Minor Bodies
in the Planetary System

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

- **Dimensions:**
  - Solar system extension ~ 100000AU
  - Planetary system extension ~ 0.4-32/50/1000/100000AU

- **Geometry:**
  - Flat disk close to Ecliptic and equator of the Sun (<50AU)

- **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 $\delta v = \frac{2\pi R_0}{U_{Jup}}$
  - $R_0 =$ Sun radius (700000km)
  - $U_{Jup} =$ orbit period of Jupiter (11.8y)
  - $\delta v \sim 10 \text{ m/s} \quad \text{(over 11.8y)}$

  - Measurement accuracy ~ few m/s (HD spectrographs)

  - Problem is orbital period
Basic Physics

- Planck’s law
  \[ B(\lambda) = \frac{(2hc^2/\lambda^5)}{\left[\exp\left(hc/(2\pi\lambda kT)\right) - 1\right]} \]
- Wien’s law
  \[ \lambda_{\text{max}} T = 2880 \text{ [\mu mK]} \]
- Energy balance
  \[ \frac{F_0}{r^2 \pi R^2} (1-A) = \sigma T^4 4\pi R^2 \]
- Surface temperature (atmosphereless)
  \[ T = (1-A)^{1/4} 273 \text{ r}^{1/2} \text{ (fast rotator)} \]
  \[ T = (1-A)^{1/4} 324 \text{ r}^{1/2} \text{ (slow rotator)} \]

➔ snowline \( T < 273 \text{K} \): somewhere in asteroid belt

\( \lambda \) = wavelength

\( \Lambda_{\text{max}} \) = wavelength of radiation maximum

\( T \) = temperature

\( h, c, \sigma, k \) = Planck const, speed of light, Stefan const, Boltzmann const,

\( A \) = surface albedo

\( R \) = body radius

\( F_0 \) = solar flux at 1 AU

\( r \) = distance from the Sun

Fig. 1.5, p11, A&A
Fig. 1.6, p12, A&A
Bodies with and without atmosphere

- Criterium for possible stable atmosphere:
  1. \[ E_{\text{kin}}(\text{gas}) < E_{\text{pot}}(\text{gas}) \]
  \[ v^2 < v_{\text{escape}}^2 = 2 \gamma m / R \]
  2. Mean velocity of gas
  \[ v^2 = 2 G T / \mu \]

  \[ \Rightarrow (m \mu) / (R T) < G / \gamma \]

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

\( \gamma \) = gravity constant
\( m, R \) = body mass, radius
\( G \) = gas constant
\( T \) = gas temperature
\( \mu \) = mean molecular weight
Orbits

- **Ellipse**, parabola, hyperbola
- Newtonian 2-body solution ~ good approximation
  - Orbit plane defined by
    - $I = \text{inclination (to Ecliptic/equator)}$
    - $\Omega = \text{argument of ascending node}$
  - Dynamics defined by
    
    \[
    r = \frac{a (1-e^2)}{1+e \cos v} \quad (\text{Ellipse})
    \]
    
    - $r = \text{length of radius vector}$
    - $a = \text{semi-major axis}$
    - $e = \text{eccentricity}$
    - $v = \text{true anomaly (angle between perihelion and actual orbit position as seen from central body)}$
  
  Location of orbit in plane defined by
  
  - $\omega = \text{argument of perihelion (angle between } \Omega$
• time dependance \( r = r(t) \)
  \[
  \cos v = \frac{(\cos E - e)}{(1-e \cos E)}
  \]
  \( E = M - e \sin E \)
  \( M = n (t-T_p) \)
  
  \( E \) = eccentric 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. \( r^2 \frac{dv}{dt} = G \)
    \[
    G^2 = \frac{a(1-e^2)}{[\gamma (M_0+m)]}
    \]
  3. \( P^2/a^3 = \gamma (M_0+m)/4\pi^2 \)
    \( P \) = orbital period
    \( M_0 \) = solar mass
    \( m \) = planet’s mass
    \( \gamma \) = gravity constant
Overview Tables of the Planets

Table 1: Planetary Orbits

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

*J2000, Epoch: January 1, 2000

Table 3: Physical Parameters for the Sun and Planets

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (kg)</th>
<th>Equatorial radius (km)</th>
<th>Density (g cm⁻³)</th>
<th>Rotation period</th>
<th>Obliquity (°)</th>
<th>Escape velocity (km sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>1.989 × 10³⁰</td>
<td>696,000</td>
<td>1.41</td>
<td>24.65–34 days</td>
<td>7.25°</td>
<td>617.7</td>
</tr>
<tr>
<td>Mercury</td>
<td>3.302 × 10²³</td>
<td>2,439</td>
<td>5.43</td>
<td>58.646 days</td>
<td>0</td>
<td>4.43</td>
</tr>
<tr>
<td>Venus</td>
<td>4.868 × 10²⁴</td>
<td>6,051</td>
<td>5.20</td>
<td>243.018 days</td>
<td>177.33</td>
<td>10.36</td>
</tr>
<tr>
<td>Earth</td>
<td>5.974 × 10²⁴</td>
<td>6,378</td>
<td>5.52</td>
<td>23.934 hr</td>
<td>23.45</td>
<td>11.19</td>
</tr>
<tr>
<td>Mars</td>
<td>6.418 × 10²³</td>
<td>3,396</td>
<td>3.93</td>
<td>24.623 hr</td>
<td>25.19</td>
<td>5.03</td>
</tr>
<tr>
<td>Jupiter</td>
<td>1.899 × 10²⁷</td>
<td>71,492</td>
<td>1.33</td>
<td>9.925 hr</td>
<td>0</td>
<td>59.54</td>
</tr>
<tr>
<td>Saturn</td>
<td>5.685 × 10²⁶</td>
<td>60,268</td>
<td>0.69</td>
<td>10.656 hr</td>
<td>26.73</td>
<td>35.49</td>
</tr>
<tr>
<td>Uranus</td>
<td>8.683 × 10²⁵</td>
<td>25,559</td>
<td>1.32</td>
<td>17.24 hr</td>
<td>97.92</td>
<td>21.33</td>
</tr>
<tr>
<td>Neptune</td>
<td>1.024 × 10²⁶</td>
<td>24,764</td>
<td>1.64</td>
<td>16.11 hr</td>
<td>28.80</td>
<td>23.61</td>
</tr>
<tr>
<td>Pluto</td>
<td>1.32 × 10²²</td>
<td>1,170</td>
<td>2.1</td>
<td>6.387 days</td>
<td>119.6</td>
<td>1.25</td>
</tr>
</tbody>
</table>

* 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
- **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° 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: Earth, 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)
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, first in-situ/lab analysis available (Hayabusa sample small)
- Main taxonomic classes (more classes exist, see table):
  - Indications/examples for differentiation of the internal structure of asteroids exists, however also for non-differentiation
  - A, S, V, R types: pyroxene and olivine absorptions
  - 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

Note: similarities between asteroid and meteorite spectra are used for classification and identification of surface materials
FIGURE 10  Red-sloped M, T, and E classes. These asteroids lack strong absorptions, but have large differences in albedo.
<table>
<thead>
<tr>
<th>Asteroid class</th>
<th>Inferred major surface minerals</th>
<th>Meteorite analogues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>Organics + anhydrous silicates? (+ice?)</td>
<td>None (cosmic dust?)</td>
</tr>
<tr>
<td>D</td>
<td>Organics + anhydrous silicates? (+ice?)</td>
<td>None (cosmic dust?)</td>
</tr>
<tr>
<td>P</td>
<td>Anhydrous silicates + organics? (+ice?)</td>
<td>None (cosmic dust?)</td>
</tr>
<tr>
<td>C (dry)</td>
<td>Olivine, pyroxene, carbon (+ice?)</td>
<td>“CM3” chondrites, gas-rich/blk chondrites</td>
</tr>
<tr>
<td>K</td>
<td>Olivine, orthopyroxene, opaques</td>
<td>CV3, CO3 chondrites</td>
</tr>
<tr>
<td>Q</td>
<td>Olivine, pyroxene, metal</td>
<td>H, L, LL chondrites</td>
</tr>
<tr>
<td>C (wet)</td>
<td>Clays, carbon, organics</td>
<td>CI1, CM2 chondrites</td>
</tr>
<tr>
<td>B</td>
<td>Clays, carbon, organics</td>
<td>None (highly altered CI1, CM2?)</td>
</tr>
<tr>
<td>G</td>
<td>Clays, carbon, organics</td>
<td>None (highly altered CI1, CM2?)</td>
</tr>
<tr>
<td>F</td>
<td>Clays, opaques, organics</td>
<td>None (altered CI1, CM2?)</td>
</tr>
<tr>
<td>W</td>
<td>Clays, salts?????</td>
<td>None (opaque-poor CI1, CM2?)</td>
</tr>
<tr>
<td>V</td>
<td>Pyroxene, feldspar</td>
<td>Basaltic achondrites</td>
</tr>
<tr>
<td>R</td>
<td>Olivine, pyroxene</td>
<td>None (olivine-rich achondrites?)</td>
</tr>
<tr>
<td>A</td>
<td>Olivine</td>
<td>Brachinites, pallasites</td>
</tr>
<tr>
<td>M</td>
<td>Metal, enstatite</td>
<td>Irons (+EH, EL chondrites?)</td>
</tr>
<tr>
<td>T</td>
<td>Troilite?</td>
<td>Troilite-rich irons (Mundrabilla)?</td>
</tr>
<tr>
<td>E</td>
<td>Mg-pyroxene</td>
<td>Enstatite achondrites</td>
</tr>
<tr>
<td>S</td>
<td>Olivine, pyroxene, metal</td>
<td>Stony irons, IAB irons, lodranites, windonites, siderophyres, urceilites, H, L, LL chondrites</td>
</tr>
</tbody>
</table>
• **Taxonomic class distribution in belt:**
  
  – 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 al.* (1989). (Courtesy of University of Arizona Press.)
Collision Effects

• **Impact craters**: exists in flyby images
  - Regolith surface
  - Impact events seen in asteroid belt
• **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 G3 V 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
  $a_j/a + 2 \left(a/a_j (1-e^{-2})\right)^{1/2} \cos i = C$

**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.)
Sizes, Shapes, Rotation

- **Sizes:**
  - 1000km $\rightarrow$ m $\rightarrow$ mm etc.
  - Only a few ones > 500km diameter
  - Size distribution N versus mass m:
    \[ N(m) \sim m^{-3} \]
    $\Rightarrow$ indicative for collision dominated size distribution

- **Shapes:**
  - Irregular except largest ones
    (spacecraft + radar + lightcurves)
  - Triaxial ellipsoids

- **Rotation:**
  - Fast rotators more frequent
    (irregular periodic lightcurves)
    $\Rightarrow$ in agreement with collision scenario, but strong bias from observations (long periods need longer observing time)
**Meteorites**

- **Summary**
  - Differentiated (associated with asteroids) and undifferentiated (primitive) meteorites
  - Chondrites: ‘uniform’ age $4.6 \times 10^9$ 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
Mars meteorite (SNC)

With signature of atmospheric ablations

Meteorite with crust

Only the upper few cms are heated during entry in the atmosphere, the interior remains at deeply frozen temperature
Meteorites in the sky and hitting a car

Allende meteorite
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)
Chondrites are subclassified in Chemical-Petrologic Types

Meteorites

Undifferentiated

Chondrites

Carbonaceous
CI CM CO CV CK

Ordinary
H L LL

Enstatite
EH EL

Differentiated

Irons

Many Groups

Stony-Irons

Mesosiderites
Pallasites

Achondrites

SNC (Mars)
Lunar

Stony-Irons

Aubrites
Ureilites

HED

Eucrites
Diogenites
Howardites
Note: almost all meteorites contain iron
First check: magnetism of probe
Verification: spallation isotope

Composition of chondrites is dominated by SiO₂, Fe₂O₃ and MgO
### Oxygen Isotopics & Solar Chemistry

- **Oxygen Isotopics**
  - Concept: mass-dependent process involving O will create $^{17}$O/$^{18}$O content with ratio $\frac{1}{2}$ (mass-fractionation: slow process with minor but measurable effects)
  - Earth, moon, many chondrites and some achondrites on $\frac{1}{2}$ fractionation line
  - Some other chondrites deviate
    - solar system was created from a non-heterogeneous (O) isotopic mixture (most likely of pre-solar origin)
• Isotopic composition CI to solar photosphere:
  – 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 $10^{11}$ 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** *(carbonaceous chondrites):*
  - 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)

⇒ Obs. indications for water ice in the asteroid belt: water ice absorption in Themis, main belt comets
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 $t$
    
    $$D_t = D_0 + M_0 - M_t = D_0 + M_t (e^{-\lambda t} - 1) \quad (1)$$
  
  $D_0, M_0 = \text{daughter (unknown), mother (measured) nuclides at 'locking' time}$
  
  $D_t, M_t = \text{daughter, mother nuclides measured in lab}$
  
  $\lambda = \text{decay time of isotope}$

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

  $$\frac{(D / D_x)_t}{(D / D_x)_0} = \frac{(M / D_x)_t}{(M / D_x)_0} (e^{-\lambda t} - 1)$$

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

  $$t = \frac{1}{\lambda} \ln \left( 1 + \frac{(D / D_x)_t - (D / D_x)_0}{(M / D_x)_t} \right)$$

  Formation age = time of crystalisation
  Radiation age = duration of high energy irradiation in space

  Nuclides used:

  - $^{87}\text{Rb} \rightarrow ^{87}\text{Sr}, 4.9 \times 10^{10} \text{ y}$
  - $^{187}\text{Re} \rightarrow ^{187}\text{Os}, 5 \times 10^{10} \text{ y}$
  - $^{40}\text{K} \rightarrow ^{40}\text{Ar}, 1.25 \times 10^9 \text{ y}$
  - $^{129}\text{I} \rightarrow ^{129}\text{Xe}, 1.7 \times 10^7 \text{ y}$
Age determination of meteorites

**Recipe:**

- measure radioactive isotopes “mother” & “daughter”
- plot linear relation
- determine slope \( m = \exp(\lambda t) - 1 \)
- determine \( y_o = (D / D_x)_o \)
- calculate age
Solidification age of chondrites

- $4.56 \times 10^9 \pm 10^7$ 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 $^4$Ar.

**Figure 26** $^{136}$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)

![Graphs showing cosmic ray exposure age for different types of meteorites.](https://example.com/graphs)

**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 meteor-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

**Moon:** old surface modeled by early and late heavy bombardment

**Earth:** young surface due to tectonics, erosion, life
Cratering and planetary system formation

Impact Rates, Top of Earth's Atmosphere

Meteorite impact Rate vs. Time

planet formation

Earth data

lunar data

A?

B?

W

W

W

W

at $V = 20\text{km/s}$

at $V = 10\text{km/s}$

$1$ impact per year on Earth

$1$ impact per $10^6\text{y}$ on Earth

log$_{10}$ cumulative no. impacts of mass $> M\text{kg}$

$1\mu\text{m}$ $1\text{mm}$ $1\text{cm}$ $10\text{cm}$ $1\text{m}$ $10\text{m}$ $10\text{cm}$ $1\text{m}$ $10\text{m}$ $100\text{m}$ $1\text{km}$ $10\text{km}$ $100\text{km}$

$100\text{m}$ $1\text{km}$ $10\text{km}$ $100\text{km}$

$10^6$ $10^5$ $10^4$ $10^3$ $10^2$ $10^1$ $10^0$ $10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$ $10^{-5}$ $10^{-6}$

$10^{-15}$ $10^{-10}$ $10^{-5}$ $10^{-1}$ $10^{-15}$ $10^{-20}$ $10^{-25}$ $10^{-30}$

$\log_{10}$ meteoroid mass $M$ (kg)

meteoroid diameter ($\rho = 2500\text{ kg/m}^3$)

$5$ $4$ $3$ $2$ $1$ $0$

time before present (Gy)

today
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)
  \( \Rightarrow \) no extreme hyperbola found
  \( (e >> 1; \text{max. } 1.005) \)
  \( \Rightarrow \) 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 \( (P < 200 \text{ y}) \)
    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 $(1/a)_{\text{new}} < 5 \times 10^{-3} \text{AU}^{-1}$.

FIGURE 2 Inclination distributions of (a) long-period comets discovered after 1758 (the Krescz family of sungrazing comets has been considered as a single comet, as well as C/1988F1 and C/1980F1, which move in similar orbits), (b) intermediate-period comets with 20 ≤ P ≤ 200 yr, and (c) short-period comets with P ≤ 20 yr.
Nature

• **Nucleus:** 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)
How do they look like?

Comet Halley by Giotto

Comet Borrelly by DEEPSPACE 1

Comet Tempel 1 by DeepImpact

Comet Wild2 by STARDUST
Coma: activity develops when nucleus is heated close to the Sun (on sunward side)
- Extension: \(5 \times 10^4 - 3 \times 10^6\) km
- Frozen ice sublimates to gas
  - \(\text{H}_2\text{O}: \sim 80\%\) ice
  - \(\text{CO} + \text{CO}_2 + \text{H}_2\text{CO}: 4+3+2\)
    (distant activity to several 10 AU)
- Lots of organics identified
- Embedded dust is accelerated by gas
  - Mass ratio gas:dust 0.1-10
  - Silicate (fosterite), CHON, metallic
  - crystalline (hot) & amorphous (cold) silicates \(\rightarrow\) protosolar nebula got mixed up before comet formation
- Total production rates (gas, dust)
  - \(10^{23}-10^{32}\) molecules/s
    (several 100 tons/s max)
  - \(\rightarrow\) mass loss \(\sim 10000\) revolutions lifetime in inner solar system
  - \(\rightarrow\) 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. 5, p528 Encycl.**

**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 Ol Pyr 8%), and amorphous pyroxene (Am Pyr 70%). From Corradi et al. (2001).
## Table I

**Chemical Species Identified in Comets**

<table>
<thead>
<tr>
<th>Identification by radio, microwave, IR, visual, and UV spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
</tr>
<tr>
<td>C$_2$H$_4$</td>
</tr>
<tr>
<td>C$<em>6$N$</em>{12}$</td>
</tr>
<tr>
<td>NH$_3$</td>
</tr>
<tr>
<td>C$_6$</td>
</tr>
</tbody>
</table>

Identification by mass spectra

<table>
<thead>
<tr>
<th>Mass</th>
<th>Ions</th>
<th>Neutrals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H$^+$</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>C$^+$</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>CH$^+$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>CH$_2^+$</td>
<td>N$^+$</td>
</tr>
<tr>
<td>15</td>
<td>CH$_3^+$</td>
<td>NH$^+$</td>
</tr>
<tr>
<td>16</td>
<td>O$^+$</td>
<td>CH$_2^+$</td>
</tr>
<tr>
<td>17</td>
<td>OH$^+$</td>
<td>NH$_3$</td>
</tr>
<tr>
<td>18</td>
<td>H$_2$O$^+$</td>
<td>NH$_2$</td>
</tr>
<tr>
<td>19</td>
<td>H$_2$O$^+$</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Na$^+$</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>CO</td>
<td>N$_2$</td>
</tr>
<tr>
<td>30</td>
<td>H$_3$CO</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>H$_2$CO$^+$</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>H$_2$S$^+$</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>C$^+$</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>CH$_2^+$</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>CH$_4^+$</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>CO$_2$</td>
<td></td>
</tr>
</tbody>
</table>

## Table II

**Identified Interstellar Molecules in the Gas Phase**

<table>
<thead>
<tr>
<th>H$_2$</th>
<th>C$_2$</th>
<th>CO</th>
<th>CS</th>
<th>NaCl$^+$</th>
<th>HCl</th>
<th>SO</th>
<th>SiS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlCl$^+$</td>
<td>KCl$^+$</td>
<td>P Nil</td>
<td>SiF$^+$</td>
<td>SiH$^+$</td>
<td>HFP$^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>SO$_2$</td>
<td>H$_2$S</td>
<td>OCS</td>
<td>HNO</td>
<td>C$_2$</td>
<td>HCN</td>
<td>C$_2$O</td>
</tr>
<tr>
<td>HNC</td>
<td>SiC$^+$</td>
<td>NH$_3$</td>
<td>N$_2$</td>
<td>MgNC$^+$</td>
<td>MgCN$^+$</td>
<td>NaCN$^+$</td>
<td></td>
</tr>
<tr>
<td>NH$_3$</td>
<td>HCN</td>
<td>CH$_4$</td>
<td>HNCO</td>
<td>HNCS</td>
<td>CS</td>
<td>H$_2$CO</td>
<td>H$_2$S</td>
</tr>
<tr>
<td>C$_2$H$_5$</td>
<td>HCN</td>
<td>CH$_3$OH</td>
<td>CH$_3$CN</td>
<td>C$_3$H$^+$</td>
<td>CH$_2$OH</td>
<td>CH$_3$C$_2$</td>
<td>CH$_3$SH</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>SiH$_4$</td>
<td>C$_2$</td>
<td>HCN</td>
<td>C$_2$S$^+$</td>
<td>OHCHO</td>
<td>H$_2$CNH</td>
<td>CH$_3$CN</td>
</tr>
<tr>
<td>H$_2$NCN</td>
<td>CH$_2$CO</td>
<td>CH$_4$</td>
<td>HCCNC</td>
<td>HNCC</td>
<td>CH$_3$CN</td>
<td>C$_2$H$_4$</td>
<td>CH$_3$OH</td>
</tr>
<tr>
<td>H$_2$NCCN</td>
<td>CH$_2$CN</td>
<td>NH$_2$CHO</td>
<td>CH$_2$CHO</td>
<td>CH$_2$C$_2$</td>
<td>CH$_2$OH</td>
<td>CH$_3$C$_2$</td>
<td>CH$_3$SH</td>
</tr>
<tr>
<td>HCN</td>
<td>CH$_2$CN</td>
<td>CH$_2$CO</td>
<td>CH$_2$CN</td>
<td>CH$_2$CN</td>
<td>CH$_2$OH</td>
<td>CH$_2$CH$_3$</td>
<td>CH$_3$H</td>
</tr>
<tr>
<td>CH$_3$CN</td>
<td>CH$_2$CN</td>
<td>(CH$_2$)CO</td>
<td>HCN</td>
<td>CH$_3$CN</td>
<td>C$_2$H$_4$</td>
<td>CH$_3$CN</td>
<td>CH$_3$CN</td>
</tr>
<tr>
<td>CH$_3$</td>
<td>HCO</td>
<td>CH</td>
<td>CN</td>
<td>NO</td>
<td>NS</td>
<td>NH</td>
<td>SO</td>
</tr>
<tr>
<td>SO$^+$</td>
<td>HCO</td>
<td>C$_2$S</td>
<td>C$_2$H</td>
<td>CH$_2$</td>
<td>C$_2$H</td>
<td>CH$_2$CN</td>
<td>CH$_2$H</td>
</tr>
</tbody>
</table>

$^1$ Detection only in the envelopes around evolved stars.

$^2$ Claimed but not yet confirmed.
- **Dust Tail**: 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

\[ F_{\text{total}} = F_{\text{grav}} + F_{\text{rad}} = ma \ e_r \]

\[ F_{\text{grav}} = -\gamma m M / r^2 \ e_r \]

\[ F_{\text{rad}} = \frac{LA}{4\pi cr^2} \ Q \ e_r \]

\[ ma \ e_r = -\gamma m M / r^2 \ e_r + \frac{LA}{4\pi cr^2} \ Q \ e_r \]

\[ = F_{\text{grav}} (1 - \beta) \]

with

\[ \beta = \frac{LA}{4\pi c Q \gamma m M} \]  

(radiation pressure coefficient)

- 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

\[ \Rightarrow \text{synchernes & syndynes} \]
**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**

<table>
<thead>
<tr>
<th>Element</th>
<th>Comet P/Halley</th>
<th>CI-Chondrites</th>
<th>Solar Photosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2025</td>
<td>4062</td>
<td>520</td>
</tr>
<tr>
<td>C</td>
<td>814</td>
<td>1010</td>
<td>74</td>
</tr>
<tr>
<td>N</td>
<td>42</td>
<td>95</td>
<td>5.9</td>
</tr>
<tr>
<td>O</td>
<td>890</td>
<td>2040</td>
<td>748</td>
</tr>
<tr>
<td>Na</td>
<td>10</td>
<td>10</td>
<td>5.61</td>
</tr>
<tr>
<td>Mg</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Al</td>
<td>6.8</td>
<td>6.8</td>
<td>8.32</td>
</tr>
<tr>
<td>Si</td>
<td>185</td>
<td>185</td>
<td>97.7</td>
</tr>
<tr>
<td>S</td>
<td>72</td>
<td>72</td>
<td>43.7</td>
</tr>
<tr>
<td>K</td>
<td>0.2</td>
<td>0.2</td>
<td>0.363</td>
</tr>
<tr>
<td>Ca</td>
<td>6.3</td>
<td>6.3</td>
<td>6.31</td>
</tr>
<tr>
<td>Ti</td>
<td>0.4</td>
<td>6.4</td>
<td>0.234</td>
</tr>
<tr>
<td>Cr</td>
<td>0.9</td>
<td>0.9</td>
<td>1.32</td>
</tr>
<tr>
<td>Mn</td>
<td>0.5</td>
<td>0.5</td>
<td>0.912</td>
</tr>
<tr>
<td>Fe</td>
<td>52</td>
<td>52</td>
<td>83.2</td>
</tr>
<tr>
<td>Co</td>
<td>0.3</td>
<td>0.3</td>
<td>0.224</td>
</tr>
<tr>
<td>Ni</td>
<td>4.1</td>
<td>4.1</td>
<td>4.90</td>
</tr>
</tbody>
</table>

* 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.


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

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Abundance</th>
<th>Molecule</th>
<th>Abundance</th>
<th>Molecule</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>100</td>
<td>H₂CO</td>
<td>0–5</td>
<td>N₂</td>
<td>~0.02</td>
</tr>
<tr>
<td>CH₃</td>
<td>0–2</td>
<td>CH₃OH</td>
<td>&lt;1</td>
<td>NH₃</td>
<td>1–2</td>
</tr>
<tr>
<td>CO</td>
<td>7–8</td>
<td>OCS</td>
<td>&lt;7</td>
<td>HCN</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>CO₂</td>
<td>3</td>
<td>CS₂</td>
<td>1</td>
<td>SO₂</td>
<td>&lt;0.002</td>
</tr>
</tbody>
</table>
Isotopic ratios suggest that cometary material is home-made, i.e. typical for the solar system.

### 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

#### TABLE V

<table>
<thead>
<tr>
<th>Species</th>
<th>Solar system</th>
<th>Interstellar matter</th>
<th>Comets</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/H</td>
<td>1 to 2 × 10⁻⁵</td>
<td>1.5 × 10⁻⁵</td>
<td>3.2 × 10⁻¹⁴</td>
</tr>
<tr>
<td>D/H</td>
<td>10⁻¹ to 3 × 10⁻⁴</td>
<td>1.9 to 3.5 × 10⁻¹⁴</td>
<td></td>
</tr>
<tr>
<td>^12C/^13C</td>
<td>89</td>
<td>43 ± 4</td>
<td>95 ± 12</td>
</tr>
<tr>
<td>^12C/^13C</td>
<td>65 ± 20</td>
<td>70 to 130</td>
<td></td>
</tr>
<tr>
<td>^12C/^13C</td>
<td>12 to 110</td>
<td>10 to 1,000</td>
<td></td>
</tr>
<tr>
<td>^14N/^15N</td>
<td>272</td>
<td>≈400</td>
<td>&gt;200</td>
</tr>
<tr>
<td>^16O/^18O</td>
<td>498</td>
<td>≈400</td>
<td>493</td>
</tr>
<tr>
<td>^24Mg/^25Mg</td>
<td>7.8</td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>^25Mg/^24Mg</td>
<td>0.9</td>
<td>&lt;2</td>
<td></td>
</tr>
<tr>
<td>^32S/^34S</td>
<td>22.6</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>^56Fe/^54Fe</td>
<td>15.8</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

*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.
Oort Cloud formation – The movie

• **Start:** planetesimals in planetary disk between Jupiter and Neptune

• **Clean-up:** by gravitational scattering of gas giants

• **Thermalization:** through galactic neighbourhood

• **Return of Oort Cloud comet:** 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)
  - ~1500 TNOs discovered so far

- **Brightness:**
  - 20-28mag and fainter
  - slow moving
  - Discovered in wide and deep survey
  - $T \sim 40K \Rightarrow$ thermal emission in submm radio range
The Transneptunian Region and its dynamical Population

- Cubiwanos
- Plutinos
- ShortP.
- Comets
- Centaurs
- Scattered
Dynamical Classification

- Plutinos:  \(a \sim 39 \text{ AU}\)
  \(e \sim 0.1 - 0.3\)
  \(\rightarrow\) 2:3 resonance with Neptune
- Cubewanos:  \(a \sim 40 - 46 \text{ AU}\)
  (classical disk)  \(e < 0.1\)
  \(\rightarrow\) outside of planet resonance
- Scattered Disk:
  \(a > 50 \text{ AU} \& q < 35\text{AU}\)
- Centaurs:
  Jupiter …. Neptune
  \(\rightarrow\) “eccentric” KB members
  no resonance beyond 2:1 \(\sim 50 \text{ AU}\)
- Detached Disk:
  \(a > 50 \text{ AU} \& q > 50\text{AU}\)

\(-\) Plutinos, Cubewanos, detached disk objects are in dynamically stable orbits
\(-\) Scattered disk will have encounters with planets (Neptune)
\(-\) Centaurs are transferred from EKB to inner solar system within \(~10 \times 10^6 \text{ y}\)
\(\rightarrow\) 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 ln KB < 50 AU | Approx. Radius [km]
---|---|---|---
< 24 | 2.7 | 270000 | 110
< 26 | 33 | 330000 | 45
< 28 | 390 | 3900000 | 20
Physical Properties

- **Size & Shape:** 50-1200km radius
  - Pluto = 2nd 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

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

Simulation of reddening changes
• Surface chemistry: some with water/methane ice absorption,
• One case of hydrated silicate detected → surprise liquid water?

visible spectra: mostly featureless
Pluto & Charon (since 1978)
- Orbit: stable in past, chaotic after ~ 2 $10^7$ y
- Size: 1200/600km radius, 2$^{nd}$ largest TNO
- Density: $\sim 1.9 \text{ g/cm}^3$ (high! $\Rightarrow$ 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 $\Rightarrow$ resurfacing
- Surface: P: CH$_4$, N$_2$, CO  T $\sim$ 45-60K patchy
  C: H$_2$O, 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
  \[ \Rightarrow \text{more} \ 1000-10000 \ \text{Earth masses needed in Kuiper Belt region} \]
  \[ \Rightarrow \text{More than one Pluto is formed (Eris & Sedna & Triton)} \]

(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) \( \Rightarrow \) 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**

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

**FIGURE 3** Comparison of meteoroid sizes and masses covered by different observational methods.
Leonid meteor stream

Zodiacal light
• **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**

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>RA</th>
<th>DEC</th>
<th>Speed</th>
<th>Rate</th>
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<td>48</td>
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<td>May 3</td>
<td>336</td>
<td>-2</td>
<td>66</td>
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<td>P/Halley</td>
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<td>June Lyrids</td>
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<td>S. Delta Aquarids</td>
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<td>327</td>
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<td>3000 (1966)</td>
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<td>217</td>
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<td>33</td>
<td>20</td>
<td>P/Tuttle</td>
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</table>

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

<table>
<thead>
<tr>
<th>Element</th>
<th>C1</th>
<th>IDP</th>
<th>Variation</th>
<th>$T_c$ (°C)</th>
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<td>0.9</td>
<td>0.6–1.1</td>
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<td>0.8–1.7</td>
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<tr>
<td>Fe</td>
<td>900,000</td>
<td>1</td>
<td>1</td>
<td>1336</td>
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<tr>
<td>S</td>
<td>515,000</td>
<td>0.8</td>
<td>0.6–1.1</td>
<td>648</td>
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<td>Al</td>
<td>84,900</td>
<td>1.4</td>
<td>0.8–2.3</td>
<td>1630</td>
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<td>2.0–2.5</td>
<td>1000</td>
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<td>1.9–4.2</td>
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<td>Ge</td>
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<td>Br</td>
<td>12</td>
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<td>23–50</td>
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</table>

*The IDP abundances are normalized to iron (Fe) and to C1. C1 abundance is normalized to 8.0 1000,000 condensation temperatures $T_c$ (°C). From E. K. Jessberger et al. (1992), *Earth Planet. Sci. Lett.* 112, 91–99.*

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**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^{-16} g. The zodiacal core population comprises particles of all sizes, whereas the asteroidal population comprises only big (>10^{-16} g) particles.
• **Lifetime of dust:** 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 $\beta$ 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 21** Orbits of beta-meteoroids that were generated from a parent body at the position indicated by the asterisk. $\beta$ values of differently sized fragments are indicated; big $\beta$ values refer to small particles.

**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.
Mass flow of IDPs

Lifetime of IDPs
- radiation pressure
- collision

**FIGURE 25** Life-times of meteoroids in interplanetary space with respect to destruction by collisions $\tau_c$ and transport to the Sun by the Poynting–Robertson effect $\tau_{PR}$ 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 $\Rightarrow 4.56 \times 10^9$ a
    $\Rightarrow$ not necessarily in present stellar neighbourhood, but probably in star cluster
    (Galactic rotation and differential motion of stars, proper motion of the Sun)

• For formation time scales:
  – Meteorites, i.e. cm$\rightarrow$m size bodies $\pm 10 \times 10^6$ y around formation time
  – Oldest impact craters (on moon) $\sim 4.3 \times 10^9$ y
    $\Rightarrow$ planet (moon!) formation widely 'finished' within $100 \times 10^6$ y from chondrite formation

• For the typical size and geometry (some times during formation process):
  – Kuiper Belt extension $\sim 50$ 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
    $\Rightarrow$ flat disk-shape geometry
  – Mass concentrated in Sun, angular momentum in planets

• Objects produced:
  – Sun (star) $\quad 1$ solar mass
  – Terrestrial planets $\quad 10^5$ solar mass
  – Gas giants $\quad 10^3$ solar mass
  – Icy planetesimals and fragile comets $\quad 10^3$ solar mass

\textit{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 ~ GM²/R ~ GMρR²
    (M,R = mass/radius of cloud, G = grav. Const)
    thermal energy ~ Mv_s² ~ k²MT² (v_s/T = speed of sound/temperature in cloud)
    
    \[ R = \left(\frac{\pi v_s^2}{G\rho}\right)^{1/2} \quad \text{(Jeans criterion)} \]
    
    → from star forming regions:
    \[ R \sim 0.1 \text{ pc (3 } \times 10^{15} \text{ m), T \sim 10K} \]

    collapse time scale: \( t \sim R/v_s \sim 10^6 \text{y} \)
    min. mass involved for protosolar nebula \( \sim 1.02 \) solar mass (Sun+planets)
Step 2 – Disk formation:
- 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: $2 \times 10^7$ y
- Most of mass in Sun
- Disk thickness ~ 1/10 diameter
- Inner disk ($\sim 1$ AU) is hot $>1500$K dust vaporizes, lighter molecules dissociates (not heavier ones) mass ~ 0.03 solar masses
- Outer disk ($>2$ AU) remains cool dust intact, more molecular gas
Step 3 – Growth of cm/m size grains (meteorites):

- 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

\[
dm/dt \sim a^3 v\rho_{\text{dust}} \quad (a/\rho_{\text{dust}} = \text{radius/density of dust})
\]

\[v \sim \text{speed of dust settling towards disk plane}\]

Important: 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
• **Step 4 – Growth of planetesimals:**
  - 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

• **Step 5 – Runaway accretion of planets:**
  - 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 of numbered bodies as a function of mass and accretion mass.
(a) Initial conditions. Ac = 0 for the planetesimal model and 100 AU in a binary system. (b) The evolution in time, from the start of the simulation, shows the growth of planetesimals. Growth is "runaway" due to the gravitational interaction between planetesimals. (c) The evolution in time of the distribution of planetesimal sizes for the case with no dynamical friction. (d) The evolution in time of the distribution of planetesimal sizes for the case with dynamical friction. (e) The evolution in time of the distribution of planetesimal sizes for the case with dynamical friction, with gravitational effects included. (f) The evolution in time of the distribution of planetesimal sizes for the case with dynamical friction and gravitational effects included.
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: H₂, He disk gas too 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 H₂, He gas since in colder environment

Time scale: $10^7$-$10^8$ y
• Some notes to step 6:
  – 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
→ 'thermalization' 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

• **End of the spectaculum:**
  ~ 4 \(10^9\) y from now
**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 destroyed 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 delivers further volatile gases
  - original atmosphere (reducing character) forms

- **Giant planets:** hot core is surrounded by dense $\text{H}_2/\text{He}$ atmosphere, i.e. efficient cooling of core, gets colder and solid again in parallel differentiation of gas atmosphere ($\text{H}_2$ 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: 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?

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