ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM:
An overview

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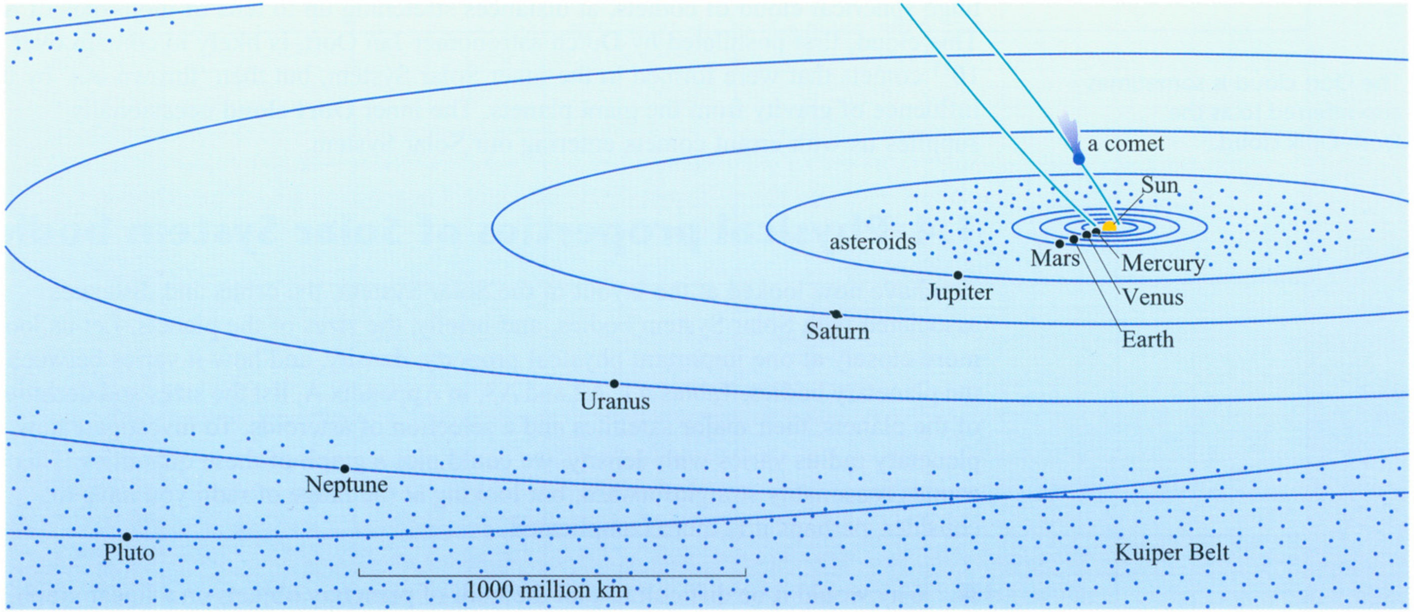
∗ Basic features of the solar system
∗ First cosmogonic theories and the angular momentum problem
∗ The observation of disks around stars
∗ The protoplanetary disk: physical features
∗ Accretion of grains into planetesimals and growth to planets
∗ Planet migration and scattering of residual planetesimals
∗ Some reflections about the discovered extrasolar systems
∗ Residual populations: comets, asteroids and TNOs
∗ Some further problems: the early heavy bombardment, the origin of the ocean water, the formation of the Moon

The solar system



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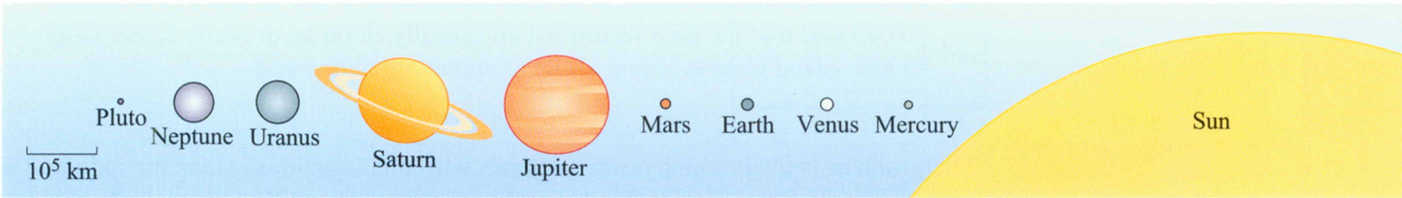

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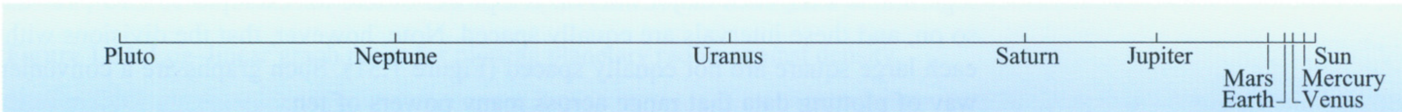


(c)

Planets and some 'dwarf planets'

Planet	Hel. distance (AU)	Mass ($M_\oplus$)	R (km)	Mean density (g cm^{-3})	No. satellites
Mercury	0.39	0.06	2440	5.43	0
Venus	0.72	0.82	6051	5.20	0
Earth	1.00	1.00	6371	5.52	1
Mars	1.52	0.11	3390	3.93	2
Ceres	2.77	1.58×10^{-4}	490	2.1	0
Jupiter	5.20	318	71492	1.33	63
Saturn	9.54	95.2	60268	0.69	47
Uranus	19.19	14.5	25559	1.32	27
Neptune	30.07	17.1	24766	1.64	13
Pluto	39.52	0.0021	1137	2.05	3
Eris	67.67	0.0028	1200	2.3	1

$\underline{Basic features}$:

∗ Near coplanarity and circularity of comets' orbits

∗ The Sun concentrates 99.9% of the total mass of the system

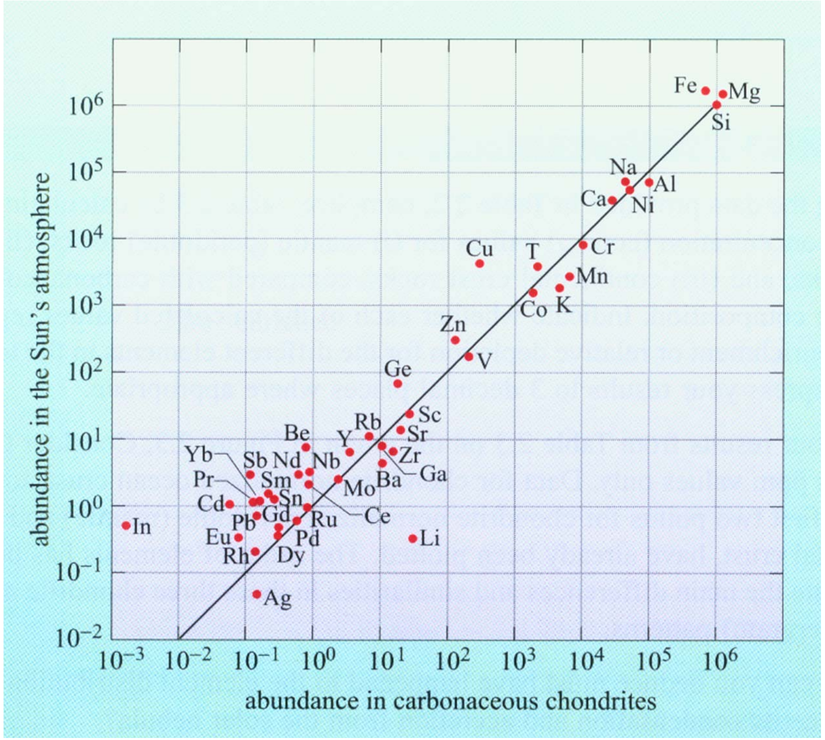
∗ The Sun contains only about 2% of the total angular momentum

∗ Terrestrial planets: rocky; Jovian planets: icy and gaseous

∗ Planets are at least 100 times more massive than the rest of the bodies of their neighborhood

The most primitive material is the lest differenciated in terms of elemental abundances

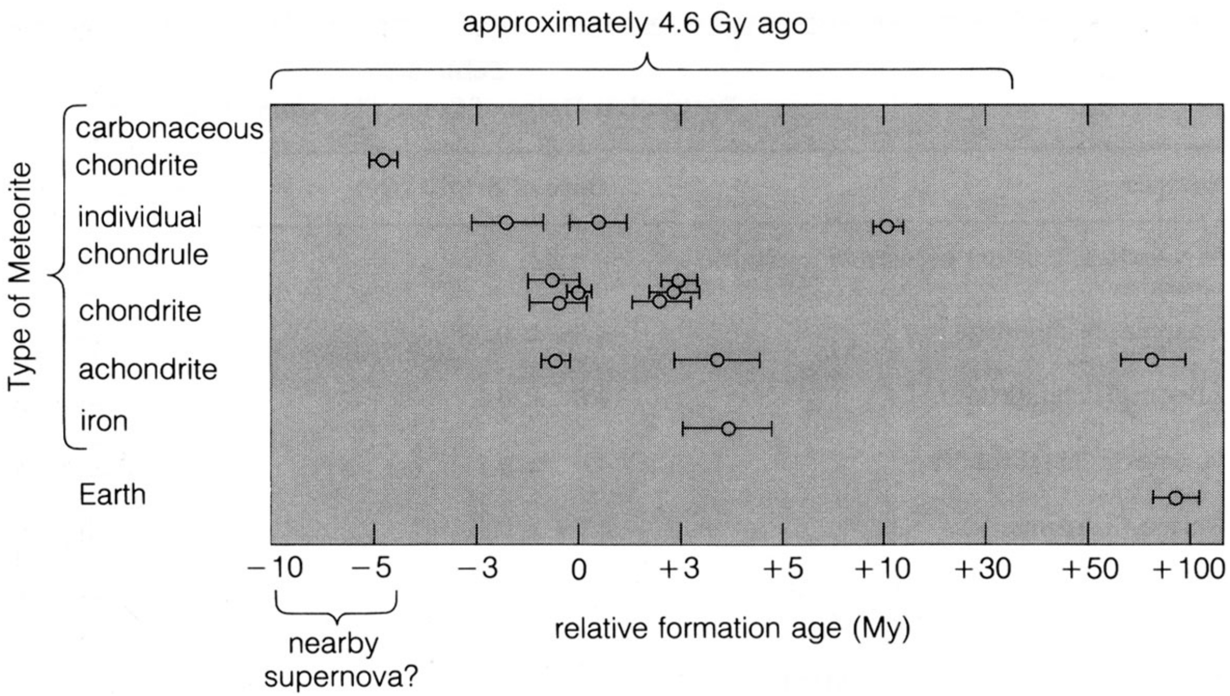
Example: Carbonaceous meteorites



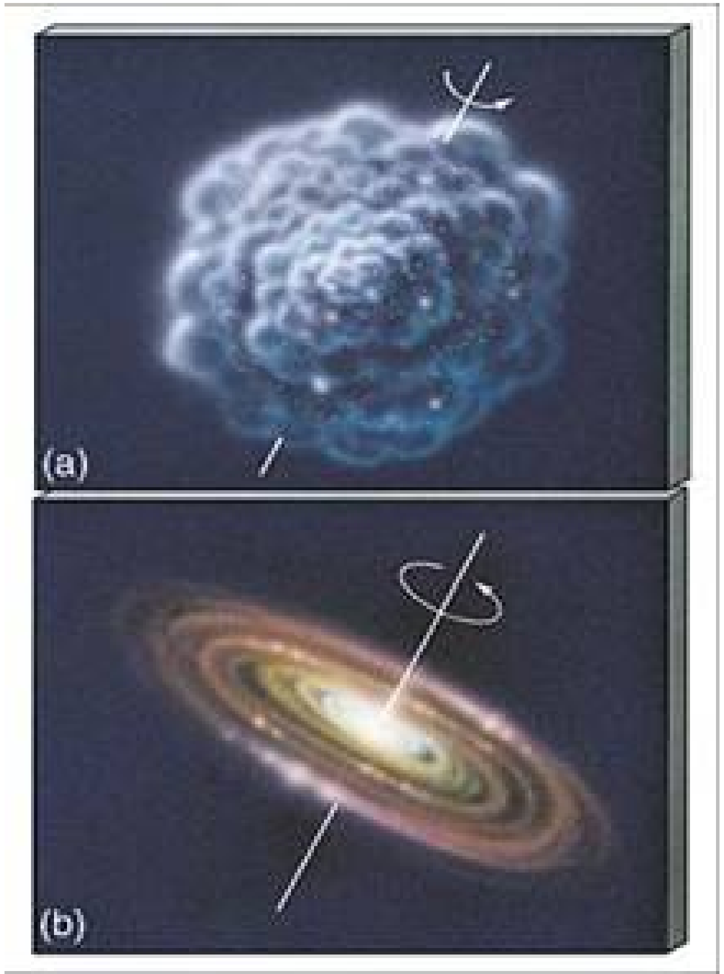
Determination of ages by radioactive decay

Half-lives of selected isotopes commonly used in geochronology

Parent	Stable daughter(s)	Half-life $t_{1/2}$ (Gyr)
^{40}K	^{40}Ar, ^{40}Ca	1.25
^{87}Rb	^{87}Sr	48.8
^{232}Th	^{208}Pb, ^{4}He	14
^{235}U	^{207}Pb, ^{4}He	0.704
^{238}U	^{206}Pb, ^{4}He	4.47



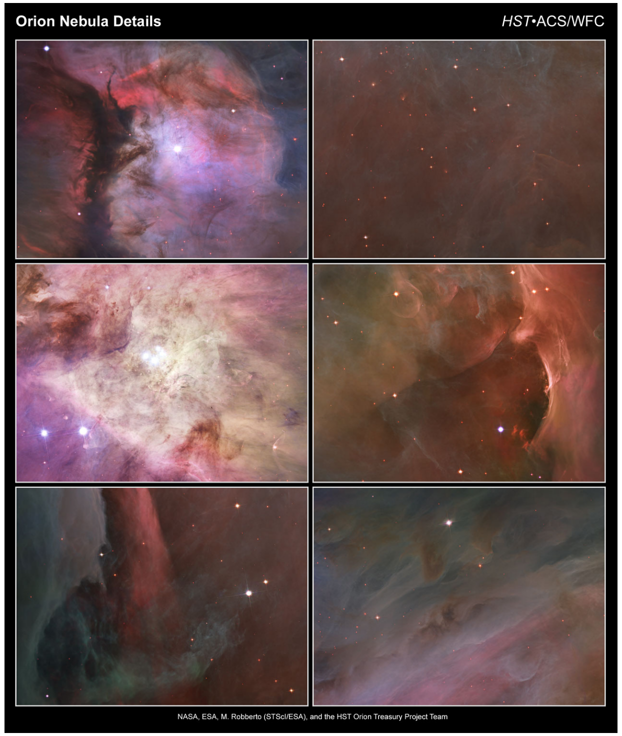
First cosmogonic theories: the solar nebula (Kant, Laplace)



Conservation of angular momentum:

$$H = I\omega, \qquad I: \text{ moment of inertia } = \alpha M R^2, \ \omega: \text{ angular velocity}$$

Star formation in interstellar molecular clouds



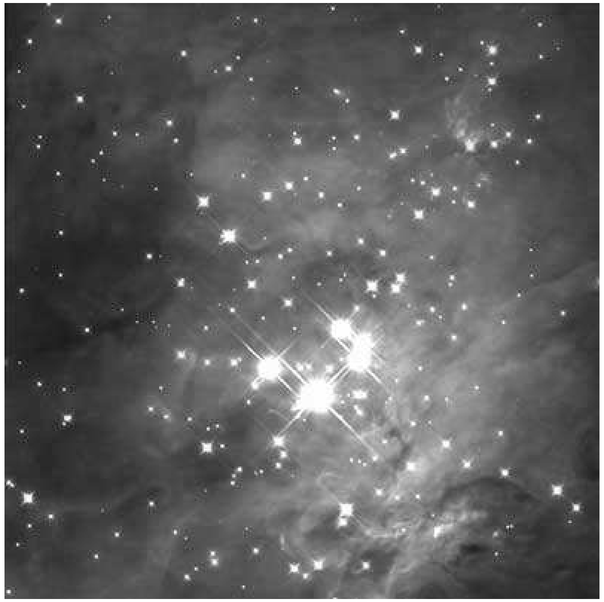
Typical physical parameters of Giant Molecular Clouds:

Temperature : $T \simeq 10$ K

Mass : 10^5 - 10^6 $M_\odot$

Diameter : ~ 50 pc

Average density : $\sim 10^2$ H_2 cm^{-3} (up tp $\sim 10^{5-6}$ H_2 cm^{-3} in dense cores)



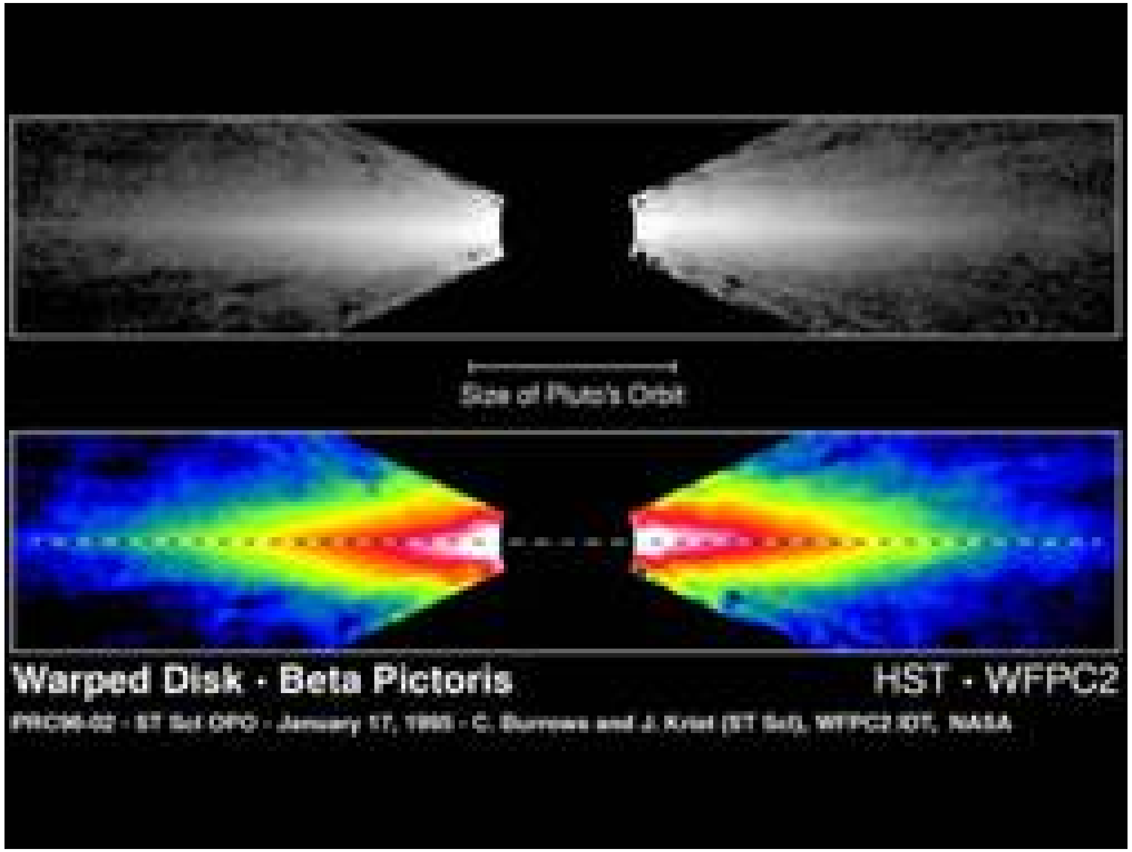
The Jeans criterion for collapse of a gas cloud of density n and temperature T:

Self-gravity $>$ Thermal pressure $\Rightarrow$

$$M_J \approx 10 \frac{T^{3/2}}{\sqrt{n}} \ \mathrm{M}_\odot$$

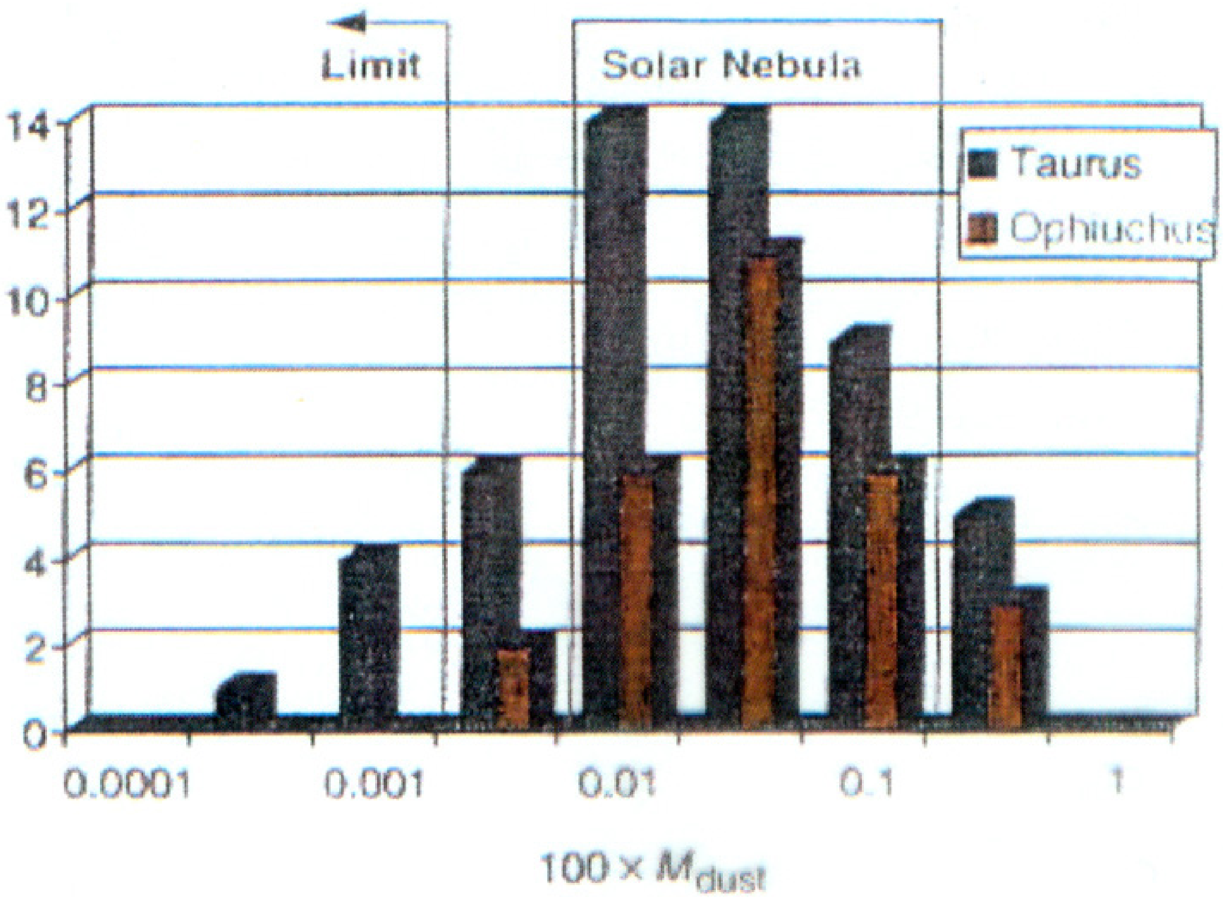
In a dense core $M_J \simeq 1$ $\mathrm{M}_\odot$

The first discovered disks by the IRAS satellite (1984)

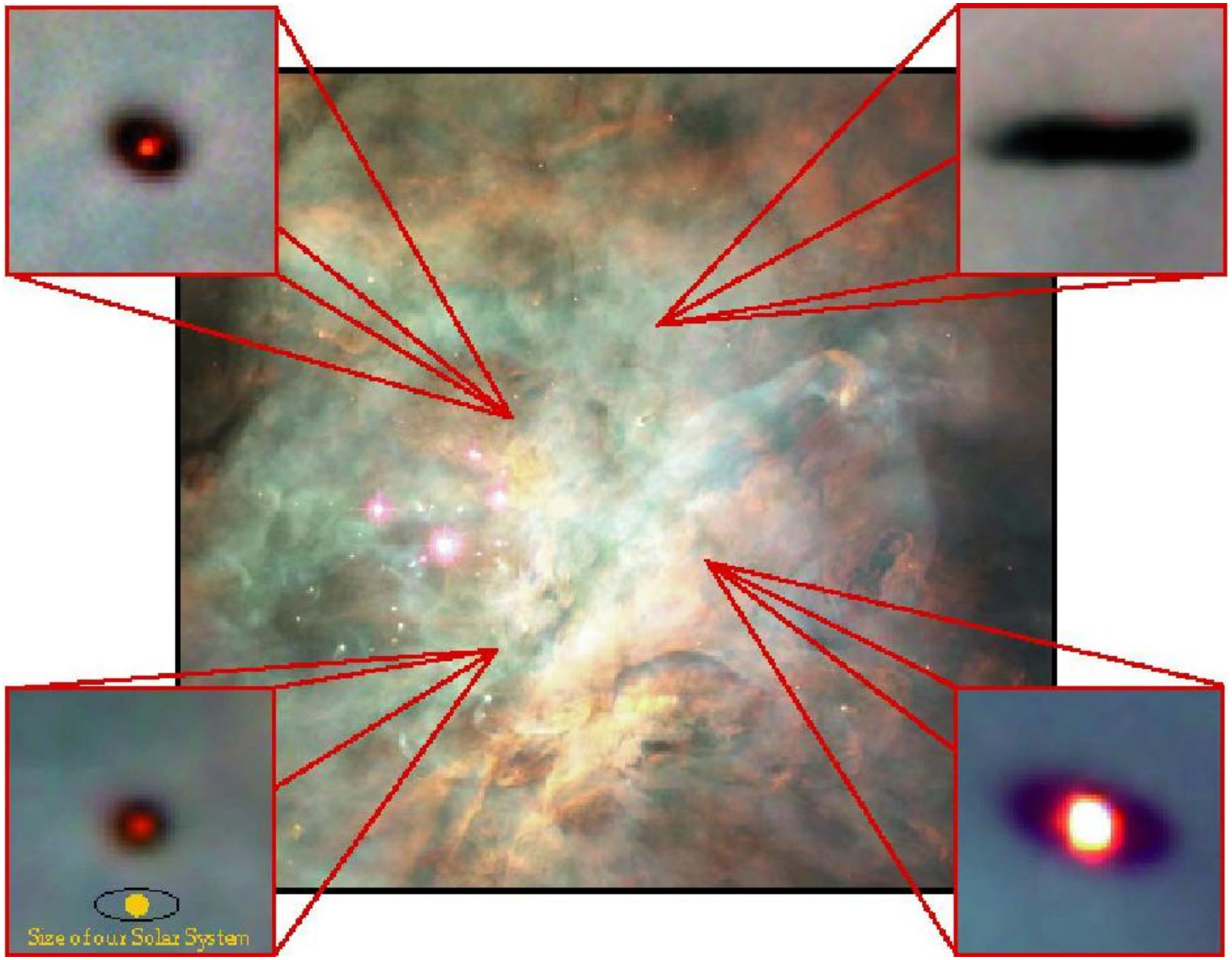


Masses of the disks

Methods for estimating:
∗ Infrared excess (dust content)
∗ CO emission line at 2.6 mm (gas content)

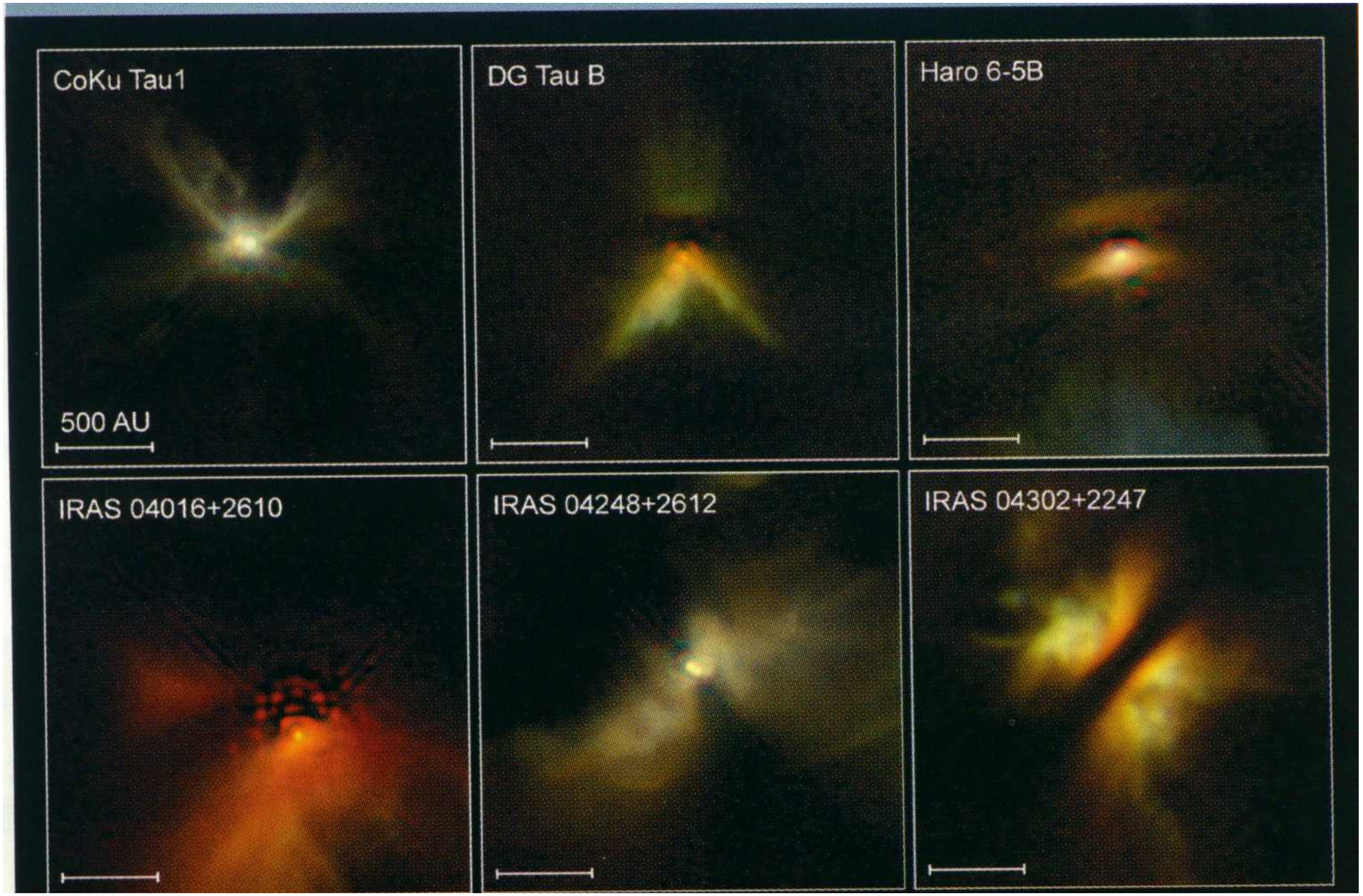


Protoplanetary disks in the Orion nebula



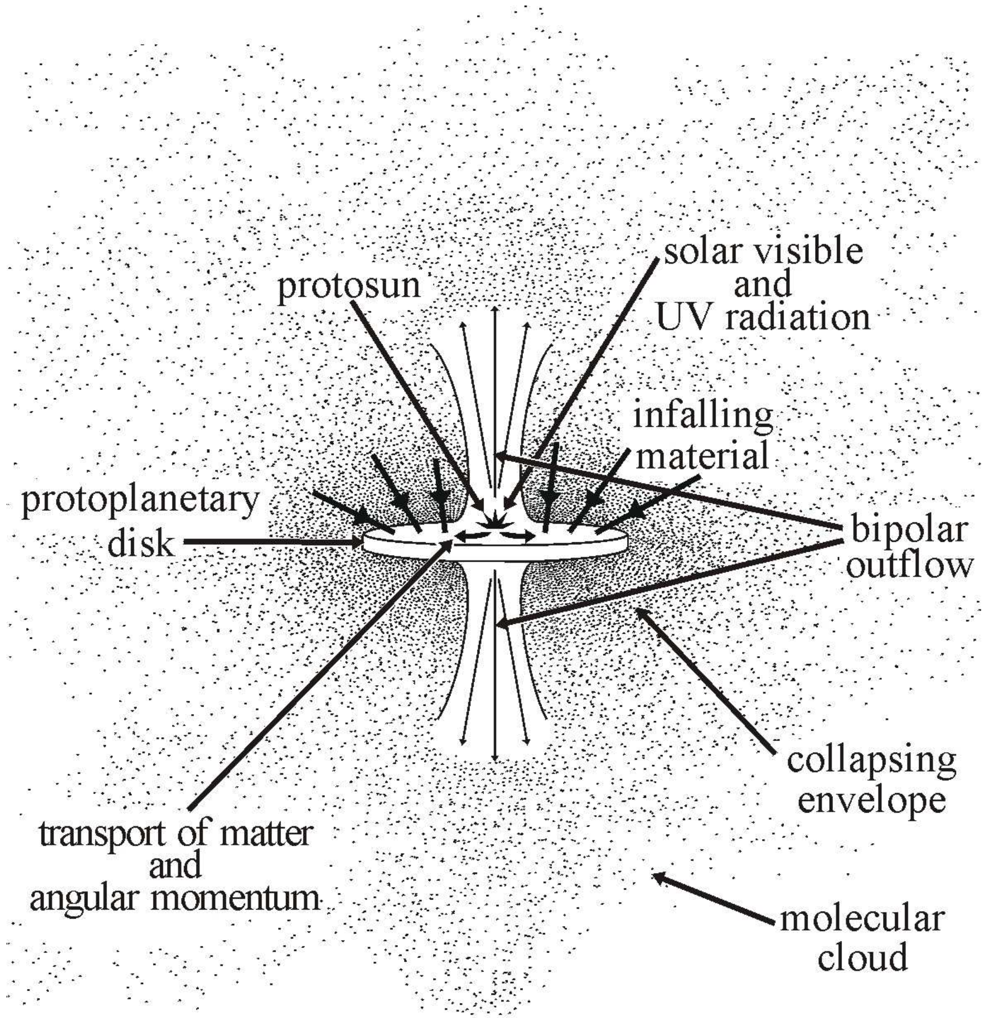
HST images

Some examples of edge-on protoplanetary disks



Lifetime : $\sim 10^7$ yr. Gas is blown away by the strong UV flux from nearby O and B stars, and/or removal by strong (T-Tauri) winds from the central star

Collapsing nebula and formation of a protoplanetary disk: A summary



Physical properties of the protoplanetary disk

* Mass : 0.01 - 0.1 $M_\odot$
* Mass density : $\rho = \rho_o (r/r_o)^{-m}$
* Temperature : $T = T_o (r/r_o)^{-n}$

∗ Disk isothermal in the vertical direction $\vec{z}$ and in hydrostatic equilibrium

$$\frac{dp}{dz} = \rho F_z, \qquad F_z = -\frac{GM_\odot z}{(r^2+z^2)^{3/2}} \simeq -\frac{GM_\odot z}{r^3}$$

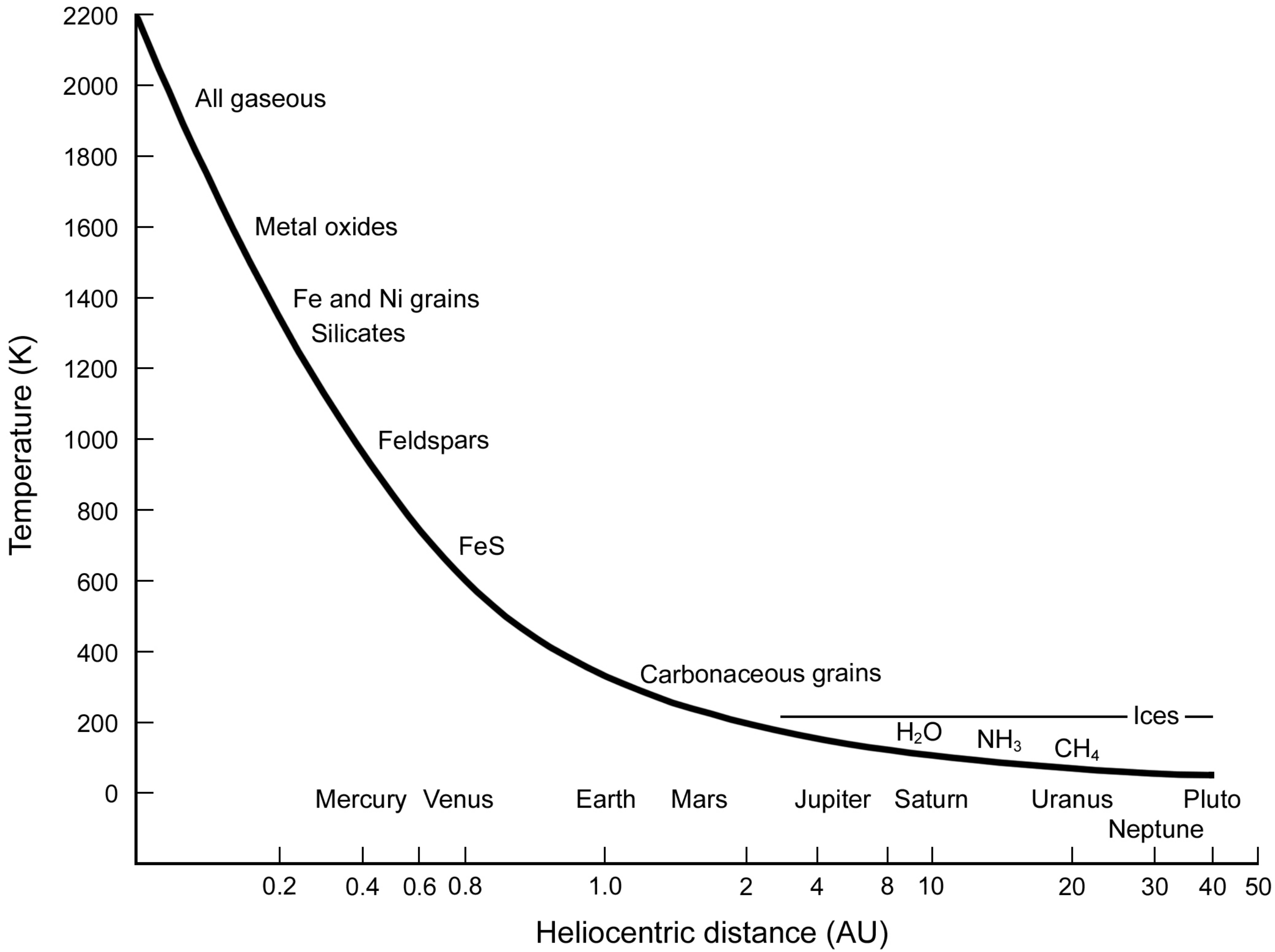
∗ Surface density : $\Sigma = \Sigma_o(r/r_o)^{-l}$

∗ Thickness of the gas disk: $H_g = \propto r$

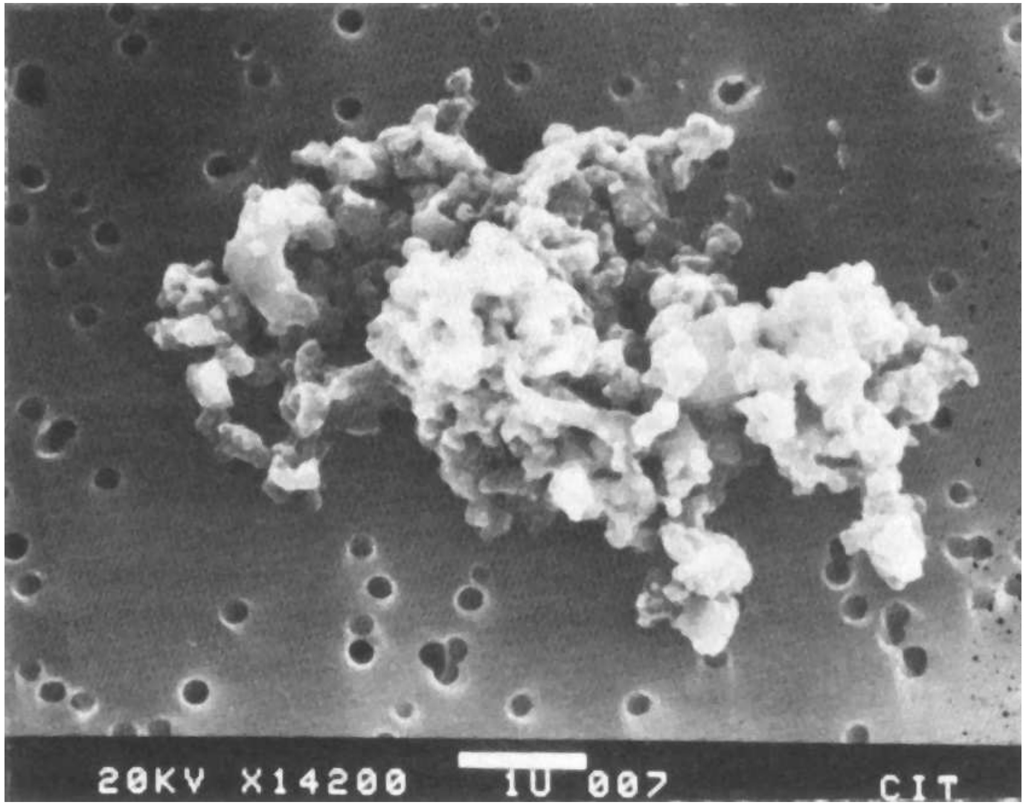
∗ Time scale for dust particles of radius s to settle in the mid-plane :

$$\tau_z \simeq \frac{1}{\Omega}\frac{\Sigma_g}{\rho_p}\frac{1}{s} \propto \frac{1}{s}$$

The condensation of the different materials as a function of the heliocentric distance



How did solid bodies form and grow?



Brownlee particle collected in the stratosphere. Highly porous aggregation of submicron and micron-size dust grains.

Form dust particles to planets

∗ New condensation nuclei
∗ Gas condensation onto pre-existing interstellar dust grains
∗ Dust coagulation after gentle collisions (adhesion by van der Waal forces)
∗ Formation of fractal aggregates
∗ Formation of kilometer-size planetesimals either by mutual collisions at low velocity or by gravitational instabilities in the fine dust disk

Goldreich-Ward condition for gravitational instabilities in a thin dust disk:

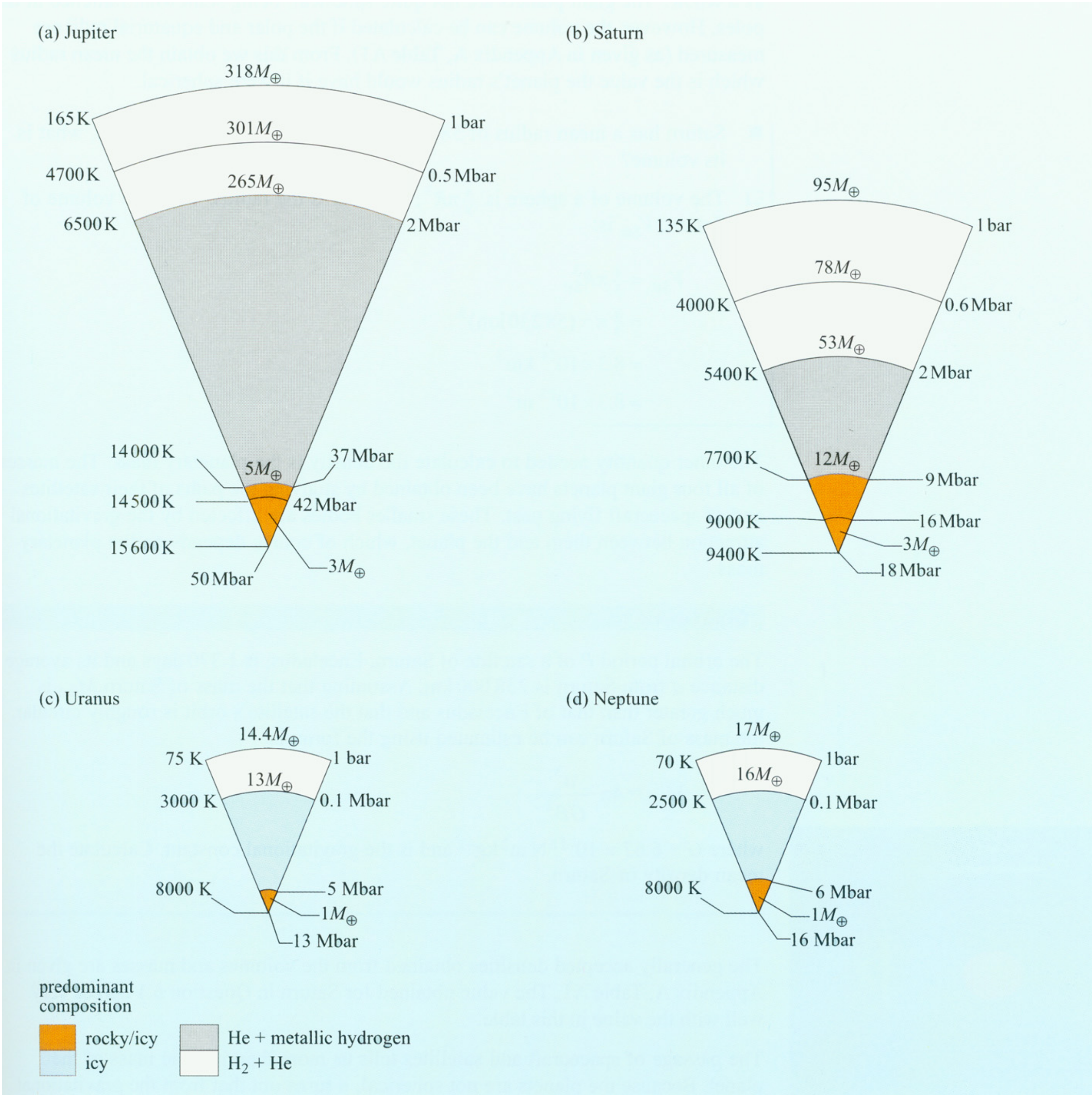
$$F(\lambda) = \Omega^2\lambda^2 - 4\pi G\Sigma_d\lambda + 4\pi^2 c^2 < 0$$

∗ Oligarchic accretion: planets dominant in their accretion zones

$$\frac{dM}{dt} = AM^{2/3} + BM^{4/3}$$

∗ Gas accretion by massive solid cores

Model of the interiors of the Giant planets



Different stages of planet formation: A summary

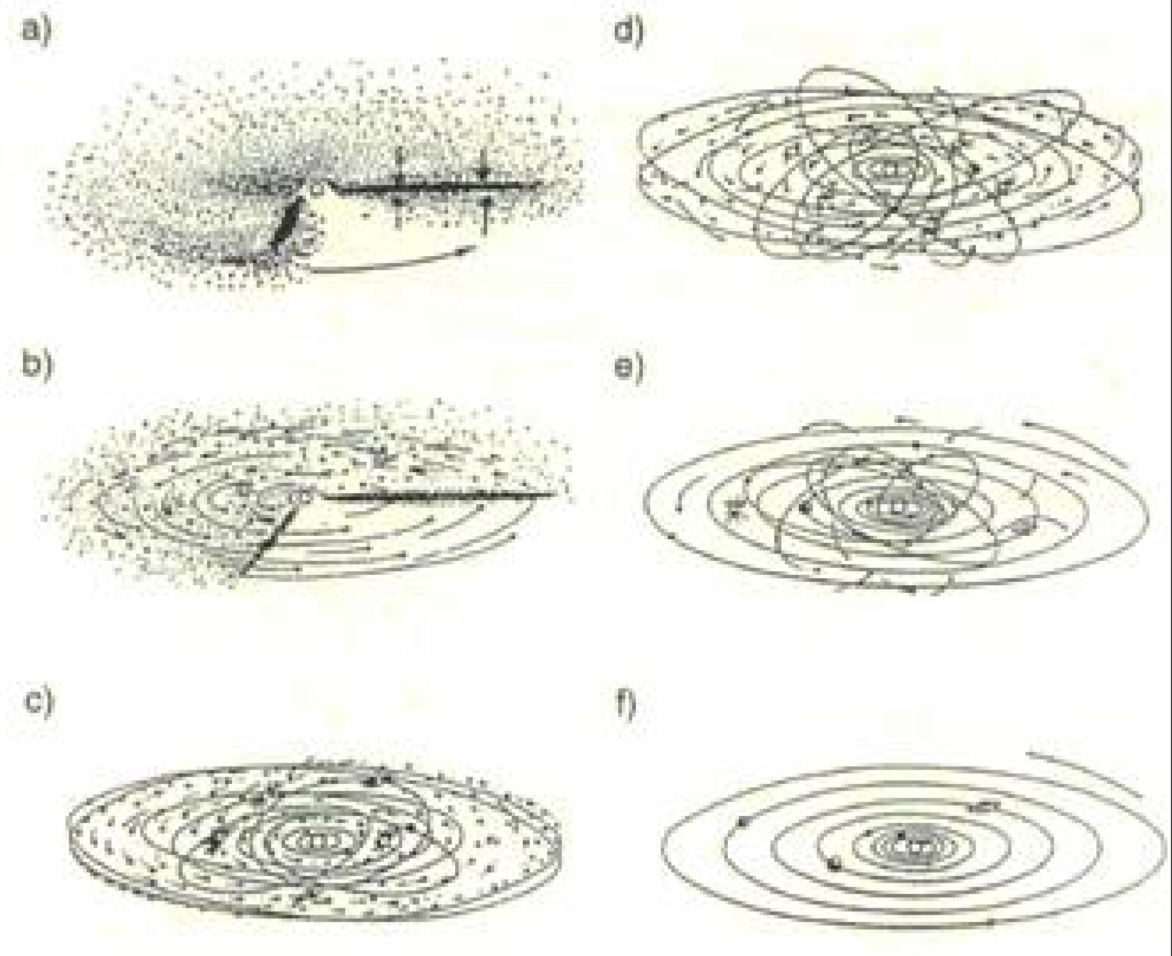


Figura 3.8: Las diversas etapas de la evolución de los discos planetarios hasta la formación de los planetas (ver texto).

Planet migration by exchange of angular momentum between the protoplanets and the scattered planetesimals

The orbital radius a_N of a planet (Neptune) will suffer a change Δa_N due to the exchange of angular momentum with an interacting planetesimal given by

$$\frac{\Delta a_N}{a_N} \sim -2\frac{m}{M_N}\frac{\Delta h}{h_N}$$

Δh : change in the specific angular momentum of the interacting planetesimals

Two possible outcomes:

1. All the interacting planetesimals are ejected to interstellar space

A planetesimal will gain an amount of specific angular momentum:

$$\Delta h = (\sqrt{2} - 1) a_N v_N$$

$v_N = (\mu / a_N)^{1/2}$: heliocentric circular velocity at Neptune's distance

m_r : total mass of planetesimals ejected to interstellar space.

Change in the orbital radius:

$$\frac{\Delta a_N}{a_N} \sim -2(\sqrt{2} - 1) \frac{m_r}{M_N}$$

For instance, if Neptune ejected a total mass $m_r = 0.5 M_N$, its orbital radius would have shrunk to $a'_N = a_N + \Delta a_N \sim 0.6 a_N$.

2. All the residual planetesimals of Neptune's accretion zone are scattered inwards to Jupiter's influence zone, where this planet takes dynamical control and finally ejects them

The average specific angular momentum lost by each one of the interacting planetesimals (and gained by Neptune) is

$$\Delta h \simeq - \left[1 - \left(\frac{2a_J}{a_N + a_J} \right)^{1/2} \right] a_N v_N$$

a_J : radius of Jupiter's orbit

In this case Neptune will increase its orbital radius by

$$\frac{\Delta a_N}{a_N} \sim +2 \left[1 - \left(\frac{2a_J}{a_N + a_J} \right)^{1/2} \right] \frac{m_r}{M_N}$$

∗ The balance is not zero. Process 2 predominates oves Process 1, so Neptune, Uranus and Saturn will move outward, while Jupiter will move inward (Fernández and Ip 1984, 1996)

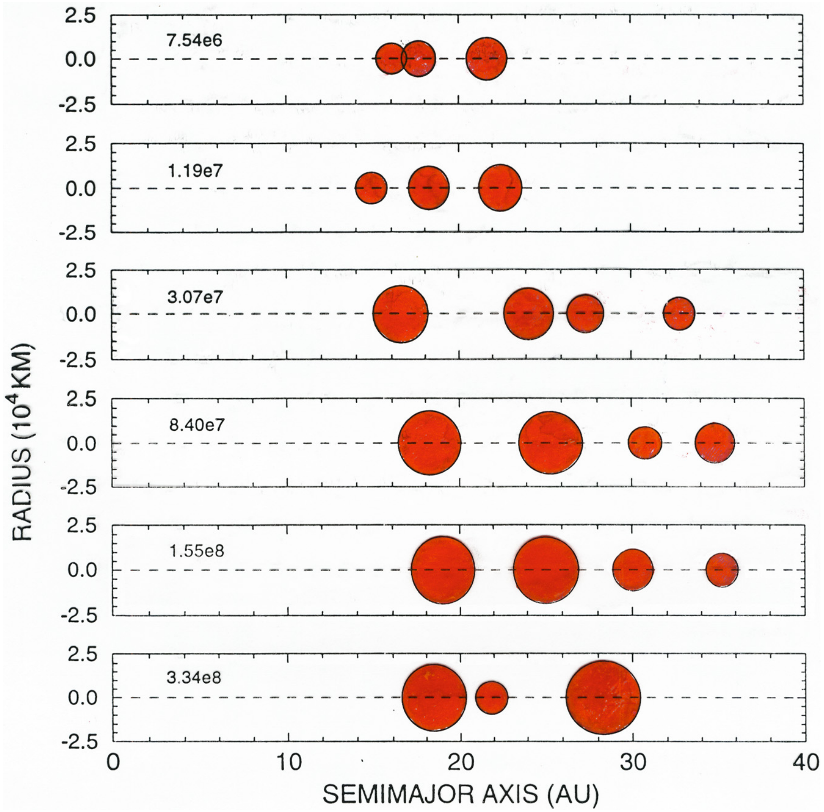
Planet migration: A numerical model

Initial conditions :

∗ Samples of 750 Mars-sized bodies distributed in the outer planetary region

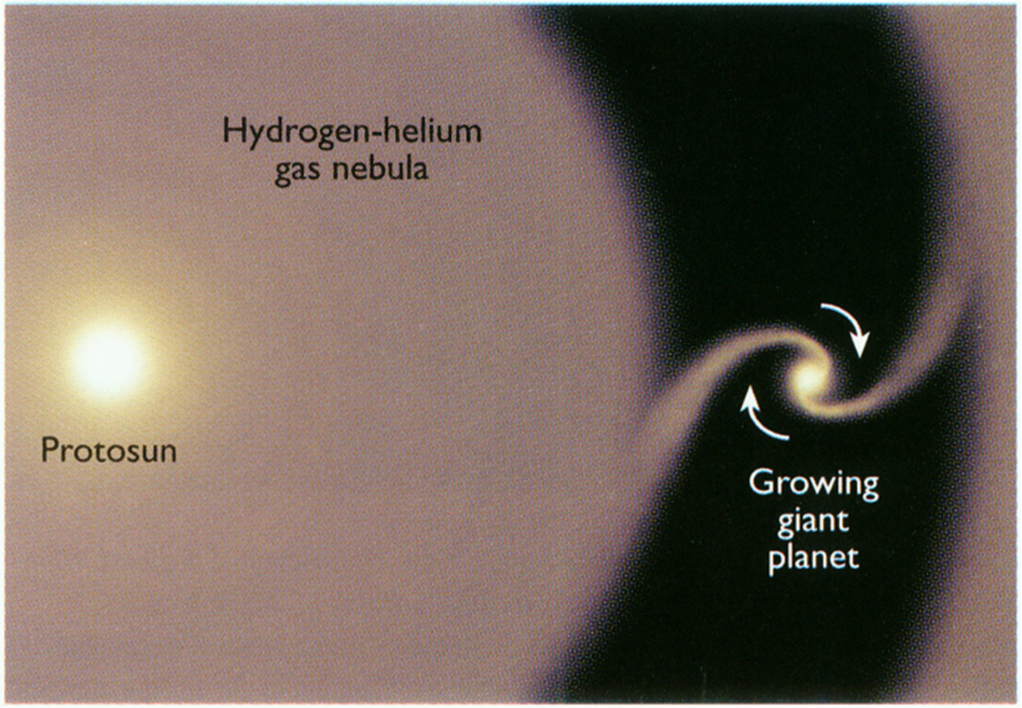
∗ Mutual interactions computed by Öpik's two body formalism (either collisions or gravitational scattering)

∗ Simulation followed over the solar system age



(Fernández & Ip 1996)

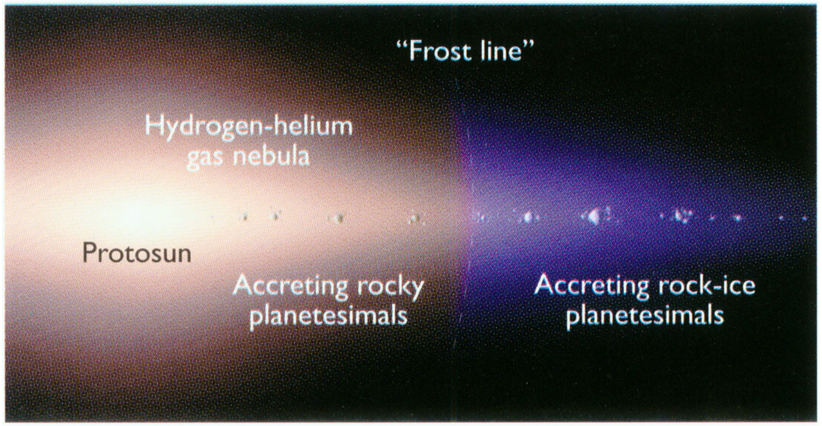
Planet migration by tidal torquing between the proto-giant planet and the gaseous disk

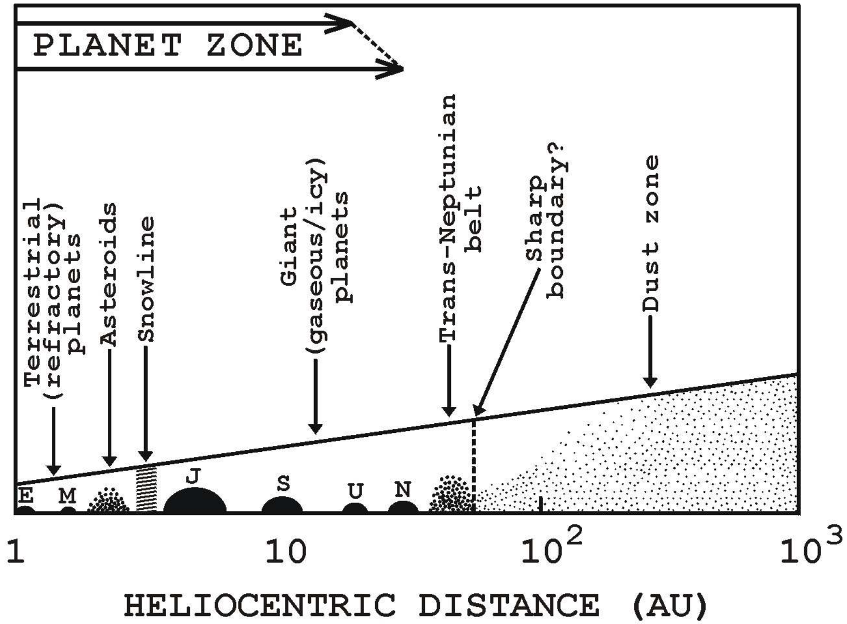


This mechanism has been proposed for explaining the existence of Jovian-sized exoplanets close to the central star

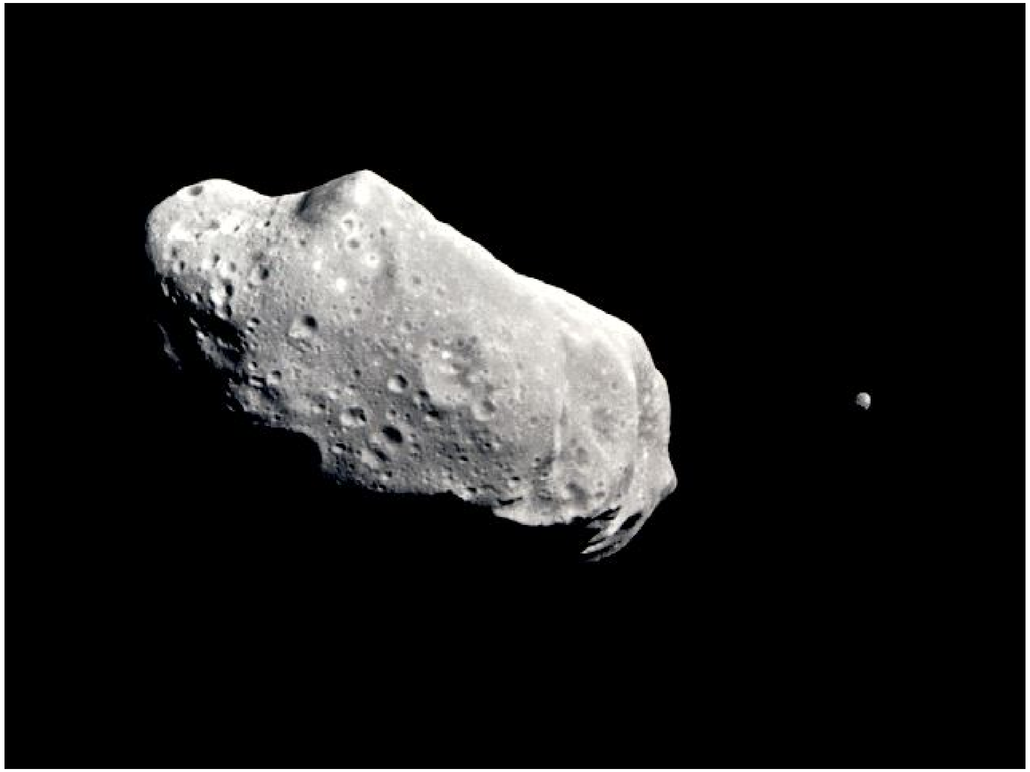
∗ Planet migration is a very important mechanism that may contribute to explain the different architectures of extrasolar systems

Accretion in the protoplanetary disk: The end product

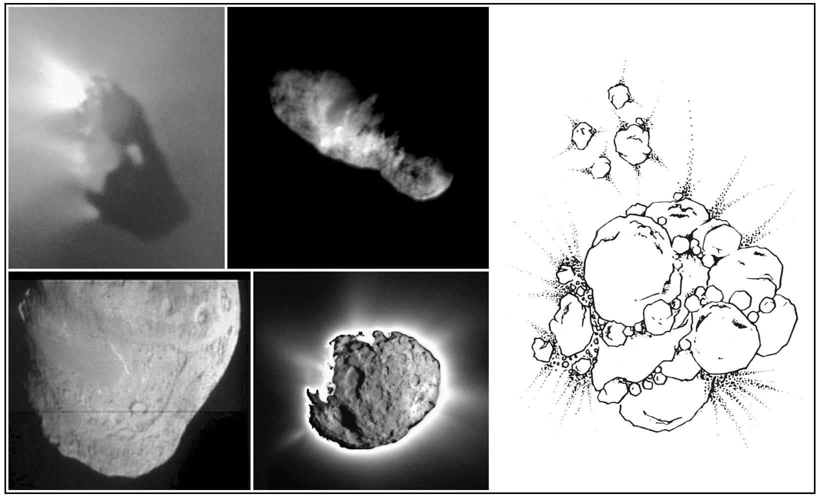




Residual populations



Asteroid Ida and small satellite Dactyl imaged by Galileo (NASA/JPL)



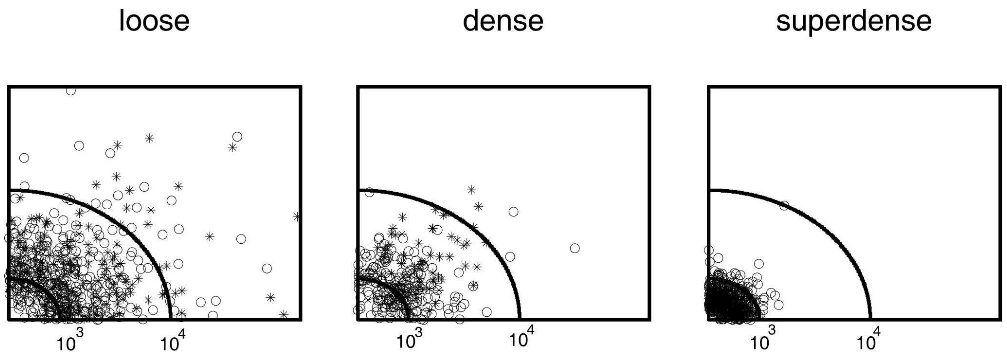
Comets Halley, Borrelly, Tempel 1 and Wild 2 (left). Rubble-pile model of the comet nucleus (right)

Relative abundances of molecular species in comets

Molecule	Mass fraction
H_2O	$\sim$ 100
CO	$\sim$ 7-8
CO_2	$\sim$ 3
H_2CO	$\sim$ 0-5 (formaldehyde)
NH_3	$\sim$ 1-2
HCN	$\sim < 0.02$-0.1
CH_3OH	$\sim$ 1-5 (methanol)

Formation of the Oort cloud

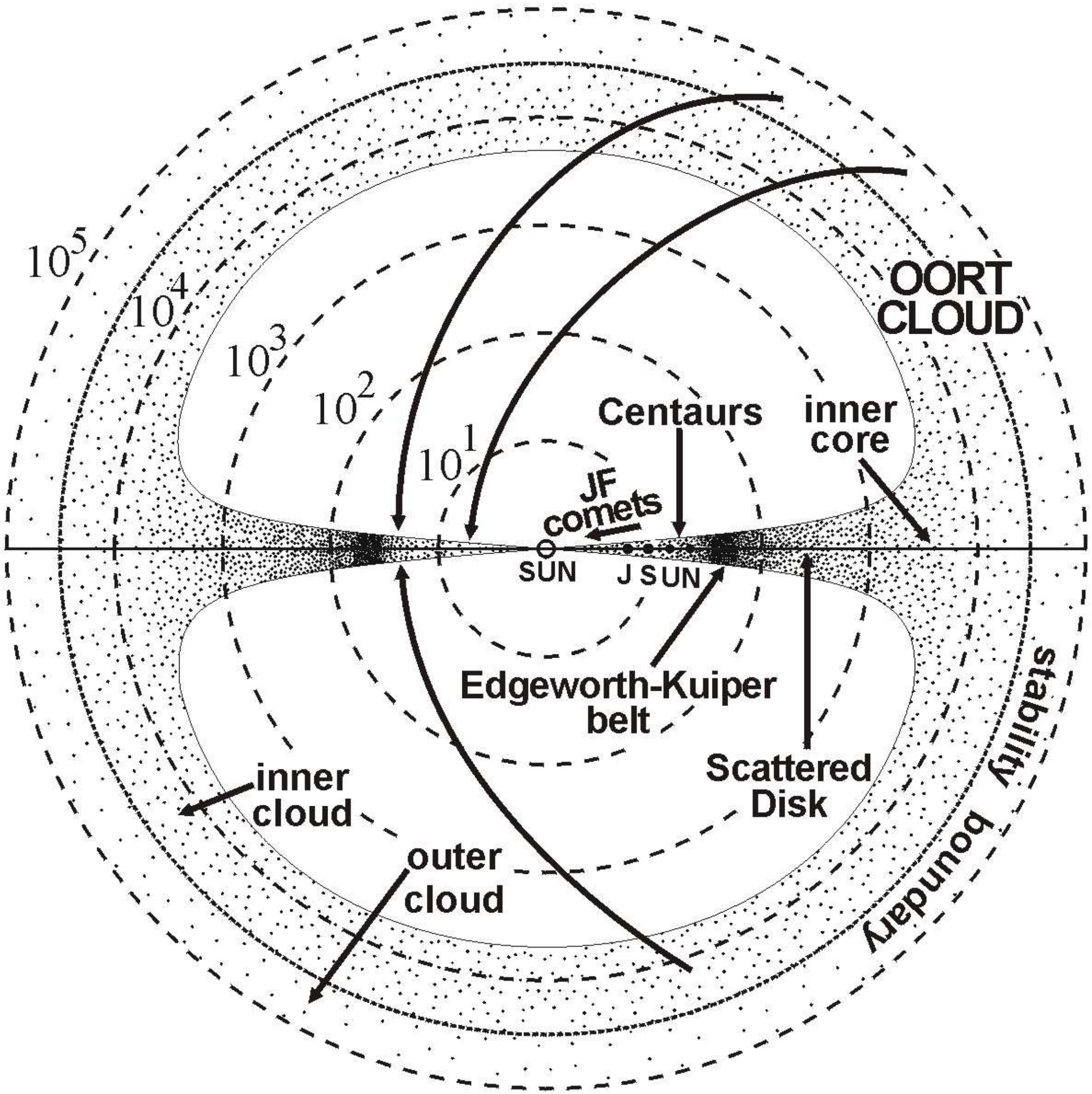
Different stages:
$*$ Planetesimals are scattered outwards by the Jovian planets
$*$ Once they reach distances $\sim 10^3 - 10^4$ AU, they are subject to stellar and molecular cloud perturbations
$*$ The comet perihelia are decoupled from the planetary region and stored in the Oort cloud



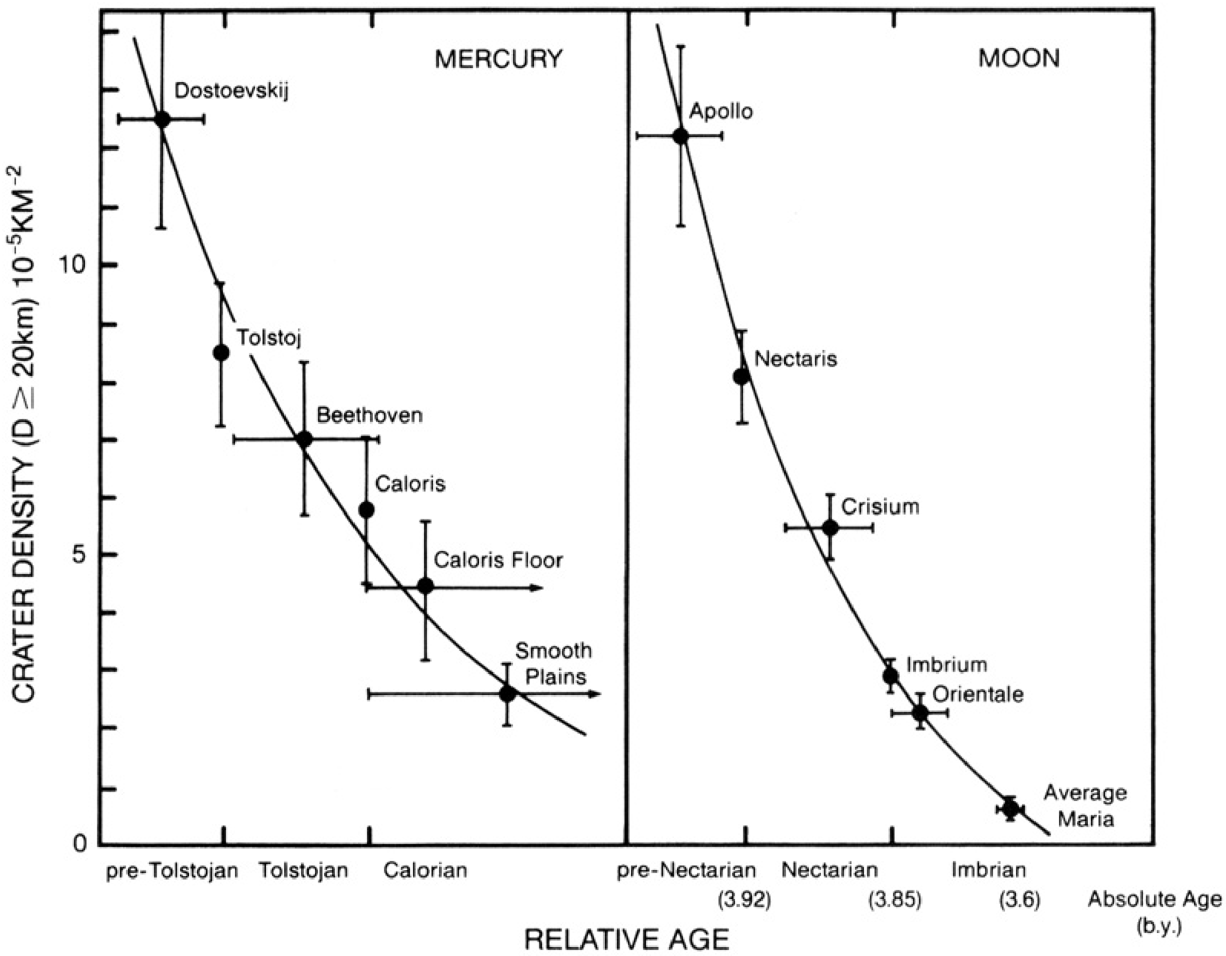
Different scenarios for formation of an Oort cloud with different degrees of central condensation. It depends on the density of stars and molecular gas surrounding the early Sun. Three models: Sun within a loose star cluster (10 * pc^{-3}) (left); Sun within a dense star cluster (25 * pc^{-3}) (middle); Sun within a superdense star cluster (100 * pc^{-3}) (right).

(Fernández & Brunini 2000)

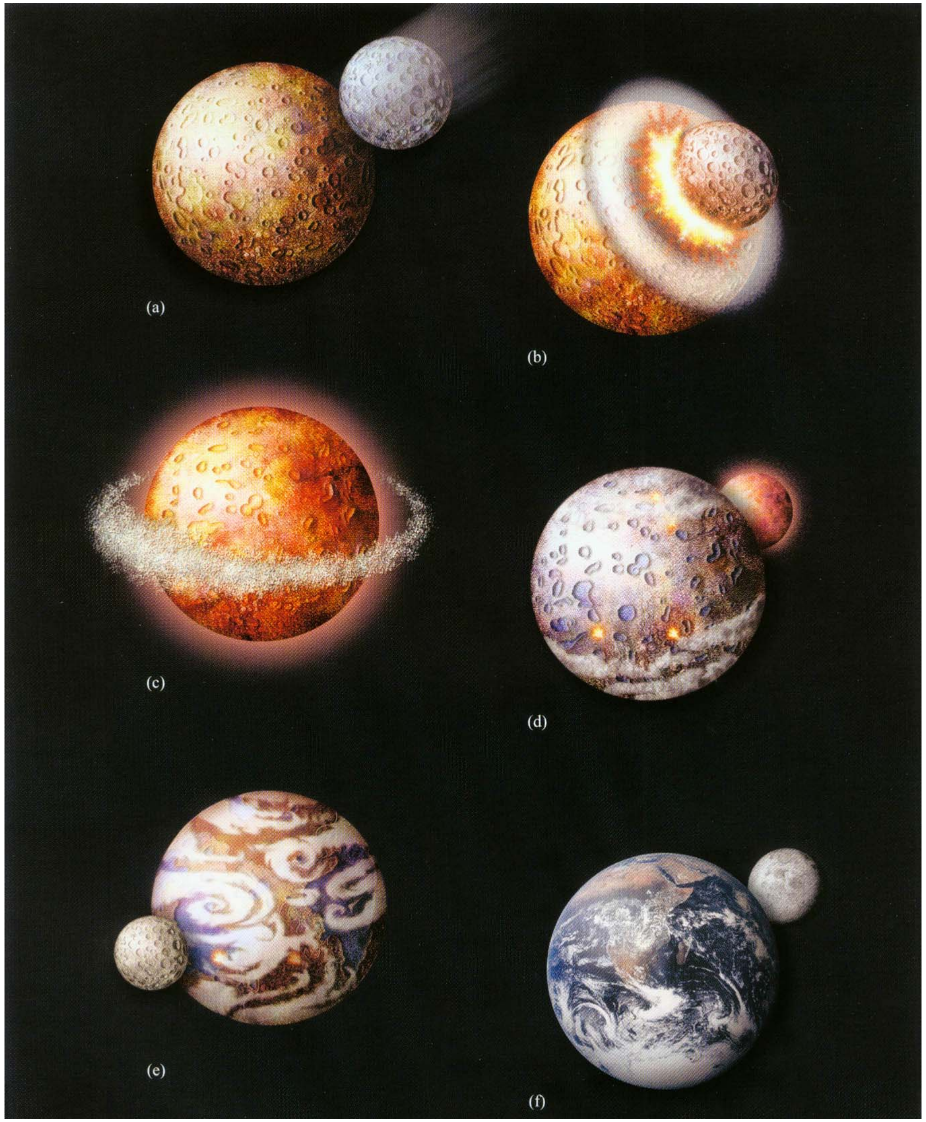
The different populations of the solar system



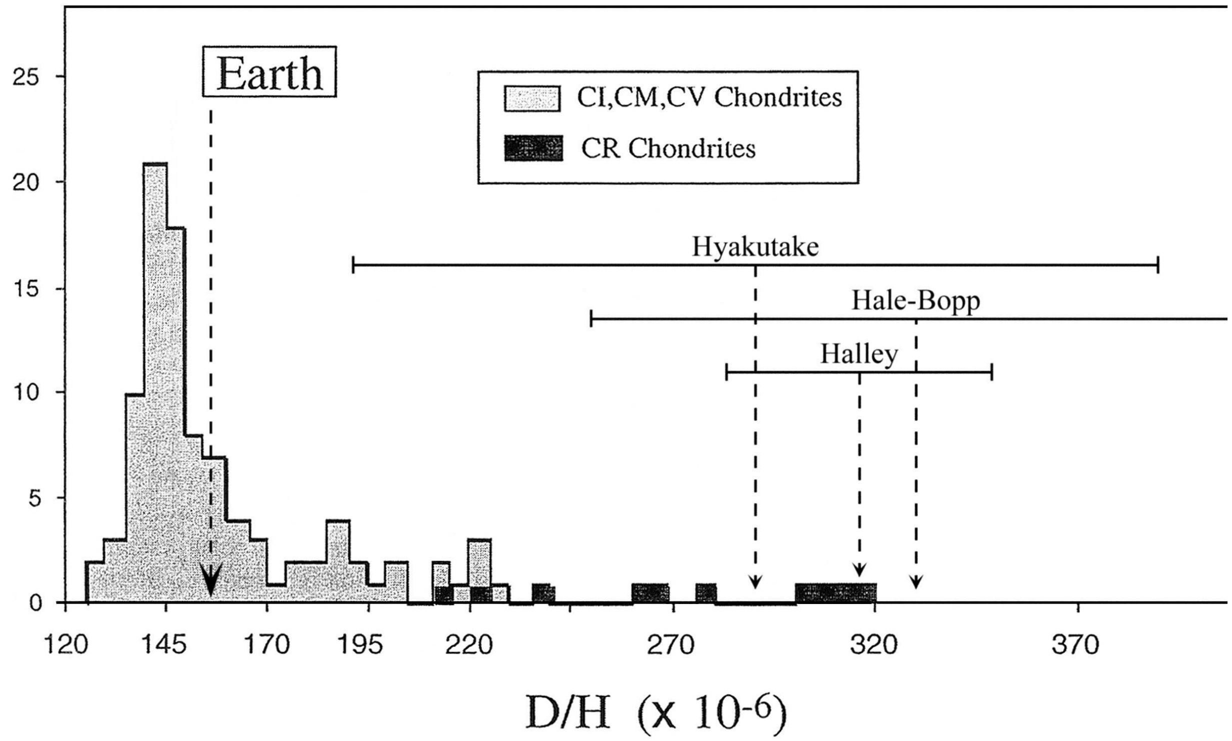
The heavy bombardment in the early solar system



The origin of the Moon as the result of a megaimpact of the proto-Earth with a Mars-sized protoplanet



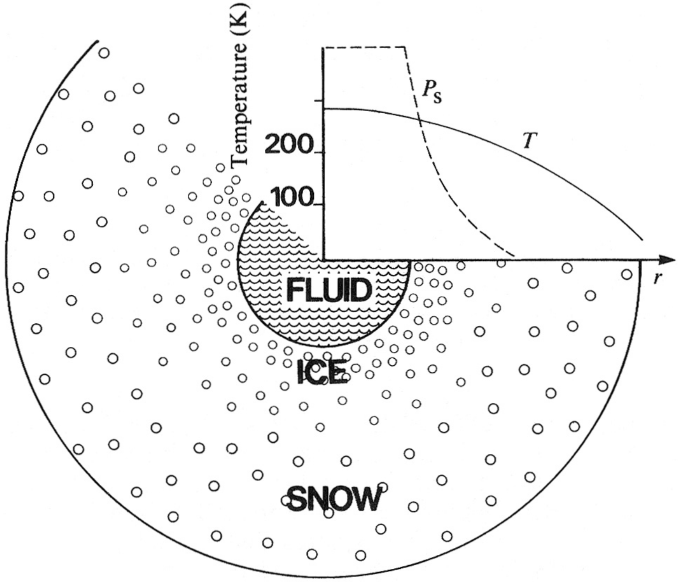
The origin of the Earth water



Exchange of deuterium with nebular hydrogen in water molecules:

$$HDO + H_2 \rightleftharpoons H_2O + HD$$

Liquid water in the interior of icy bodies?



(Wallis 1980)

Temperature $T(r)$ at a distance r from the center of the nucleus of radius R_N and density ρ:

$$T(r) \simeq T_o + \frac{\bar{Q}\rho}{6K}(R_N^2 - r^2)$$

$\bar{Q}$: average heating rate by radioactive sources (e.g. ^{26}Al)
K : Thermal conductivity