β values of differently sized fragments are indicated; big β values refer to small particles.

Mass flow of IDPs

Lifetime of IDPs

- radiation pressure
- collision

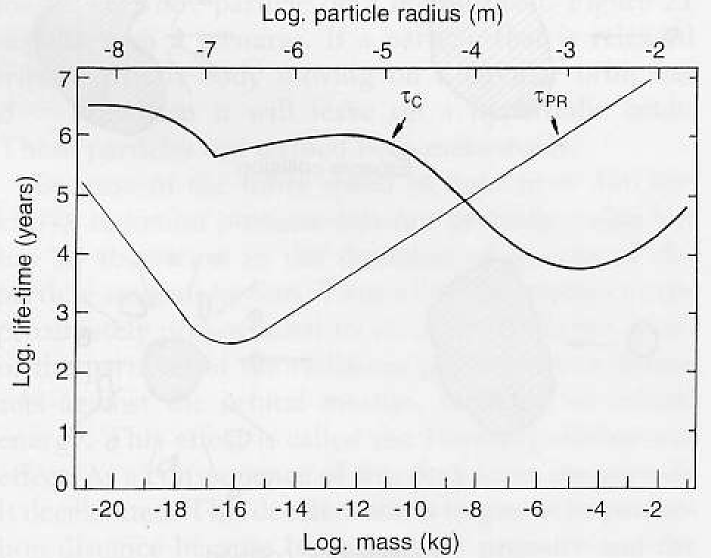


FIGURE 25 Life-times of meteoroids in interplanetaray space with respect to destruction by collisions τ_C and transport to the Sun by the Poynting–Robertson effect τ_{PR} as a function of particle mass. The shorter the lifetime, the more effective is the process of removing particles out of the zodiacal cloud.

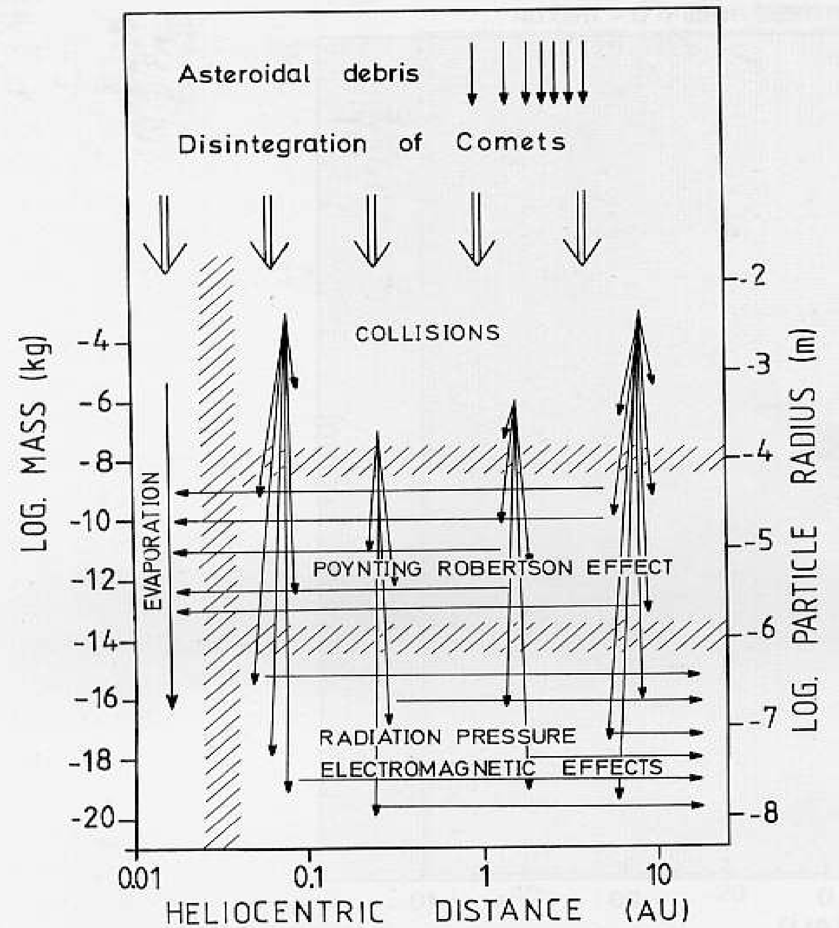


FIGURE 28 Mass flow of meteoritic matter through the solar system. Most of the interplanetary dust is produced by collisions of larger meteoroids, which represent a reservoir continually being replenished by disintegration of comets or asteroids. Most of it is blown out of the solar system as submicron-sized grains. The remainder is lost by evaporation after being driven close to the Sun by the Poynting–Robertson effect. In addition to the flow of interplanetary matter shown, there is a flow of interstellar grains through the planetary system.

Formation & Evolution of the Solar/Planetary System

- ***Summary***
  - Planetary system formed during/shortly after formation of the Sun
  - Collapse of interstellar gas/dust cloud
  - Disk formation by gas friction
  - Cold disk to grow m size bodies and planetesimals
  - Runaway grow of planets
  - Clean-up by collision down-grinding, scattering, impacts (early & late heavy bombardment) and radiation pressure
  - Atmosphere evolving from magma gas release and impacts
  - Proto-planetary disk was full of organics including L/D aminoacids
  - Sun will expand as red giant star to orbit of Mars

Observational Indications

- Primitive asteroids, comets, TNOs: primordial = remnants from formation period of planetary system (planetesimal state and before)
- For the Formation and its environment:
  - Environment: star forming regions
    - Dense interstellar clouds
  - Formation temperature: relatively cold
    - Organics in meteorites (T<300K)
    - Not from cooled Sun material: deuterium is lost in nuclear reactions within 10^6 y D/H(giant planets)>>D/H(sun)
    - Isotopic ratios Sun to Meteorites/Comets identical (for heavier elements)
    - Mixing of H and He in Jupiter/Saturn as in Sun
  - Ingredients: stellar formation regions
    - Interstellar gas with most abundant elements H, He
    - Interstellar gas that can form volatile ices (H_2O, CO, CO_2, NH_3, CH_4 etc.)
    - Interstellar dust, strongly shocked or enriched in supernova produced elements
      (diamonds=shocked C, ^{26}Mg from ^{26}Al in chondrites higher than in current neighbourhood)
  - Mass: > 1.02 solar mass

- For the Formation time:
  - Meteorites ➔ 4.56 10^9 a

    ➔ not necessarily in present stellar neighbourhood, but probably in star cluster (Gallactic rotation and differential motion of stars, proper motion of the Sun)
- For formation time scales:
  - Meteorites, i.e. cm→m size bodies +/-10 10^6 y around formation time
  - Oldest impact craters (on moon) ~4.3 10^9 y

    ➔ planet (moon!) formation widely ‚finished' within 100 10^6 y from chondrite formation
- For the typical size and geometry (some times during formation process):
  - Kuiper Belt extension ~ 50 AU at one time (maybe even smaller: Nice model and Neptune migration)
  - Ecliptic-orientation of planets and the belts and analogy to circumstellar disks and proplydes in star formation regions

    ➔flat disk-shape geometry
  - Mass concentrated in Sun, angular momentum in planets
- Objects produced:
  - Sun (star) 1 solar mass
  - Terrestrial planets 10^{-5} solar mass
  - Gas giants 10^{-3} solar mass
  - Icy planetesimals and fragile comets 10^{-3} solar mass

all appeared quasi-simultaneously

Formation Scenario

- Step 1 - Protostellar collapse:
  - Jeans criterion for collapse of gas clouds: self-gravitation energy > thermal energy in cloud

    self-gravity ~ $GM^2/R \sim GM\rho R^2$

    (M,R = mass/radius of cloud, G = grav. Const)

    thermal energy ~ $Mv_s^2 \sim k^2MT^2$ (v_s/T = speed of sound/temperature in cloud)

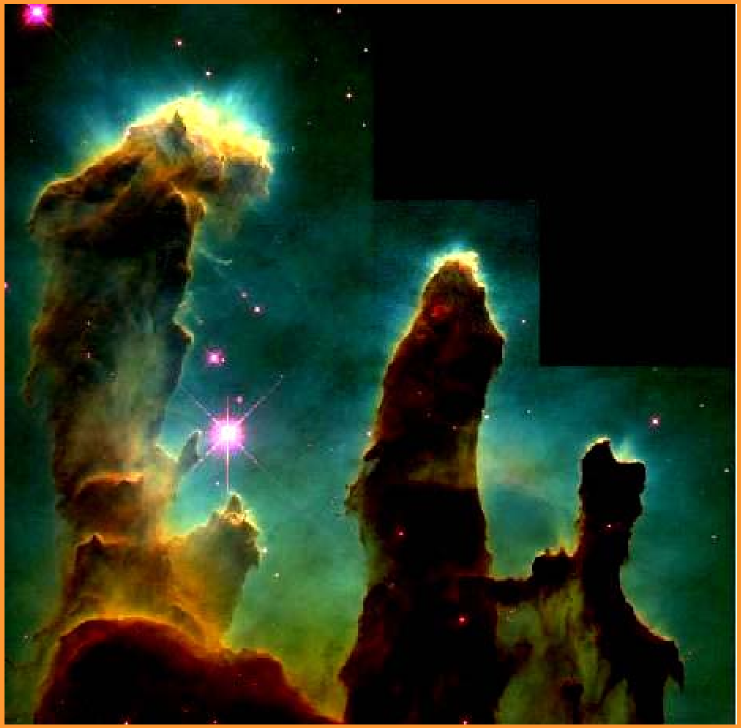
    $R = (\pi v_s^2 / G\rho)^{1/2}$ (Jeans criterion)

    → from star forming regions:

    R ~ 0.1 pc ($3\ 10^{15}$ m), T ~ 10K

    collapse time scale: $t \sim R/v_s \sim 10^6$ y

    min. mass involved for protosolar nebula ~ 1.02 solar mass (Sun+planets)



- <u>Step 2 – Disk formation:</u>
  - Radial collapse & conservation of angular momentum

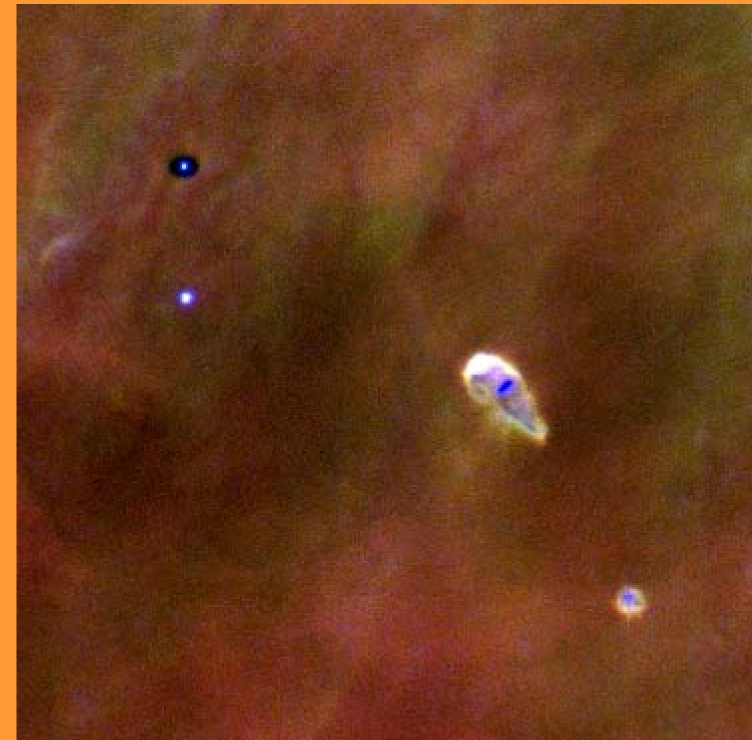
    ➔ flat disk is formed

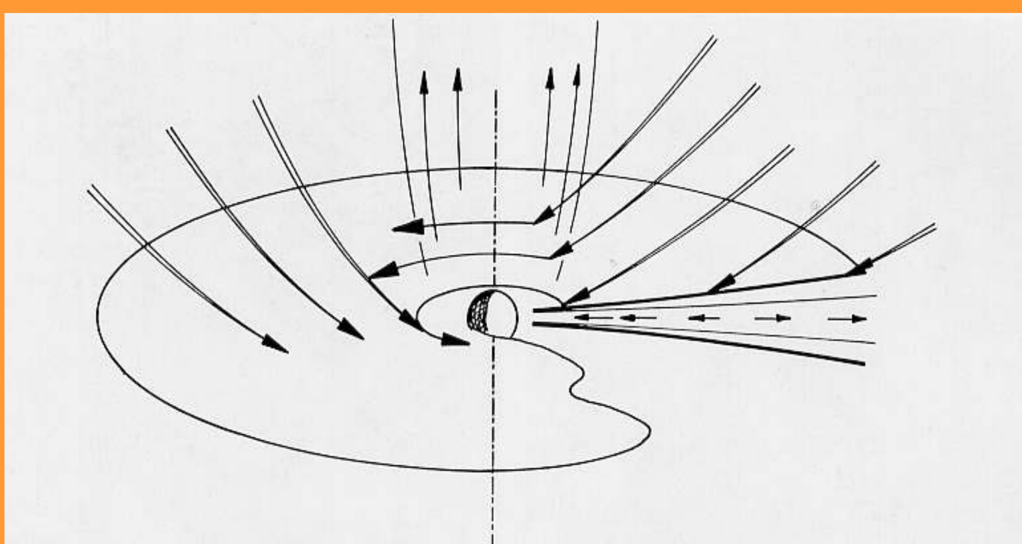
    Collapse along rotation axis of cloud continues, inside disk has to overcome centrifugal forces

    ➔ Angular momentum in disk is transformed into thermal energy via friction

    ➔ Heating, towards center stronger, i.e. more efficient friction, better angular momentum transfer

    ➔ Proto-sun forms in disk center





- Time scale: 2 10^7 y
- Most of mass in Sun
- Disk thickness ~ 1/10 diameter
- Inner disk (~1 AU) is hot >1500K

  dust vaporizes, lighter molecules dissociates (not heavier ones)

  mass ~ 0.03 solar masses
- Outer disk (>2 AU) remains cool

  dust intact, more molecular gas

- <u>Step 3 – Growth of cm/m size grains (meteorites):</u>
  - Inner disk: rapid cooling through IR radiation

    ➔ stony molecules crystallize rapidly to µm grains

    Outer disk: gas freezes on dust grains

    ➔ dust grains start to agglomerate

    dm/dt ~ $a^2 v \rho_{dust}$ (a/ρ_{dust} = radius/density of dust)

    v ~ speed of dust settling towards disk plane

    <u>Important:</u> works only for relative velocities of dust < 10 cm/s

    ➔ ***dust aggregates only in dynamically cold disk***

    dynamically cold = dust grains have similar orbits (e,i), otherwise destruction by collision

    ➔ dust sticking is supported by formation of inter-grain matrix through condensation and surface reactions of gas molecules

    ➔ larger grains grow in very thin (out-of-plane) disk

    Time scale: < 10^3 orbits ~10^3 10^5 y

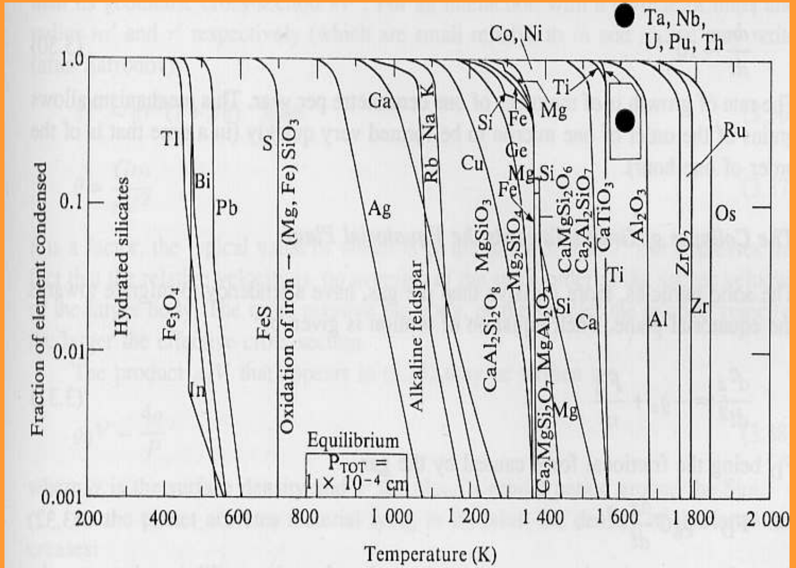


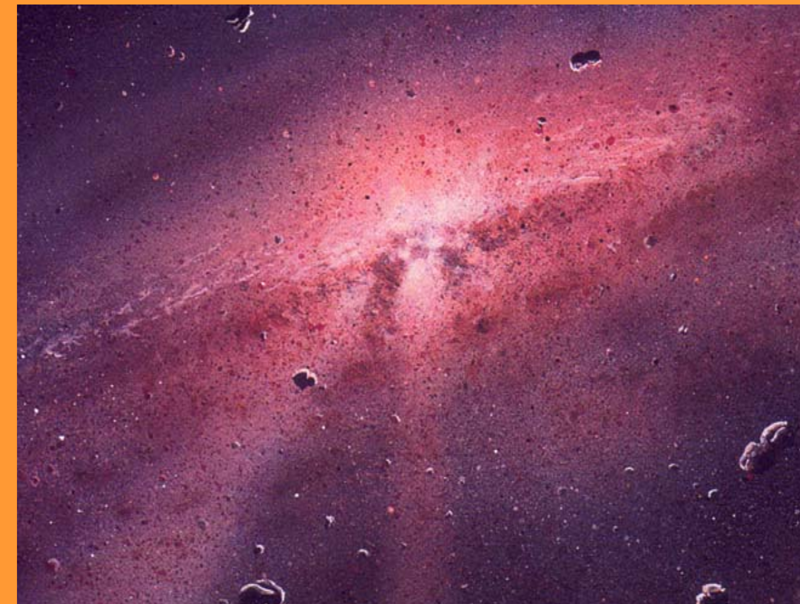
Fig. 3.1. The condensation sequence for a gas with solar composition. [After L. Grossman J.W. Larimer: Review of Geophysics and Space Physics 12, 71 (1974)]

- <u>Step 4 – Growth of planetesimals:</u>
  - continuous gentle collisions of m size bodies grow planetesimals (~1km size)

    sticking by self-gravity

    Time scale: similar to step 3

    ➔ cold disk gets slightly ‚excited‘ due grav. interaction of planetesimals



- <u>Step 5 – Runaway accretion of planets:</u>

  planetesimals continue to collide and grow

  simulations ➔ 10^6-10^7 y few planet size bodies form, random behaviour for distances of planets

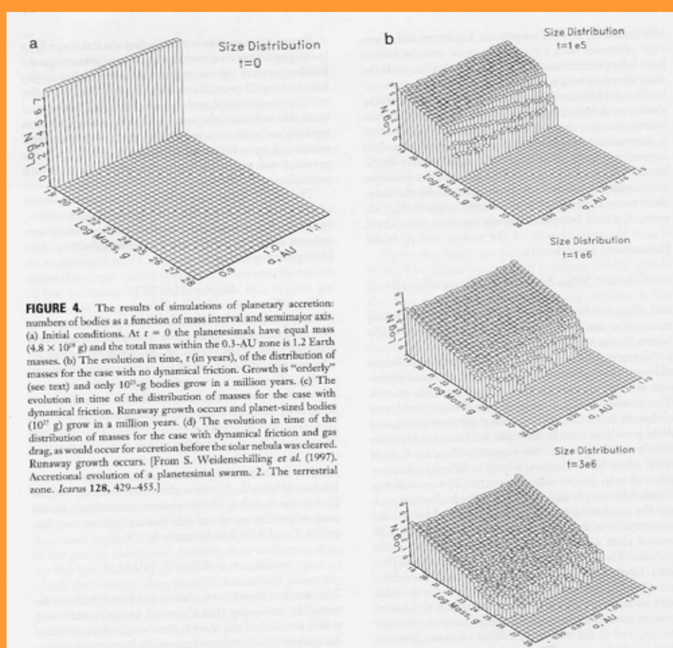
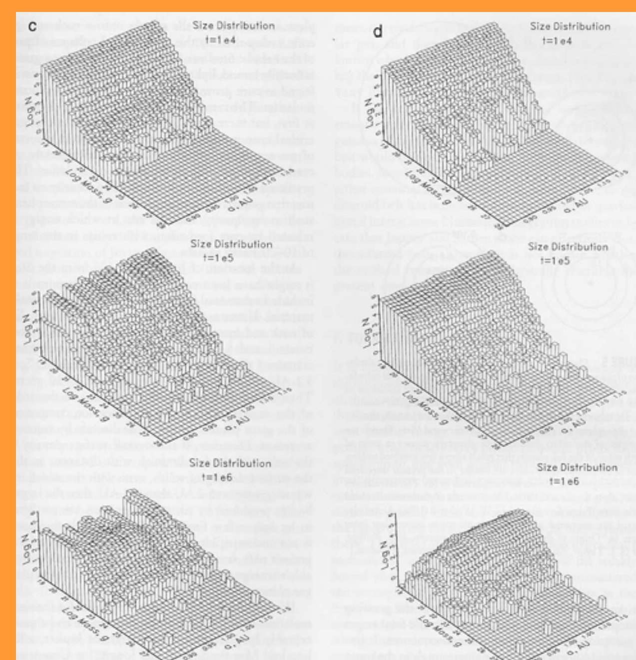


FIGURE 4. The results of simulations of planetary accretion: numbers of bodies as a function of mass interval and semimajor axis. (a) Initial conditions. At $t = 0$ the planetesimals have equal mass (4.8×10^{18} g) and the total mass within the 0.3-AU zone is 1.2 Earth masses. (b) The evolution in time, t (in years), of the distribution of masses for the case with no dynamical friction. Growth is "orderly" (see text) and only 10^{25}-g bodies grow in a million years. (c) The evolution in time of the distribution of masses for the case with dynamical friction. Runaway growth occurs and planet-sized bodies (10^{27} g) grow in a million years. (d) The evolution in time of the distribution of masses for the case with dynamical friction and gas drag, as would occur for accretion before the solar nebula was cleared. Runaway growth occurs. [From S. Weidenschilling *et al.* (1997). Accretional evolution of a planetesimal swarm. 2. The terrestrial zone. *Icarus* **128**, 429–455.]



- Step 6 – Disk clean-up:
  - Proto-planets in environment of planetesimals, meteorites, dust and gas

    all planets: perturbation on orbits in neighbouring disk environment

    ➔ cold disk gets excited

    ➔ collisions more energetic, i.e. impacts and scattering of planetesimals occur

    ➔ planetesimal collisions causes down-grinding of objects to dust grain size

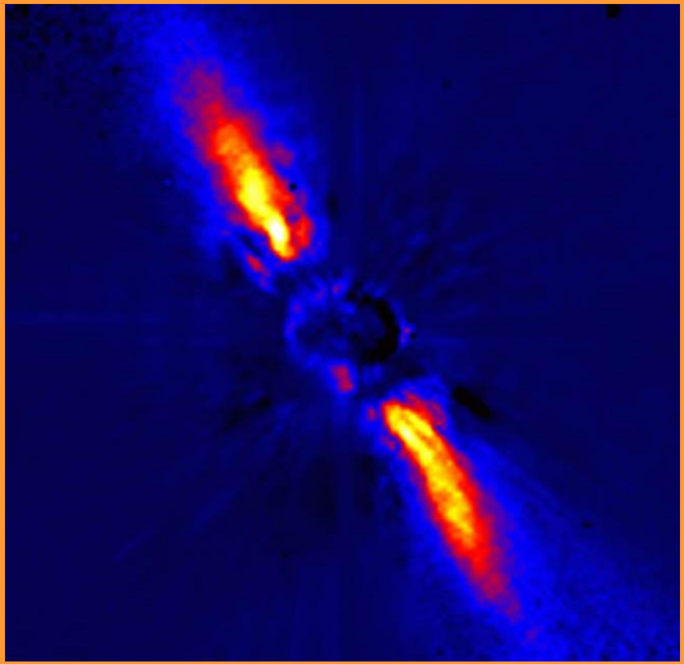
    ➔ dust removed by radiation pressure

    ➔ proto-planets grow further, disk looses mass towards Sun and outer solar system (interstellar space)

    terrestrial planets: H_2, He disk gas to hot and planet mass too small to allow accretion by condensation, only heavier molecule (H2O, CO2, CH4, NH3) can be accreted.

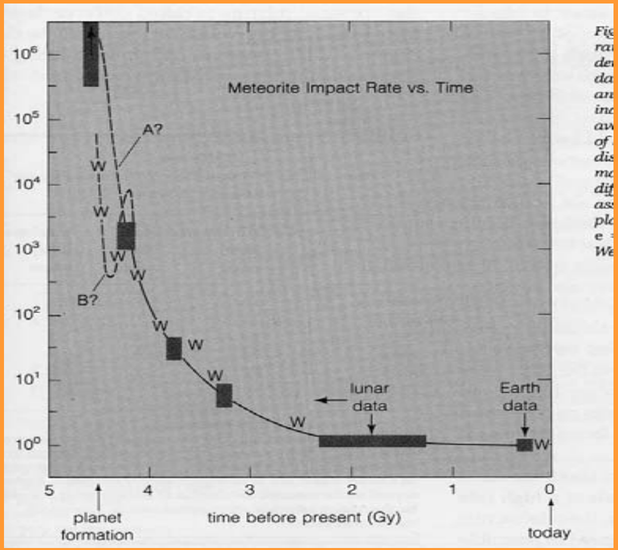
    giant planets: Earth size protoplanet is capable of accreting H_2, He gas since in colder environment

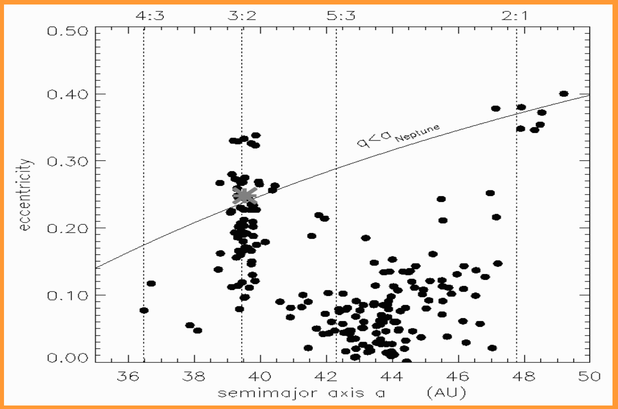
    Time scale: 10^7-10^8 y

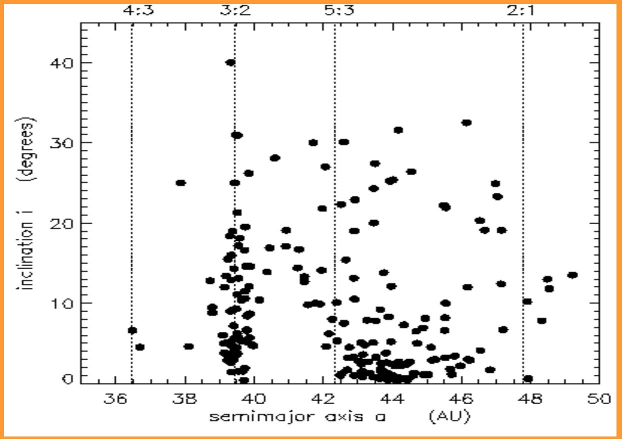


Debris disk around β Pictoris

- <u>Some notes to step 6:</u>
  - Mass transfer/removal:
    clean-up of sphere of gravitational influence around orbit of planets
  - Mass transfer through scattering is enormous
    Kuiper-Belt: several 1000 Earth masses
    closer to the Sun most likely even more
    inbound/outbound scattering occurs
    ➔ period of early & late heavy bombardment
  - Transfer of angular momentum:
    scattering transfers angular momentum to planets
    ➔ planets can migrate away from original orbit
    - Mercury: collection of heavier material at larger distances
    - Excited Cubewano population in Kuiper Belt:
      objects with a>42AU have wider (a,e) and (a,i) distributions than expected from a simple collision environment
      Excitation from swiping of Neptune resonance during outward migration of the planet
    - late heavy bombradment caused by excitement of Kuiper Belt due to 1:2 resonance crossing of Jupiter&Saturn







– Oort cloud formation:

during period of disk clean-up scattering from region of gas giants towards outer solar system

➔ ‚thermaliziation‘ of scattered comets by neighbouring stars and galactic molecular clouds

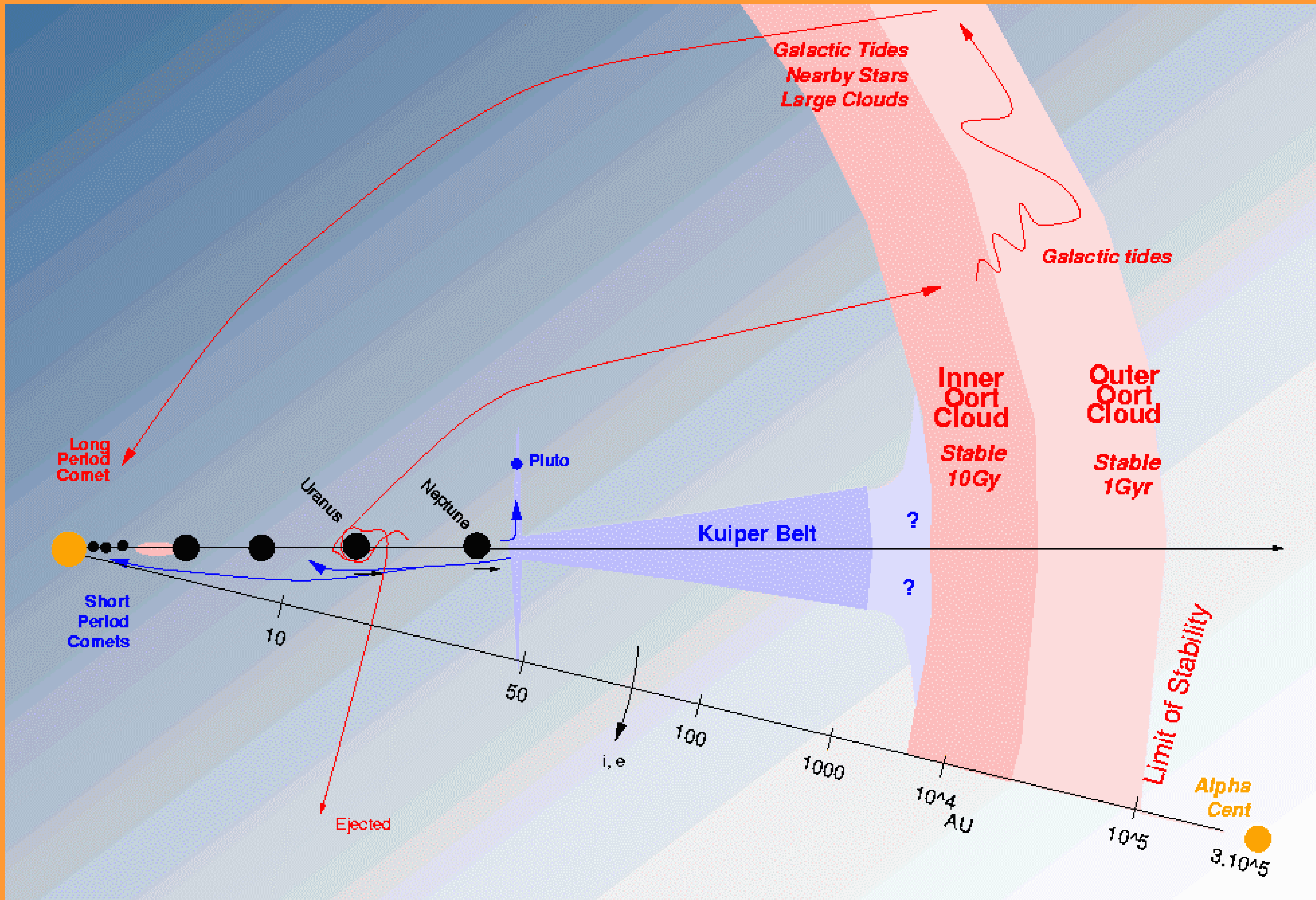
➔ distribution in spherical cloud at the edge of the solar system

Arguments: ‚temperature-tracer ices‘ present/absent in Oort cloud comets

➔ matches expected temperature range for formation in giant planet regions, Kuiper Belt too cold

- <u>End of the spectaculum:</u>

  $\sim 4\ 10^9$ y from now


Galactic Tides
Nearby Stars
Large Clouds
Galactic tides
Inner Oort Cloud
Stable 10Gy
Outer Oort Cloud
Stable 1Gyr
Long Period Comet
Pluto
Uranus
Neptune
Kuiper Belt
?
?
Short Period Comets
10
50
i, e
100
1000
10^4 AU
10^5
3.10^5
Limit of Stability
Alpha Cent
Ejected

Planet Evolution (first 10^9 y)

- Heat-up by gravitational accretion: planets get hot during accretion due to ‚absorption' of impact / gravitational energy

  ➔ planet gets liquid, volatile molecules disappear to space or get distroyed in magma

  different density of metal and silicate materials causes differentiation

  ➔iron-core formation, silicate at surface
- Terrestrial planets: cooling of silicate forms crust of terrestrial planets, vulcanism releases solved magma gases, heavy bombardment deliveres further volatile gases

  ➔ original atmosphere (reducing character) forms
- Giant planets: hot core is surrounded by dense H_2/He atmosphere, i.e. efficient cooling of core, gets colder and solid again

  in parallel differentiation of gas atmosphere (H_2 fluid, He droplets)

Planet Evolution (Scenarios for next 10^{10} y)

- Some chaotic dynamics: planets may start migrating, colliding& scattering again
- Sun becomes red giant:

  photosphere growing to Mars orbit

  ➔ terrestrial planet will be gone

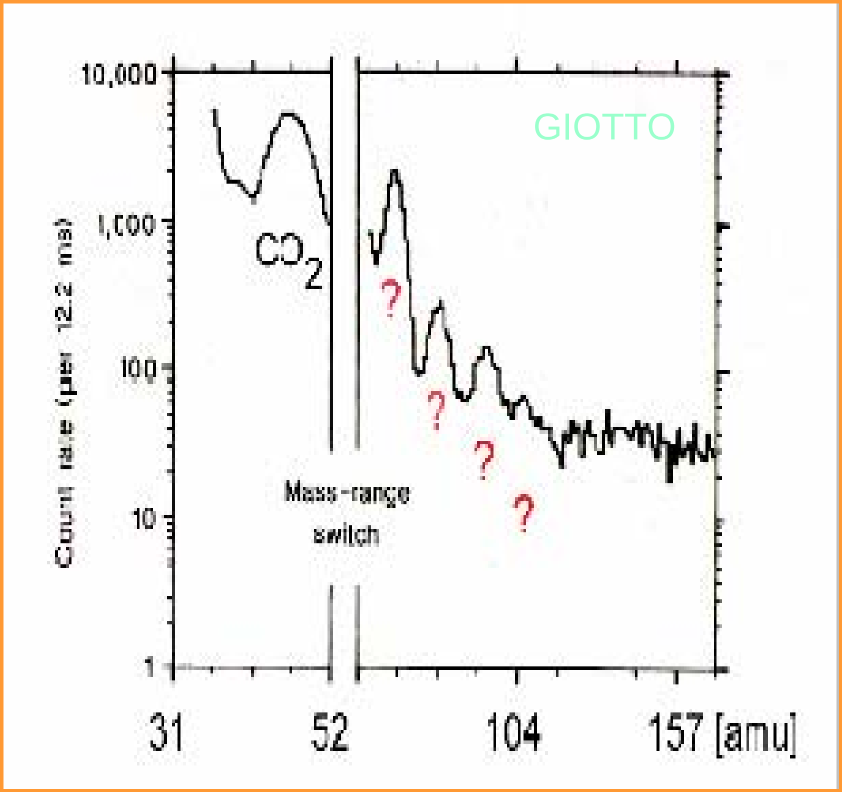
  ➔ gas giants will start evaporating their atmospheres

Bioastronomy in the Solar System

- Life on Earth (difficult to detect from space)
- Comets contain water ice (in part source of terrestrial water?; imported during late heavy bombardment)
- Existence of liquid water (oceans) is possible in large KBOs (like Pluto)

➔ KBO collision fragments = comets: hence comets may contain relics from liquid phase

- Coma gas contains organic molecules (organic polymers?)



Bioastronomy in the Solar System

- Dust contains lots of CHON particles (GIOTTO at Halley)
- CI chondrites are suspected to contain primordial material from the formation period of the Sun
- CI chondrites are suspected to originate from comets
- Aminoacids exist in interplanetary space, i.e. found in some CI chondrites
- Murchinson CI contains aminoacids in non-racemic mixture (more L type)

➔ Comets might be seen as carrier and bringer of pre-biotic material to Earth

Aminoacids: L and D Types

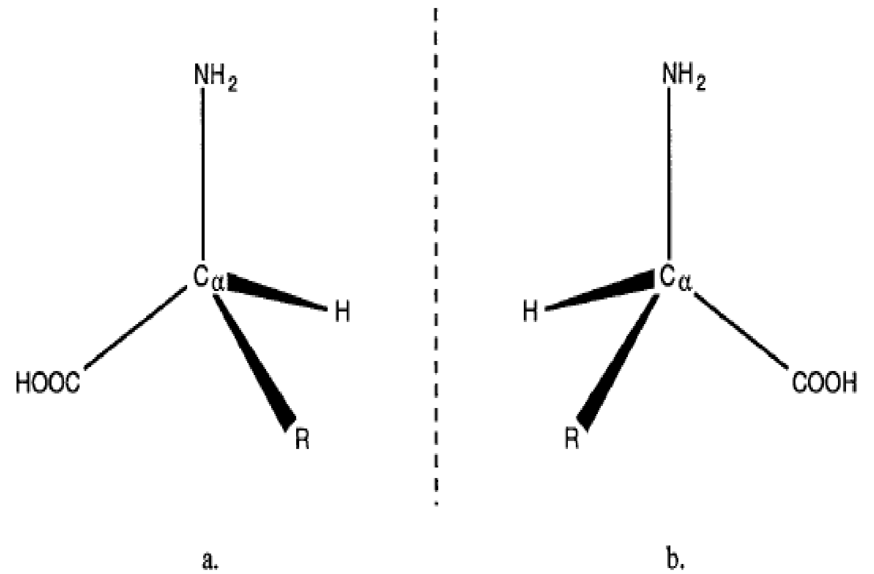


Figure 1. a. L-amino acid; b. D-amino acid

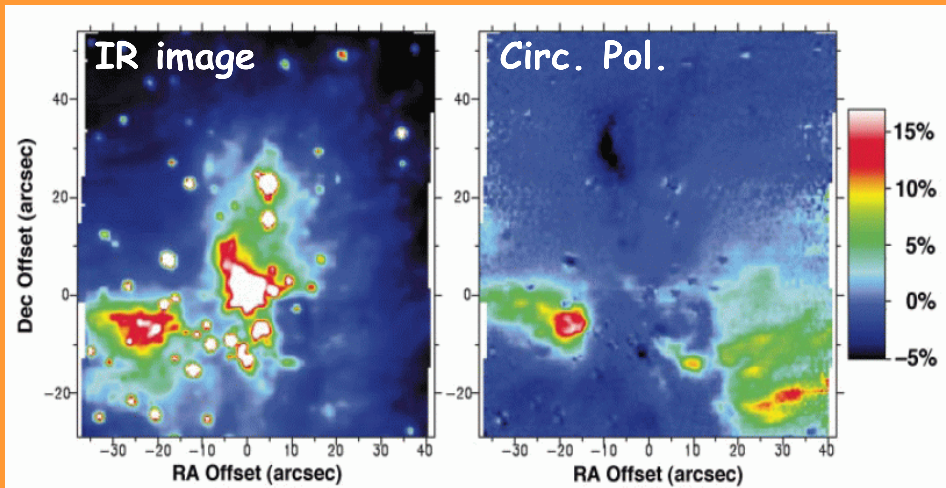
- Aminoacids: important pre-requisites for life formation on Earth
- Aminoacids come in two enantiomers: L and D type
- Terrestrial life built on L type aminoacids

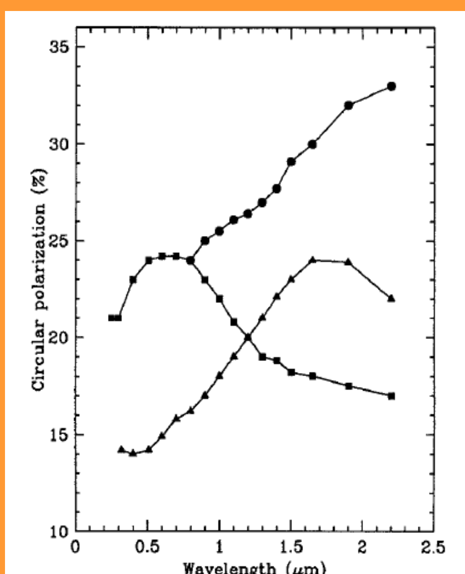
➔ Can this be produced in space?

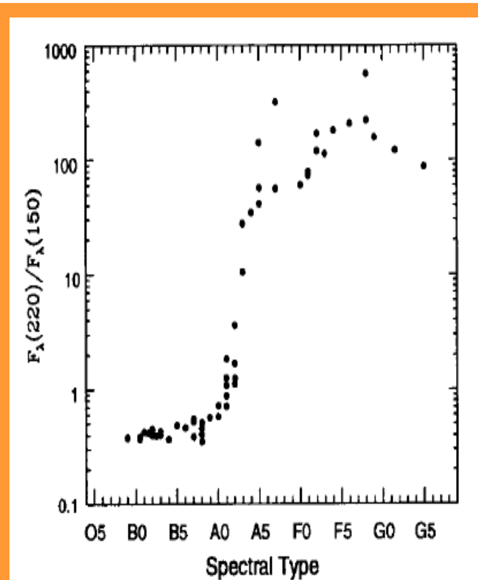
- L and D aminoacids show different optical activity: left and right-handed polarization

➔ Can this be used to detect them?

Polarized Light & Homochirality







- High (17% level) circular polarization measured in Orion dust clouds (Bailey et al. 1998)

- Photolysis of L/D molecules is affected by circ. pol. light

➔more efficient process than any other terrestrial fractionation effect for chiral molecules

- Homochirality of aminoacids through circ. pol. UV radiation from dust reflected star light

➔ most, but not all natural aminoacids on Earth are to be considered biogenic (Cref & Jorissen 2000)