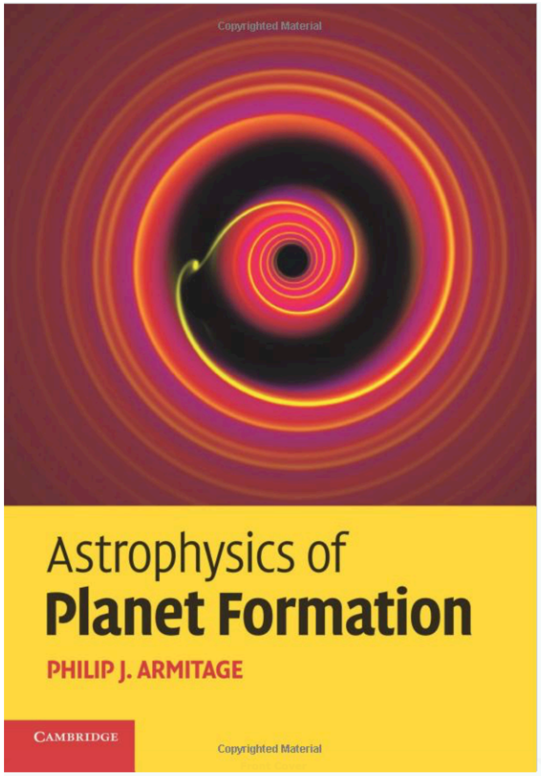
Book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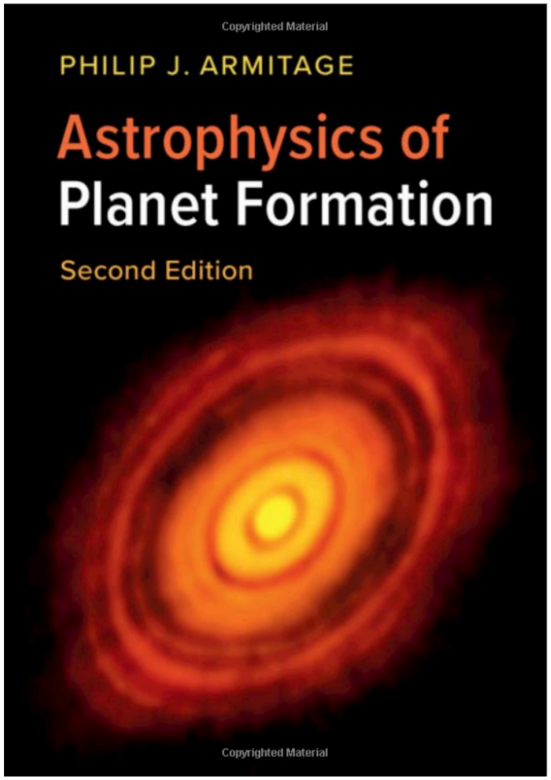
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Planet Formation
is an active and evolving field of research

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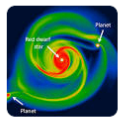
5 hours ago



Air & Space Magazine
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First, it leads us to question our traditional thoughts about planet formation, particularly on how a super-Earth can form so far away from its host ...
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UC San Diego Health (press release)
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Most of us are taught in grade school how planets formed: dust particles clump together and over millions of years continue to collide until one ...
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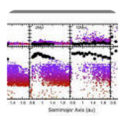

Space Ref (press release)
Massive Gas Disk Raises Questions About Planet Formation ...
Planets are formed in gaseous dusty disks called protoplanetary disks around young stars. Dust particles aggregate together to form Earth-like ...
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insideHPC
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Researchers are using a novel approach to solving the mysteries of planet formation with the help of the Comet supercomputer at the San ...
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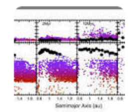

Science Magazine
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Scars on the Moon had convinced many planetary scientists that the ... As the model now goes, after the giant planets formed out of the gas disk ...
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BBC Focus Magazine
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This theory predicts the formation of giant planets happening within a few thousand years, a timescale which is extremely fast in astrophysical ...
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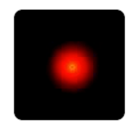

HPCwire
SDSC's Supercomputer Simulations Showcase Novel Planet Formation Models
Jan. 13, 2020 — Most of us are taught in grade school how planets formed: dust particles clump together and over millions of years continue to ...
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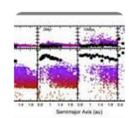
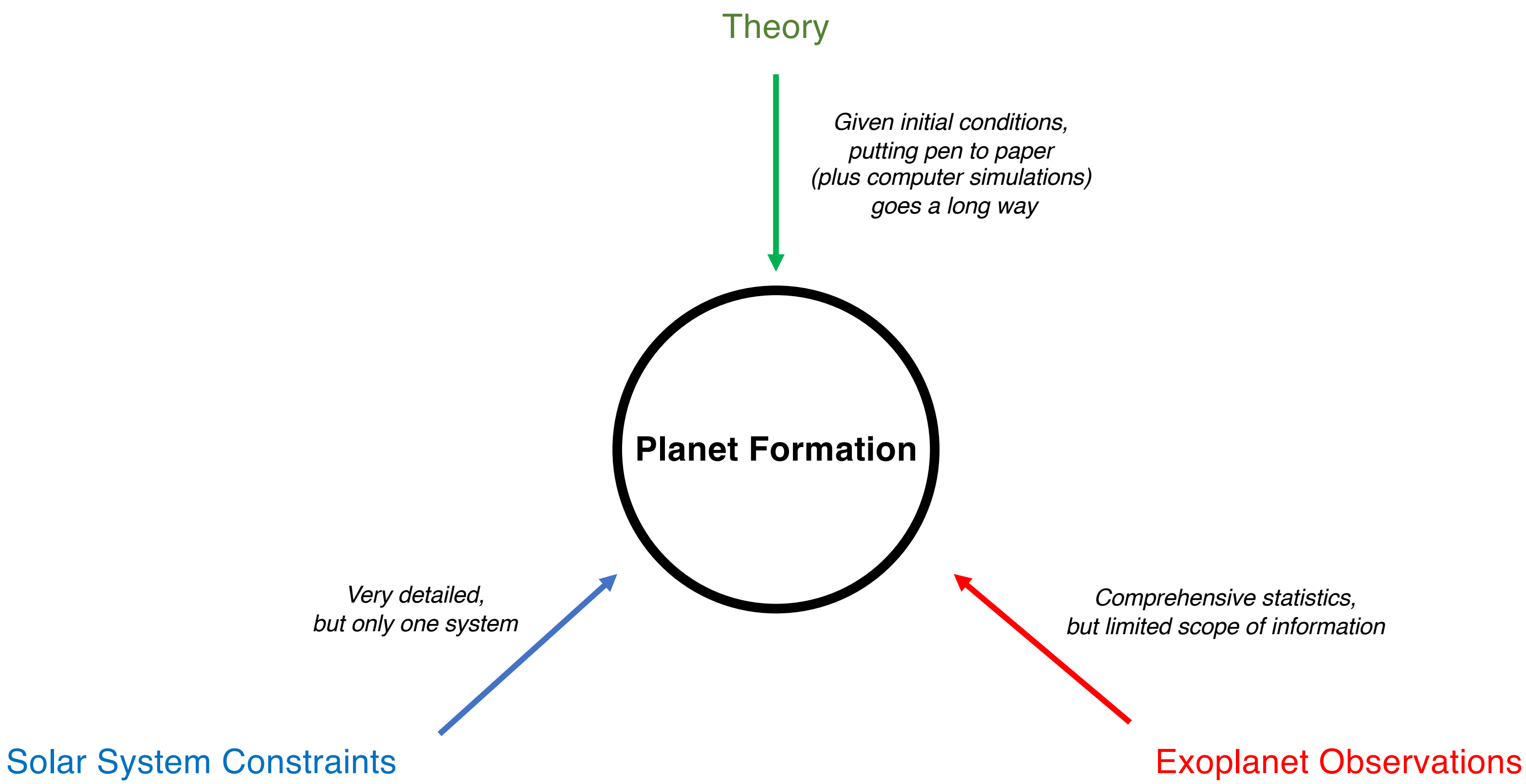
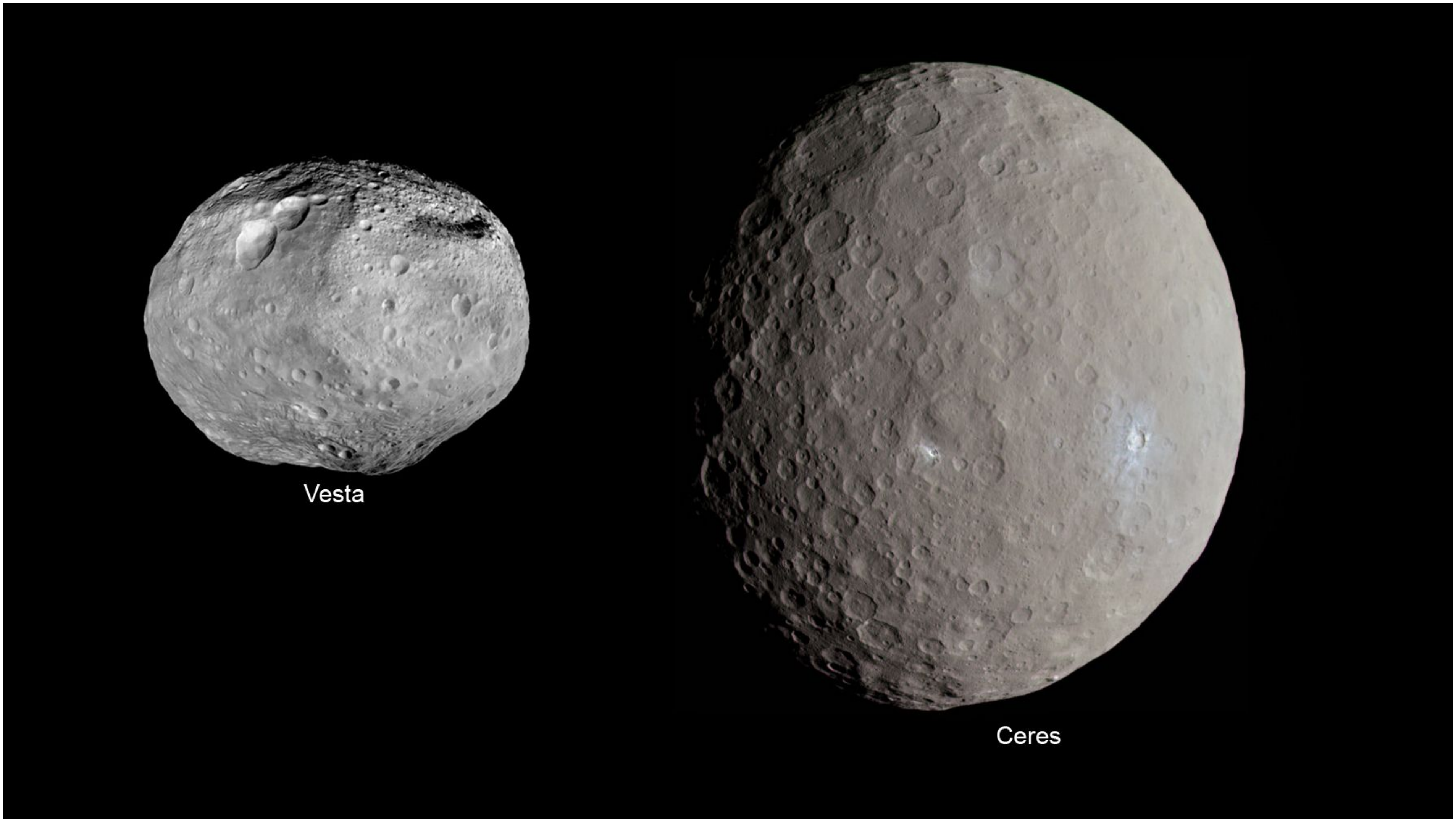


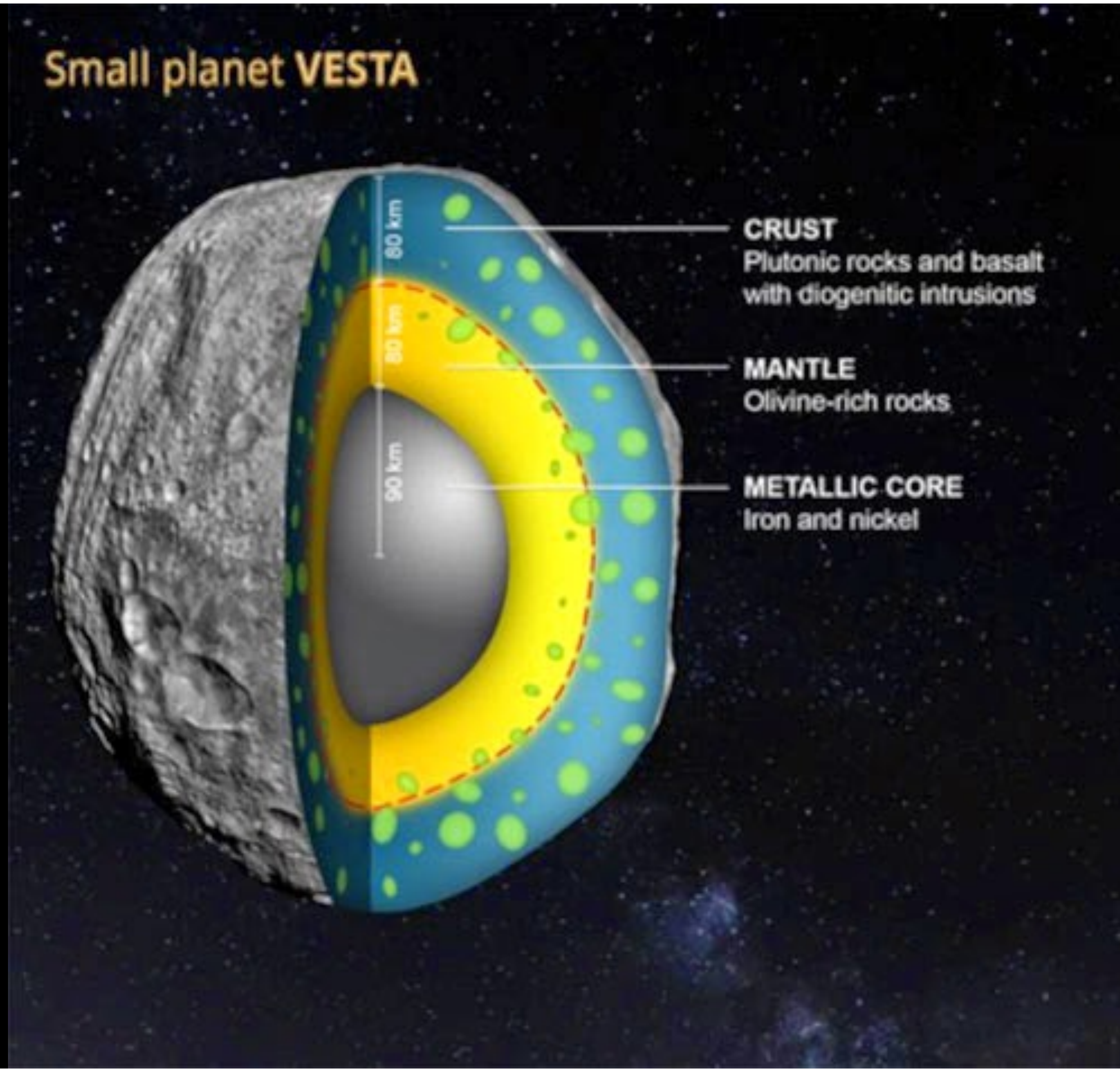

Theory
Given initial conditions, putting pen to paper (plus computer simulations) goes a long way
Planet Formation
Very detailed, but only one system
Solar System Constraints
Comprehensive statistics, but limited scope of information
Exoplanet Observations

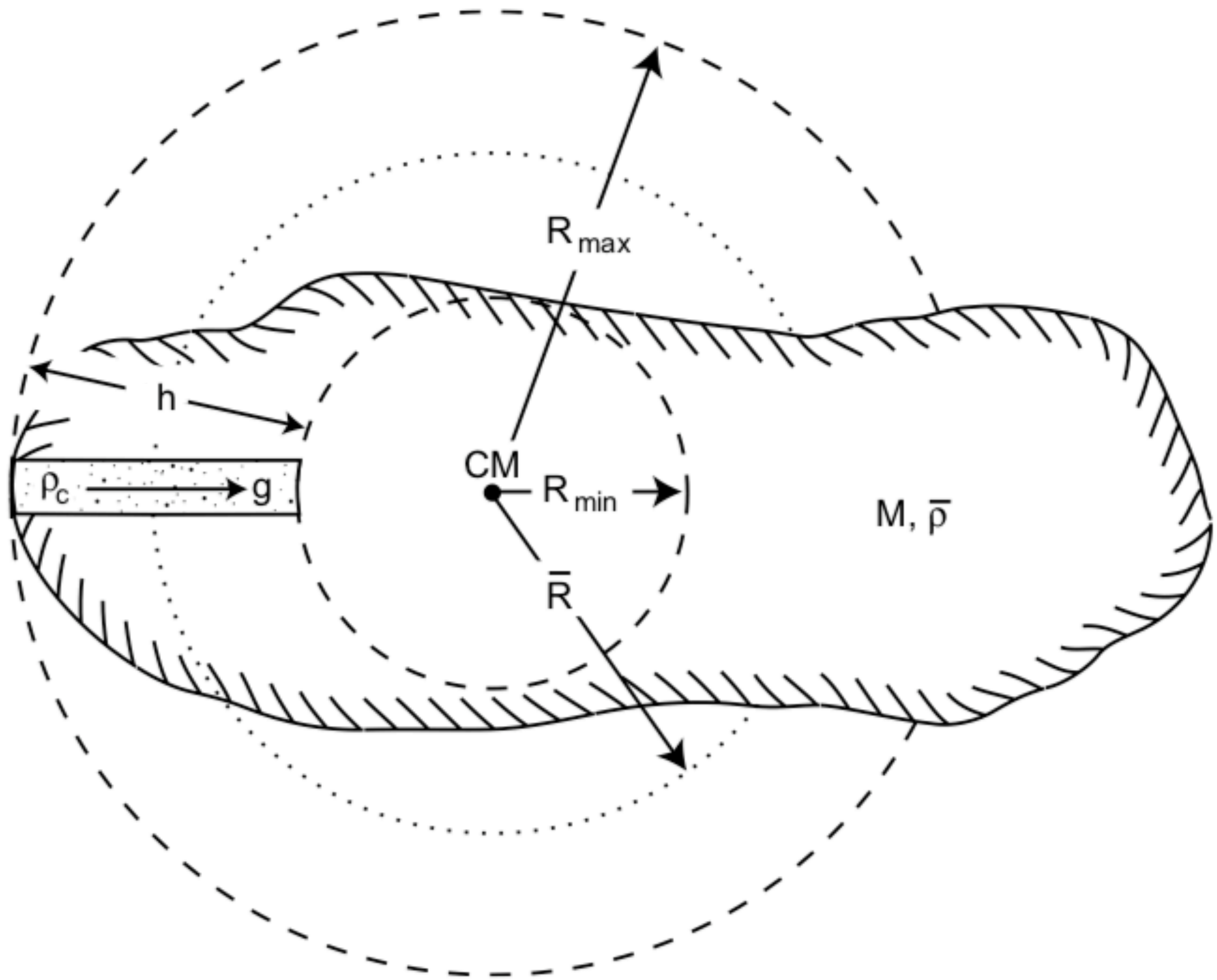
What is a planet?

- The IAU planet definition
  - Upper limit – Deuterium fusion.
  - Lower limit – Combination of
    - Mass (enough to assume hydrostatic equilibrium – planets and dwarf planets).
    - Orbital dominance (not dwarf planets).
    - Dwarf planets are not planets (“pineapples are not apples”).
- The Geophysical definition
  - Upper limit – Deuterium fusion.
  - Lower limit – Mass (enough to assume hydrostatic equilibrium – planets and dwarf planets).
    - Dwarf planets are planets


Kuiper Belt
Weywot
Hi'iaka, Namaka
Charon, Hydra, Nix
Dysnomia
Quaoar
Sedna
Haumea
Makemake
Pluto
Eris
(90482) Orcus
(28978) Ixion
(20000) Varuna
2002 AW197
Asteroid Belt
(1) Ceres
(2) Pallas
(4) Vesta
Scale
1000 km


Vesta
Ceres


Small planet VESTA
80 km
80 km
90 km
CRUST
Plutonic rocks and basalt
with diogenitic intrusions
MANTLE
Olivine-rich rocks
METALLIC CORE
Iron and nickel



R max
h
CM
R min
ρc
g
R̄
M, ρ̄

COULD CERES BE A REFUGEE FROM THE KUIPER BELT? William B. McKinnon, Department of Earth and Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130 (mckinnon@wustl.edu).

Introduction: Ceres is a most unusual asteroid. Comprising ~1/3 of the total mass of the present asteroid belt, it is classified as a relatively rare, G type, related to the more abundant carbonaceous C-type asteroids. It resides deep in the main belt, at a semimajor axis of 2.77 AU, at the center of the broad distribution of C types [1]. But it is not a C-type asteroid as usually considered. It is a differentiated dwarf planet, whose water-rich composition indicates a kinship with bodies much farther out in the solar system [2]. Here I explore the idea that Ceres originally accreted in a transneptunian orbit, was dynamically scattered inwards during a Nice-model like reorganization of the outer solar system [e.g., 3], and implanted in a more massive, primordial asteroid belt, where it remains today.

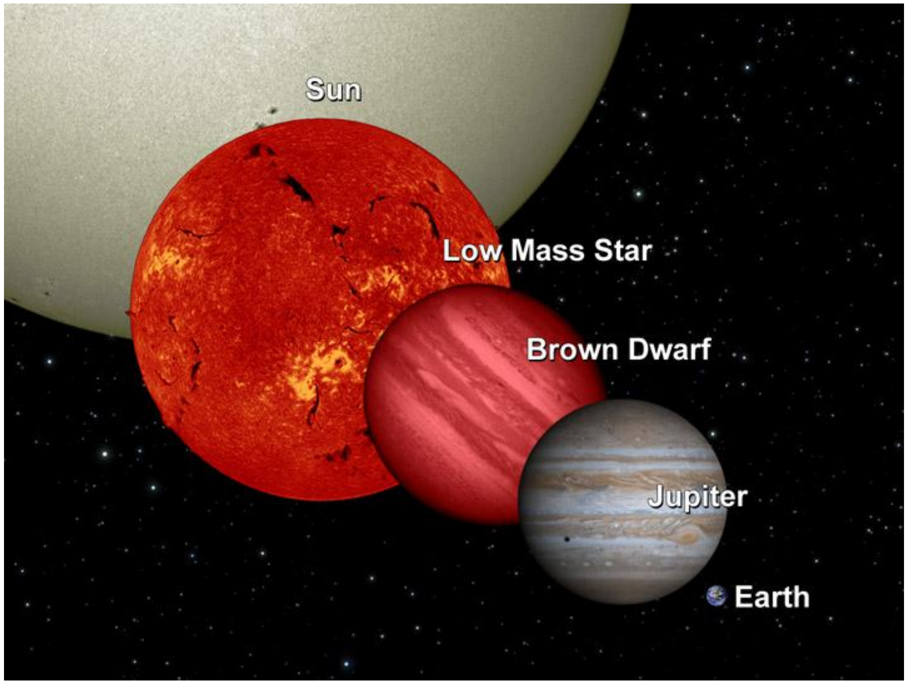
Density: Ground-based and HST imaging/occultations have converged on a picture of Ceres as a large, dwarf-planet-class body in rotational hydrostatic equilibrium, with a mean radius ~470 km and density ~2.2 g cm^{-3} [4] Ceres thus joins an interesting group of outer solar system bodies, the largest KBOs: Triton, 2.061 ± 0.007 g cm^{-3}; Eris, 2.3 ± 0.3 g cm^{-3}, and the Pluto-Charon binary, 1.94 ± 0.09 g cm^{-3} [5]. All these densities agree within uncertainties (and are quite different from Ganymede and Callisto), when self-compression is accounted for. When interpreted in terms of rock/water-ice ratio, such densities imply a and opaques, and frost has been long suspected, at least at some longitudes [e.g., 4,9]. More importantly, hydrated silicates are indicated by a broad 3-μm absorption, and a narrow absorption near 3.05 μm has been attributed to either Fe-rich or NH_4^+-bearing clays [10,11]. Ammonium-bearing phyllosilicates have been noted as unknown in meteorites [11], and for this reason perhaps not as seriously considered, but NH_3 is not unknown in the transneptunian region, having been identified on Charon and in comets [see references in 5]. The early evolution of a dwarf planet TNO would involve eruption of ammonia and methanol-bearing lavas to the surface, even before bulk rock-from-ice differentiation [5], and alteration of silicates by such liquids could be a source for ammonium-bearing clays.

Earlier ideas involving thermal metamorphism of C-type material to yield G-type spectra do not seem obviously relevant to Ceres at least, given the icy nature of its outer layer(s). Nor should Ceres, as an evolved, differentiated KBO, be expected to spectrally resemble its "primitive" D-type asteroid cousins. However, any surface volatiles (NH_3, CH_4, etc.) would have been rapidly lost after its dynamic "resettlement."

Dynamics: The key to Ceres' origin as a KBO is dynamics, and recent work offers a path whereby early solar system populations can migrate [3,12,13]. There has long been a possible link between D-type asteroids

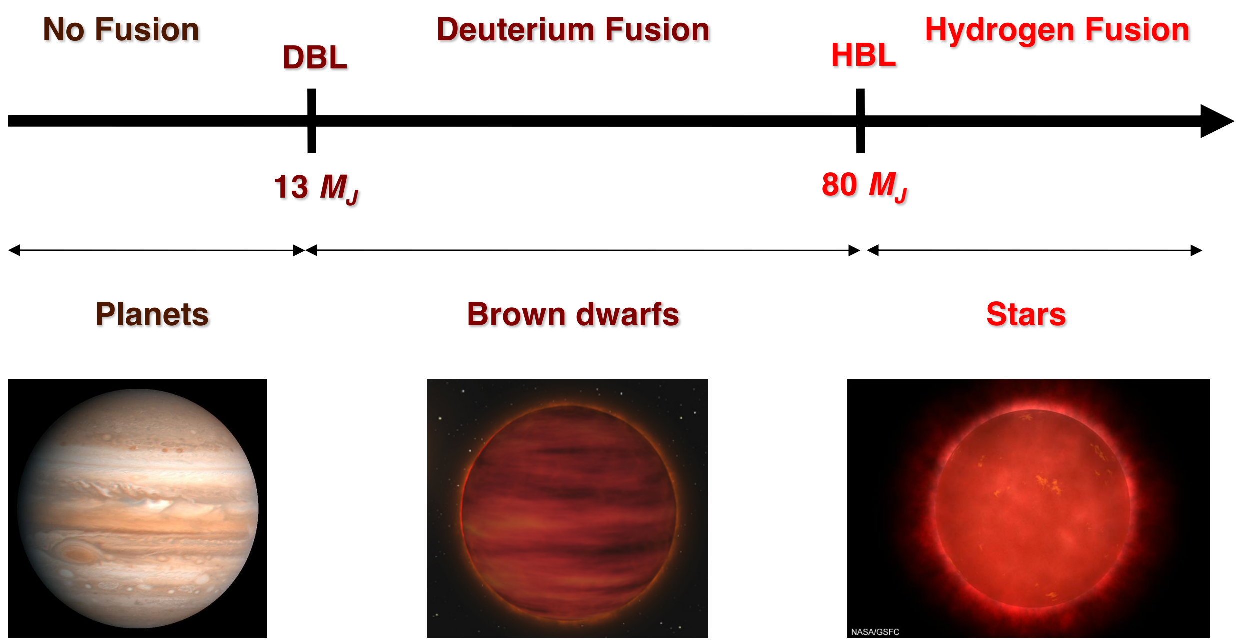
Deuterium Fusion - Brown Dwarfs

Brown dwarfs are objects with mass below the **Hydrogen Burning Limit** of **0.08 $M_\odot$**



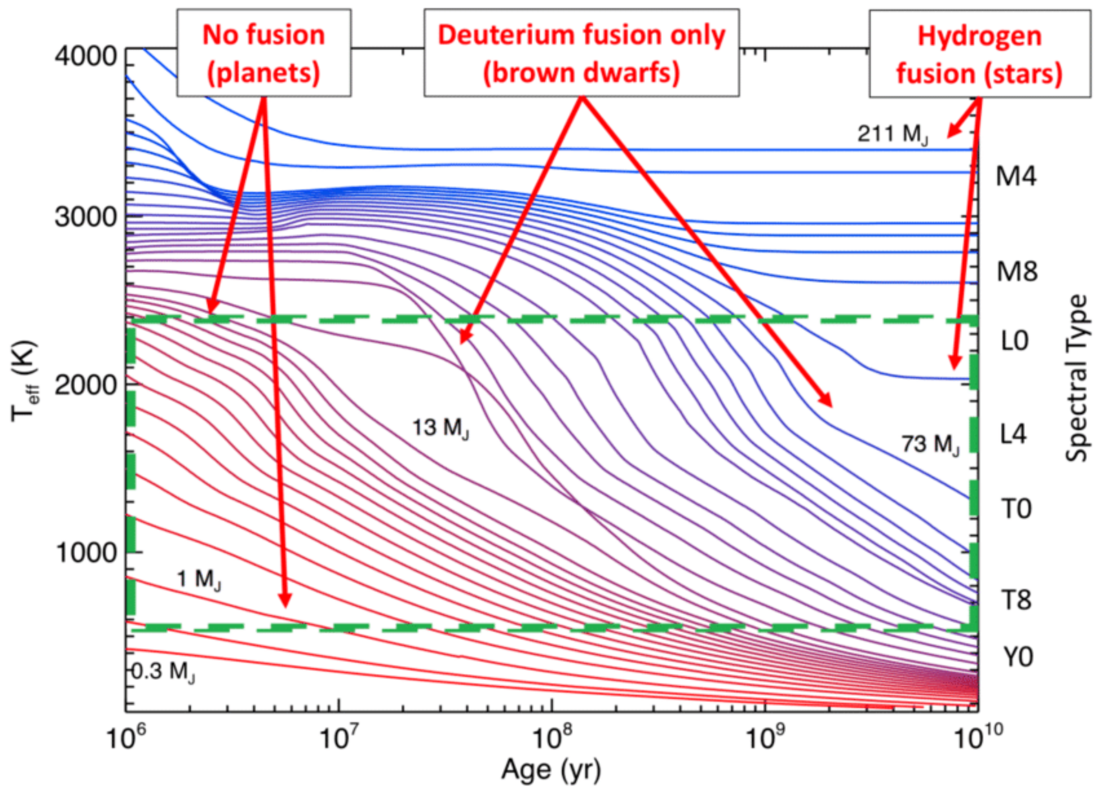
Mass Range

Hydrogen Burning Limit (80 M_J)
Deuterium Burning Limit (13 M_J)



Brown dwarf evolution

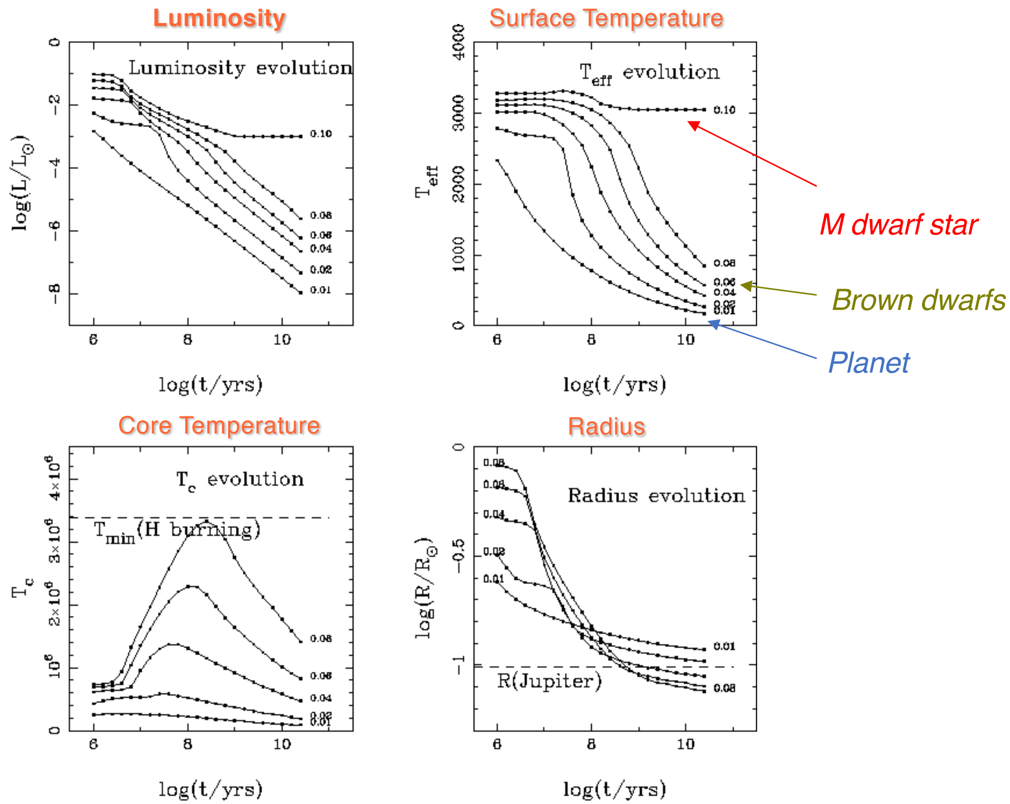
Deuterium fusion only lasts for 10^7 years !!
Irrelevant for structure



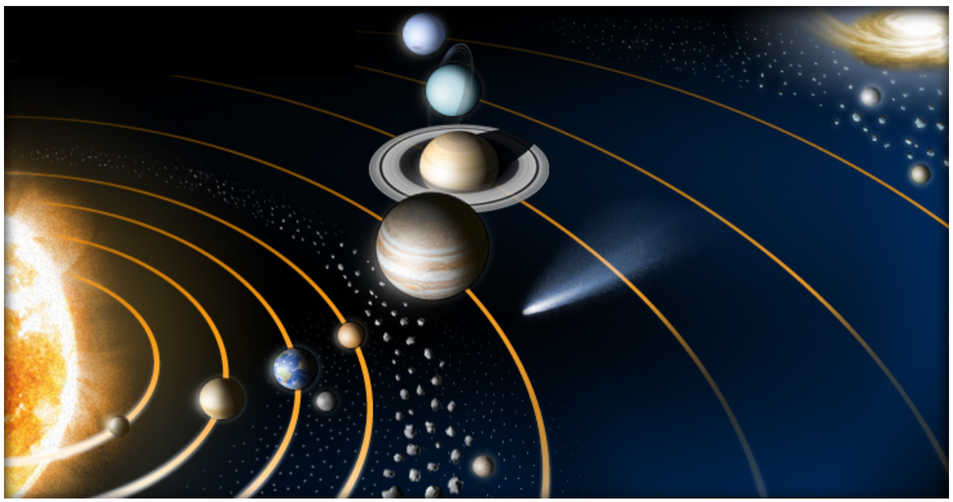
Brown dwarf evolution

Deuterium fusion only lasts for 10^7 years !!

Irrelevant for structure



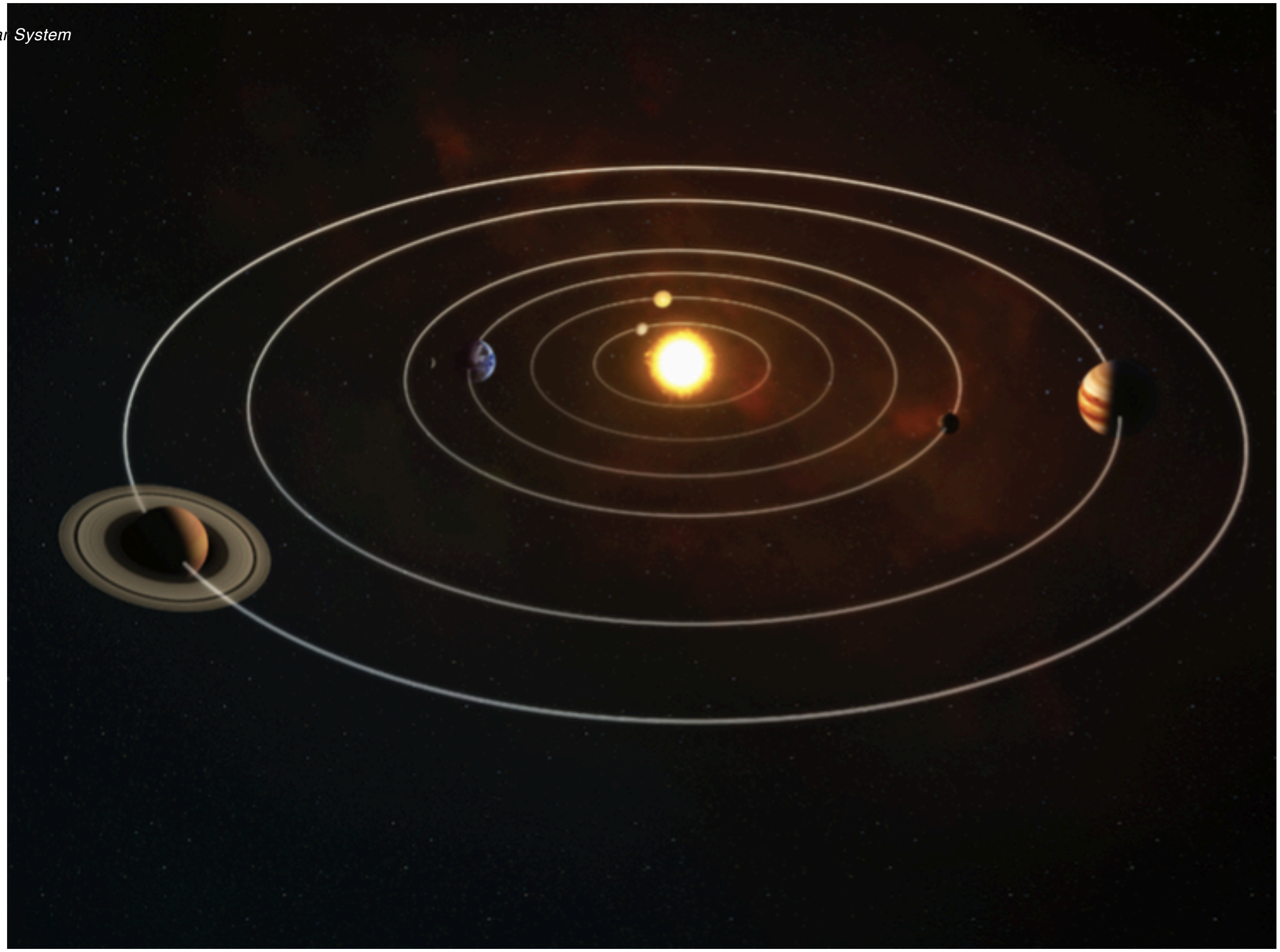
Solar System Planets



Any formation model of Solar System must explain:

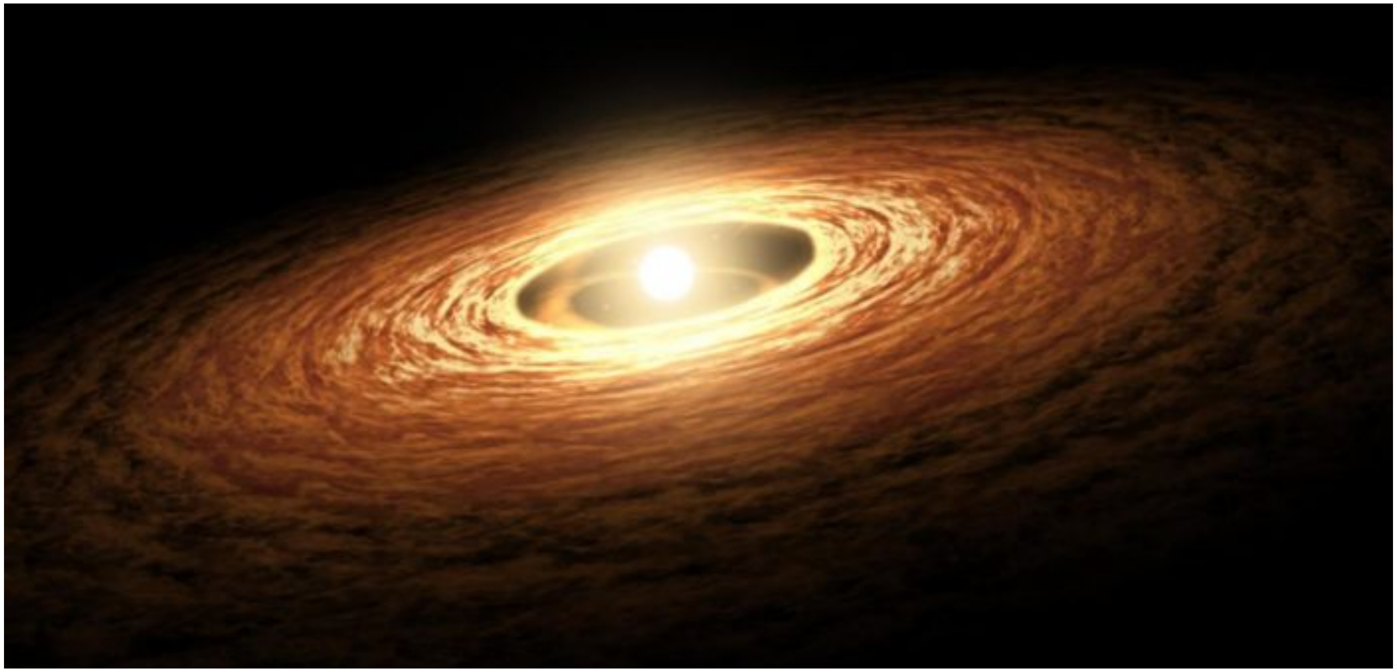
- All the orbits of the planets are prograde
- All the planets have orbital planes that are roughly in the same plane (inclined by less than 6 degrees with respect to each other).
- Inner/outer planets dichotomy
  - Inner planets are **terrestrial**: dense, rocky and small,
  - Outer planets are **jovian**: gaseous/icy and large.

Evidence from the Solar System



The Solar Nebula

Nebular hypothesis – planets form in disks of gas and dust
(Kant 1755, Laplace 1794)



AKADEMIYA NAUK SSSR
INSTITUT FIZIKI ZEMLI IMENI O. Yu. SHMIDTA

Academy of Sciences of the USSR
Shmidt Institute of the Physics of the Earth

V.S. Safronov

EVOLUTION OF THE PROTOPLANETARY CLOUD AND FORMATION OF THE EARTH AND THE PLANETS

(Evolyutsiya doplanetnogo oblaka i obrazovanie Zemli i planet)

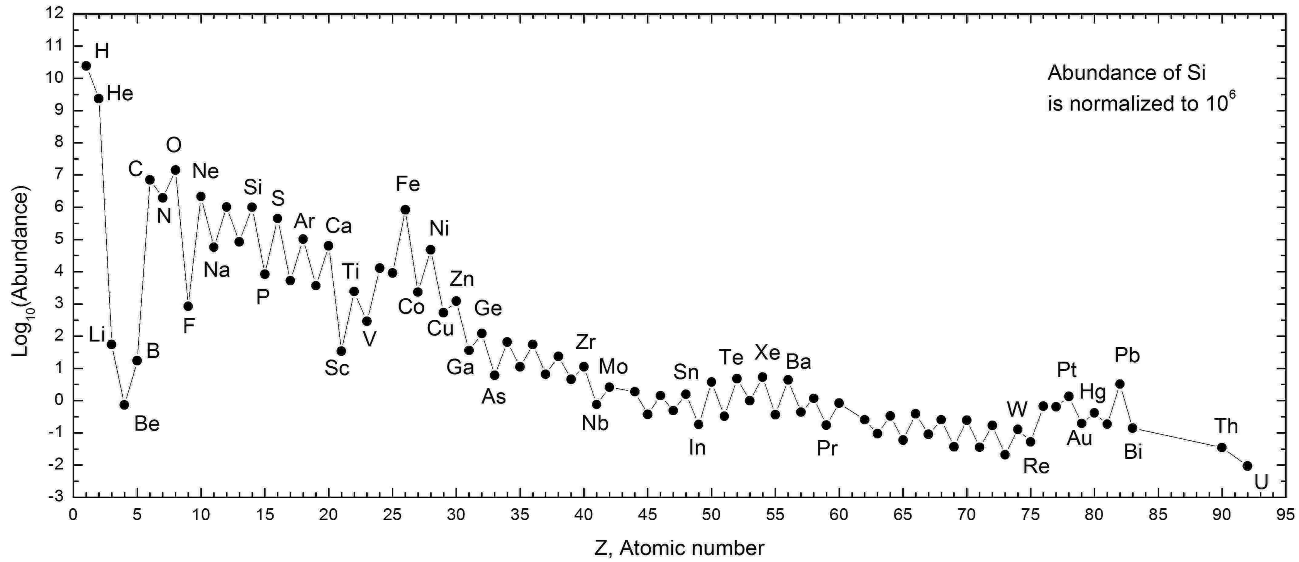
Izdatel'stvo "Nauka,"
Moskva, 1969

Translated from Russian

Israel Program for Scientific Translations
Jerusalem 1972

Chemical Composition

The chemical composition of the Sun



Most abundant elements, in order:

H (71%) He (27%)

0 (1.04%) C (0.46%)

Ne (0.13%) Fe (0.11%) N (0.1%)

Si (0.06%), Mg (0.05%), S (0.04%)

Chemistry

H (71%)

He (27%)

0 (1.04%)

C (0.46%)

Ne (0.13%)

Fe (0.11%)

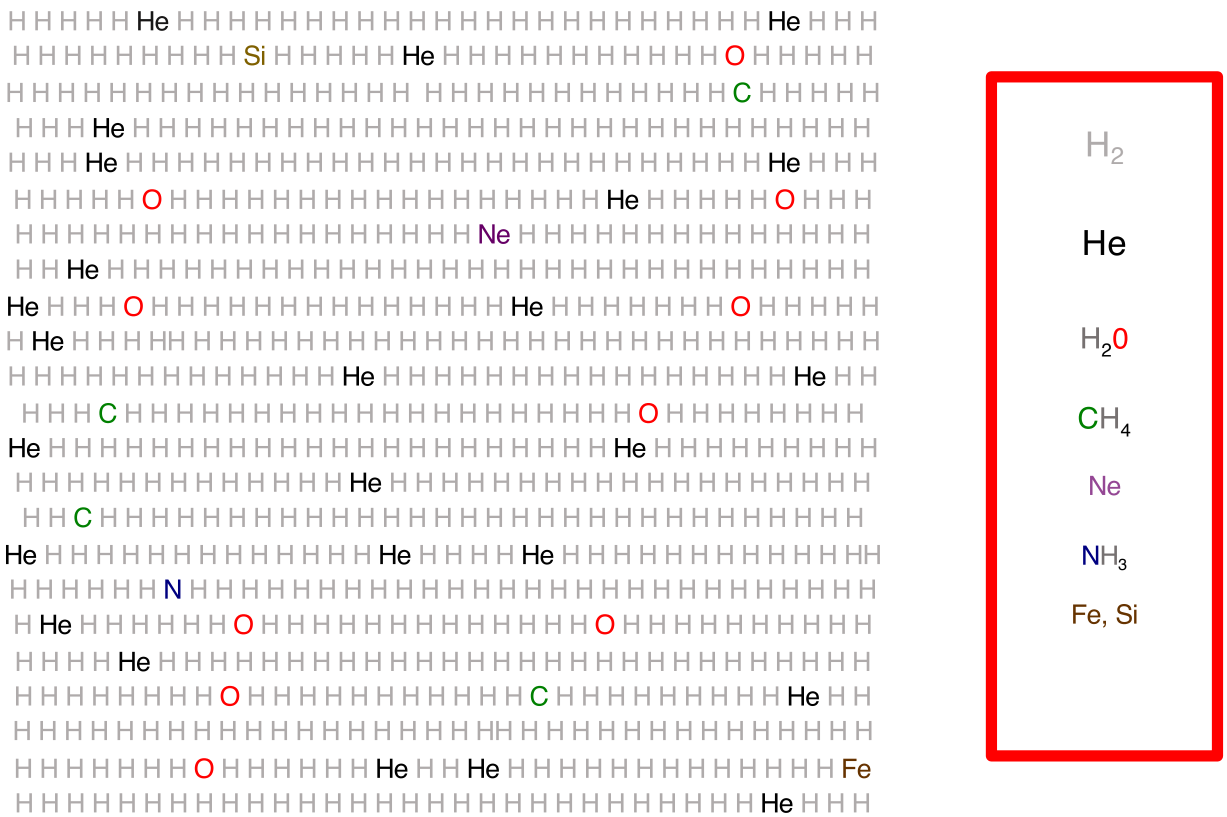
N (0.1%)

Si (0.06%)

Volatiles

Refractory

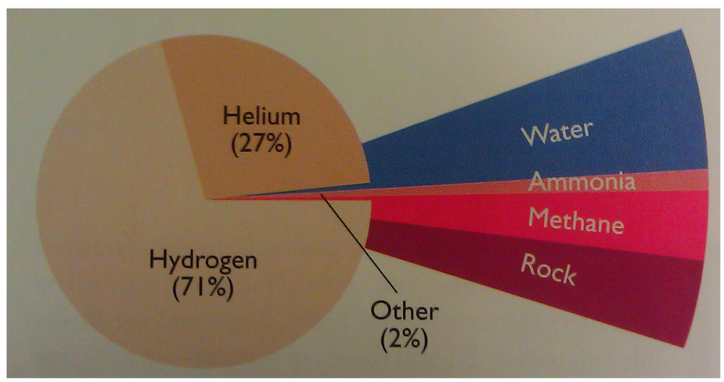
Chemistry



What will the chemistry of the mixture be?

H (71%)
He (27%)
0 (1.04%)
C (0.46%)
Ne (0.13%)
Fe (0.11%)
N (0.1%)
Si (0.06%)

H_2 He — Gas
H_20 - Water
CH_4 - Methane — Ices
Ne
NH_3 - Ammonia
Fe, Si – Rocks (metals and silicates) — Rock



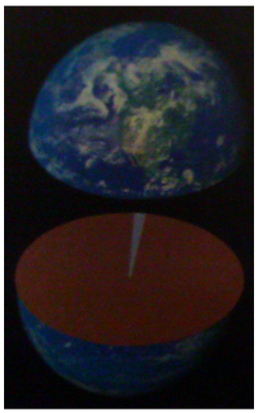
Classes of planets

Rocky Planets

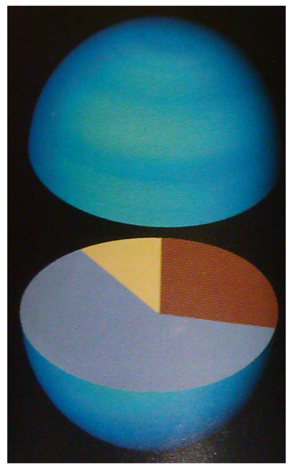
Ice Giants

Gas Giants

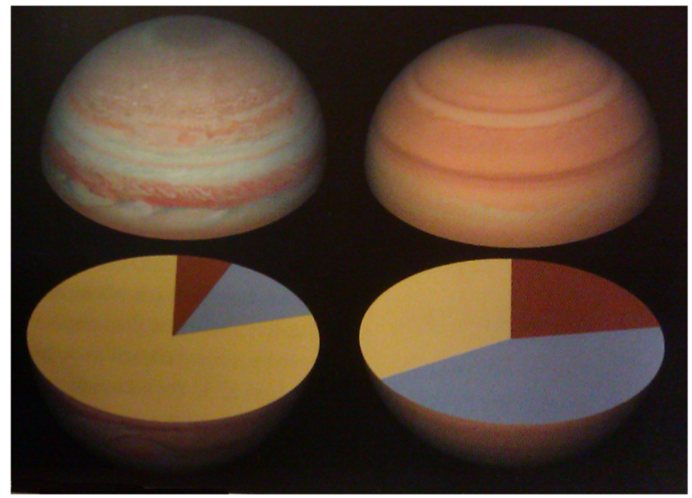
Earth



Uranus/Neptune



Jupiter   Saturn

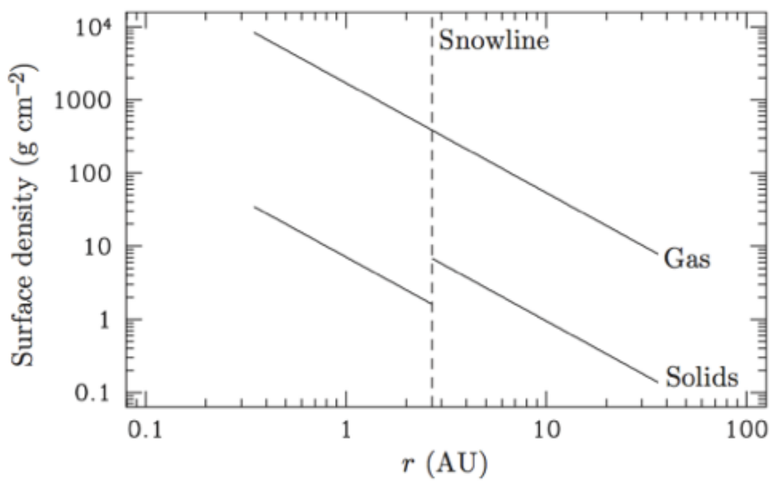


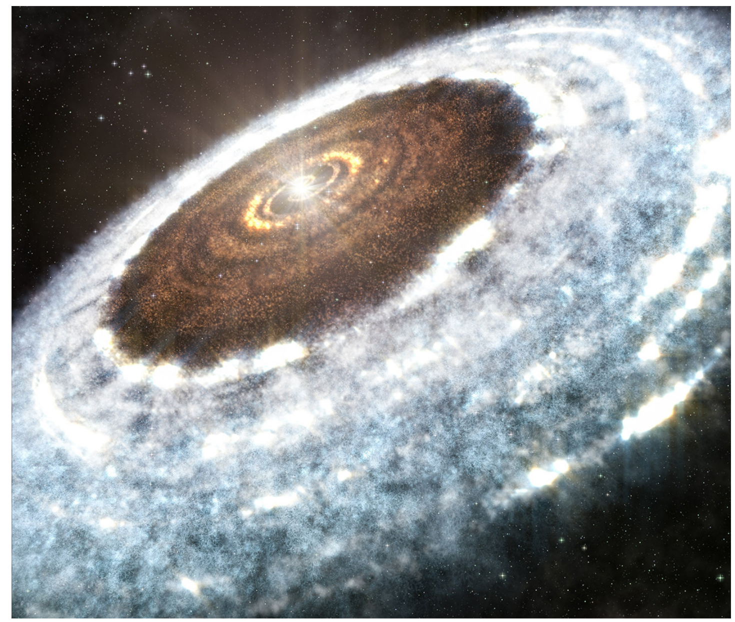
Rock

Ice

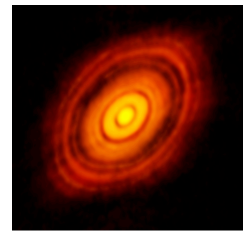
Gas

Snowline

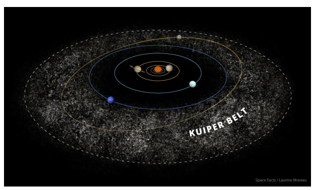

Snowline
Gas
Solids
Surface density (g cm^{-2})
10^4
1000
100
10
1
0.1
0.1
1
10
100
r (AU)



New Developments since the 1980s and 1990s

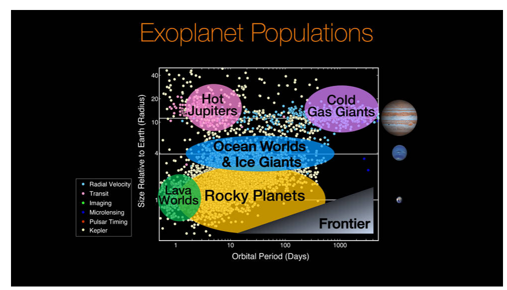


- Observations of Protoplanetary Disks
  (initial conditions)

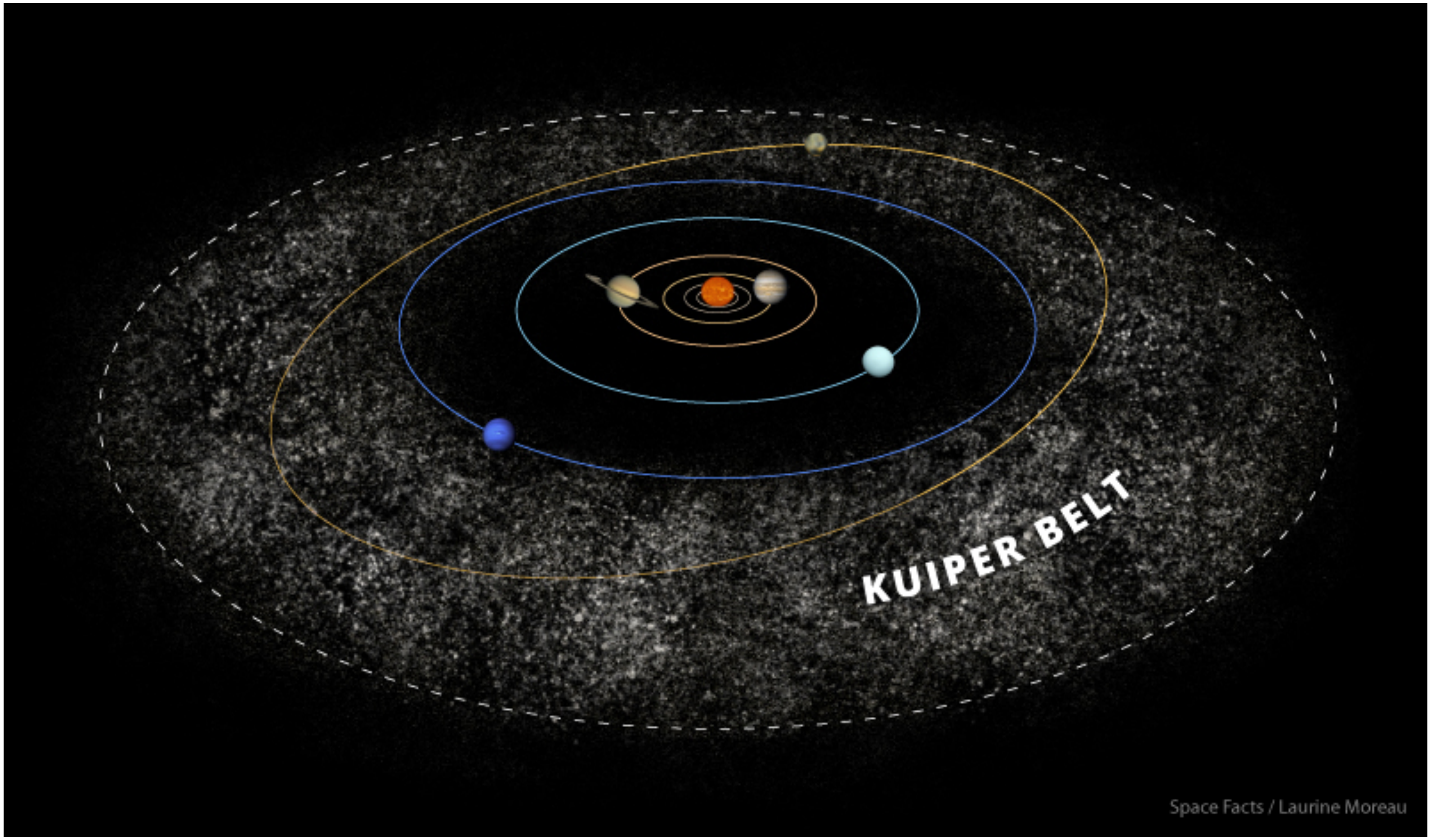


- Discovery of the Kuiper Belt
  (frozen leftovers of formations)

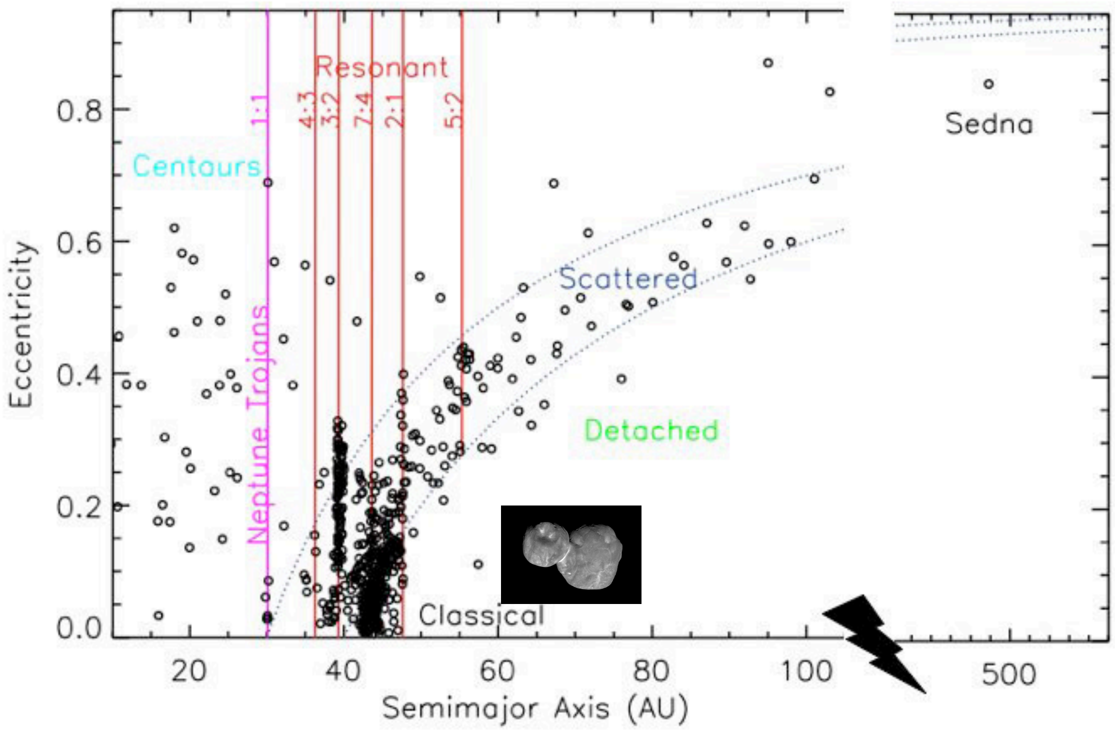
- Discovery of extrasolar planets
  (confirm earlier ideas but also points to diversity of outcomes)



Evidence from the Solar System



Kuiper Belt



Resonant
1:1
4:3
3:2
7:4
2:1
5:2
Centours
Neptune Trojans
Scattered
Detached
Classical
Sedna
0.0
0.2
0.4
0.6
0.8
Eccentricity
20
40
60
80
100
500
Semimajor Axis (AU)

Comets

Figure 1a: Comet Semimajor Axis Distribution

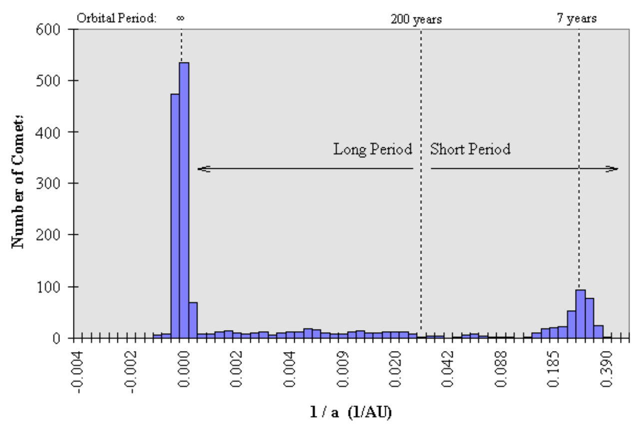
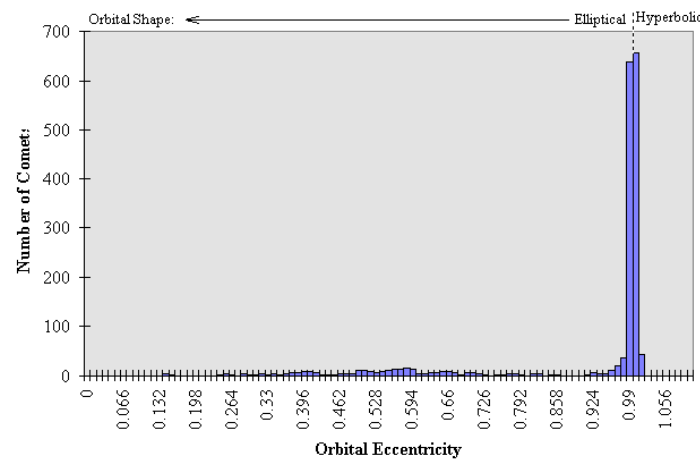


Figure 1b: Comet Eccentricity Distribution



A majority of comets have parabolic orbits

Figure 1a: Comet Semimajor Axis Distribution

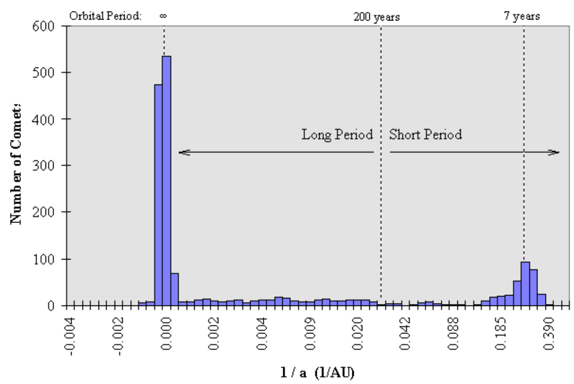
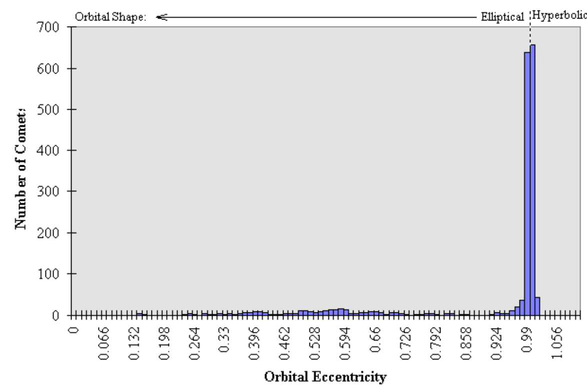
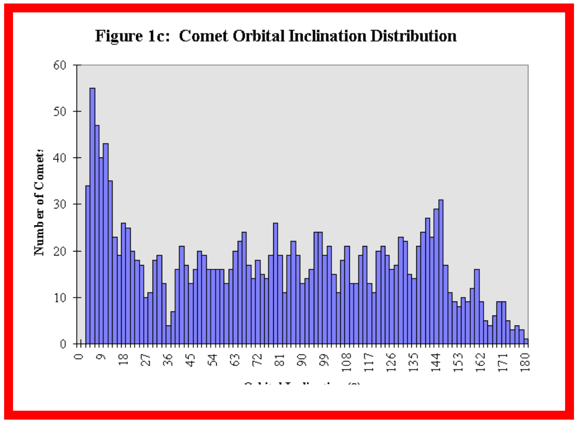


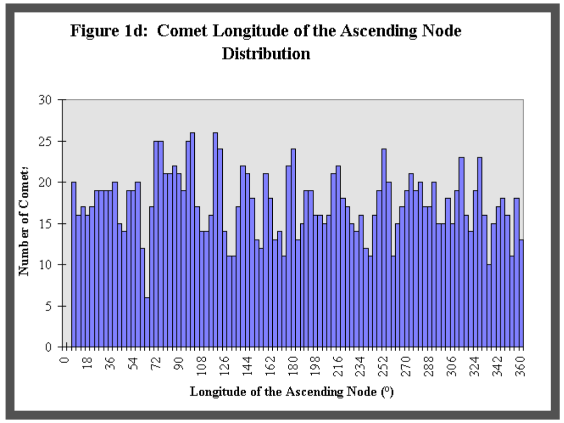
Figure 1b: Comet Eccentricity Distribution

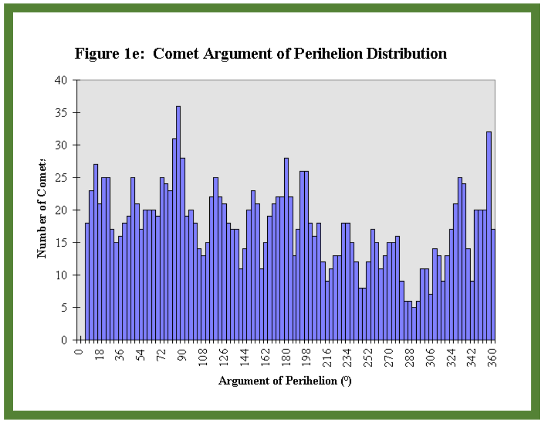




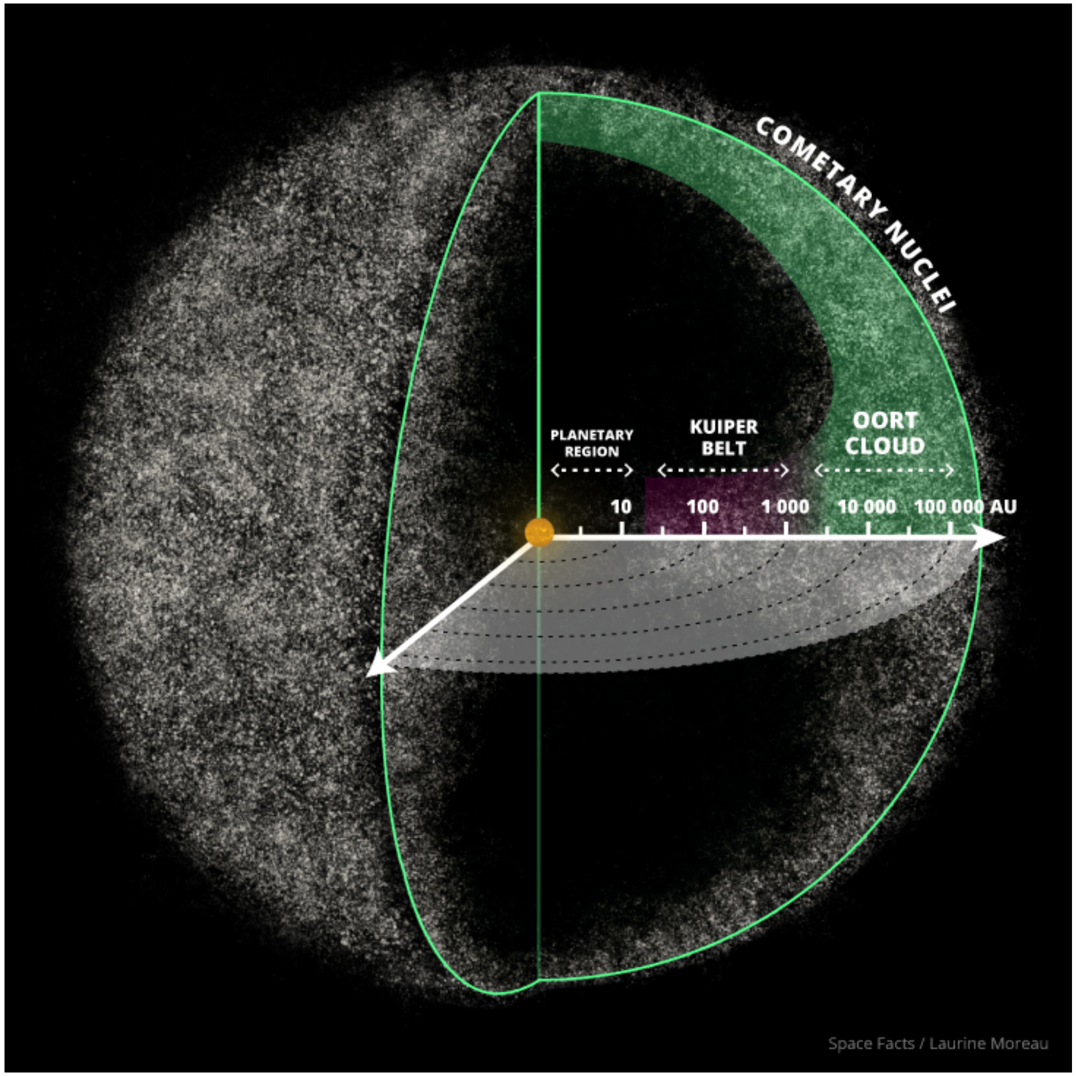
Inclination

Longitude of Ascending Node



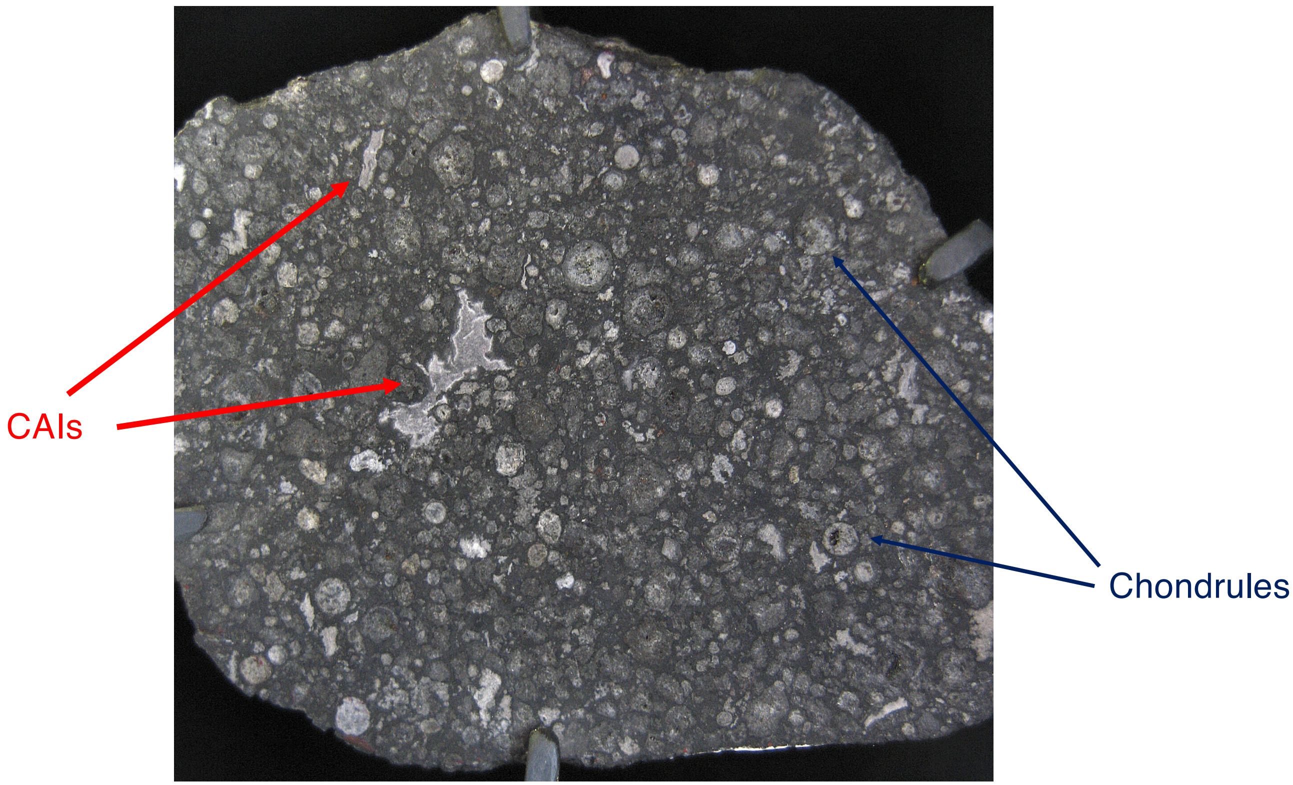


Argument of Perihelion


COMETARY NUCLEI
PLANETARY REGION
KUIPER BELT
OORT CLOUD
10
100
1 000
10 000
100 000 AU
Space Facts / Laurine Moreau

Chondrules

Chondrules and CAIs



Slice of the Allende meteorite

Nebular Lightning?

Fulgurite