Origin of the Solar System

We explore theories of the origin of the solar system, including the Sun, its entourage of planets and their moons, asteroids, and comets. We examine the evidence that the Sun and planets formed about 4.6 billion years ago, having condensed from an interstellar cloud of gas and dust, one of many dotting the spiral arms of the Milky Way Galaxy.

Key Physical Concepts to Understand

- Condensation *of Planets in a Gas Cloud Enveloping the Sun*

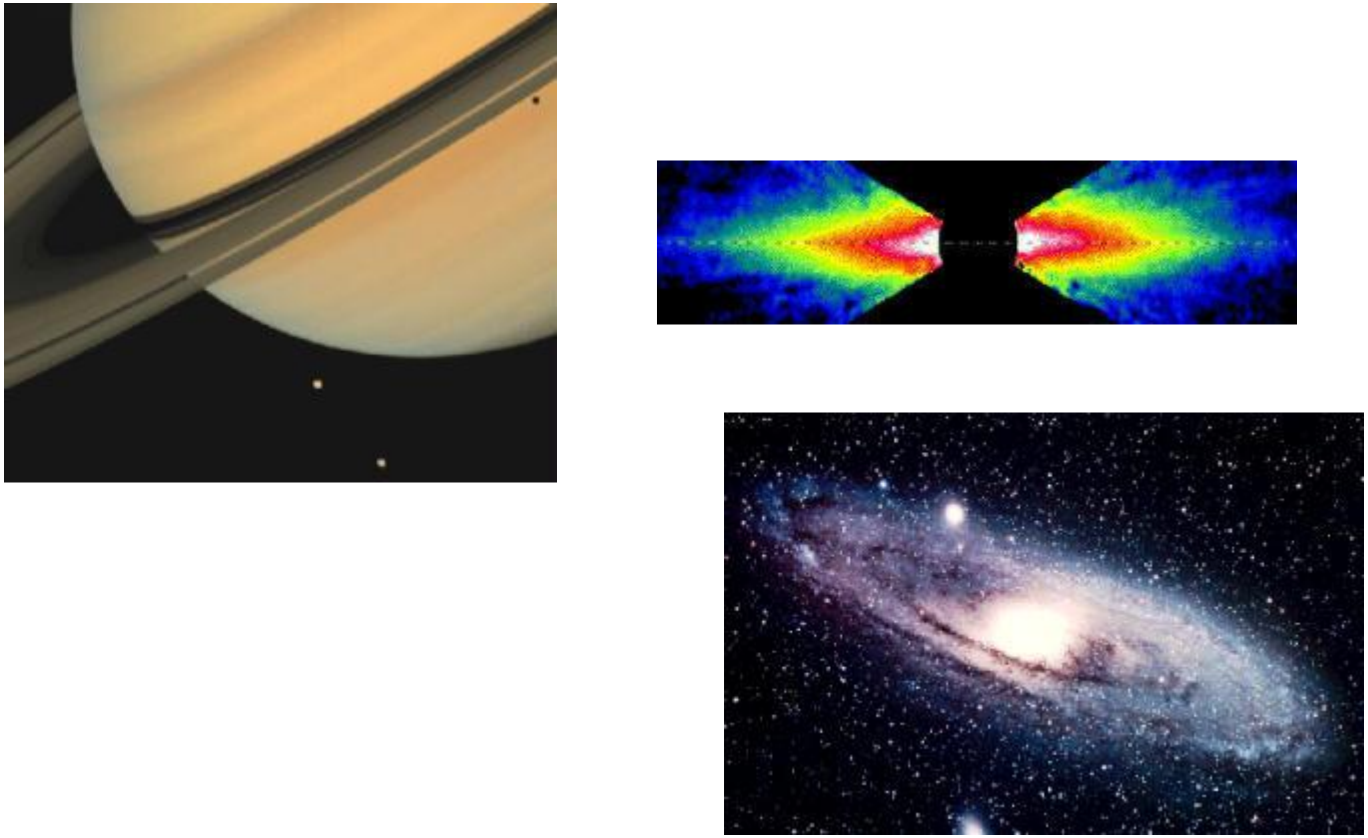


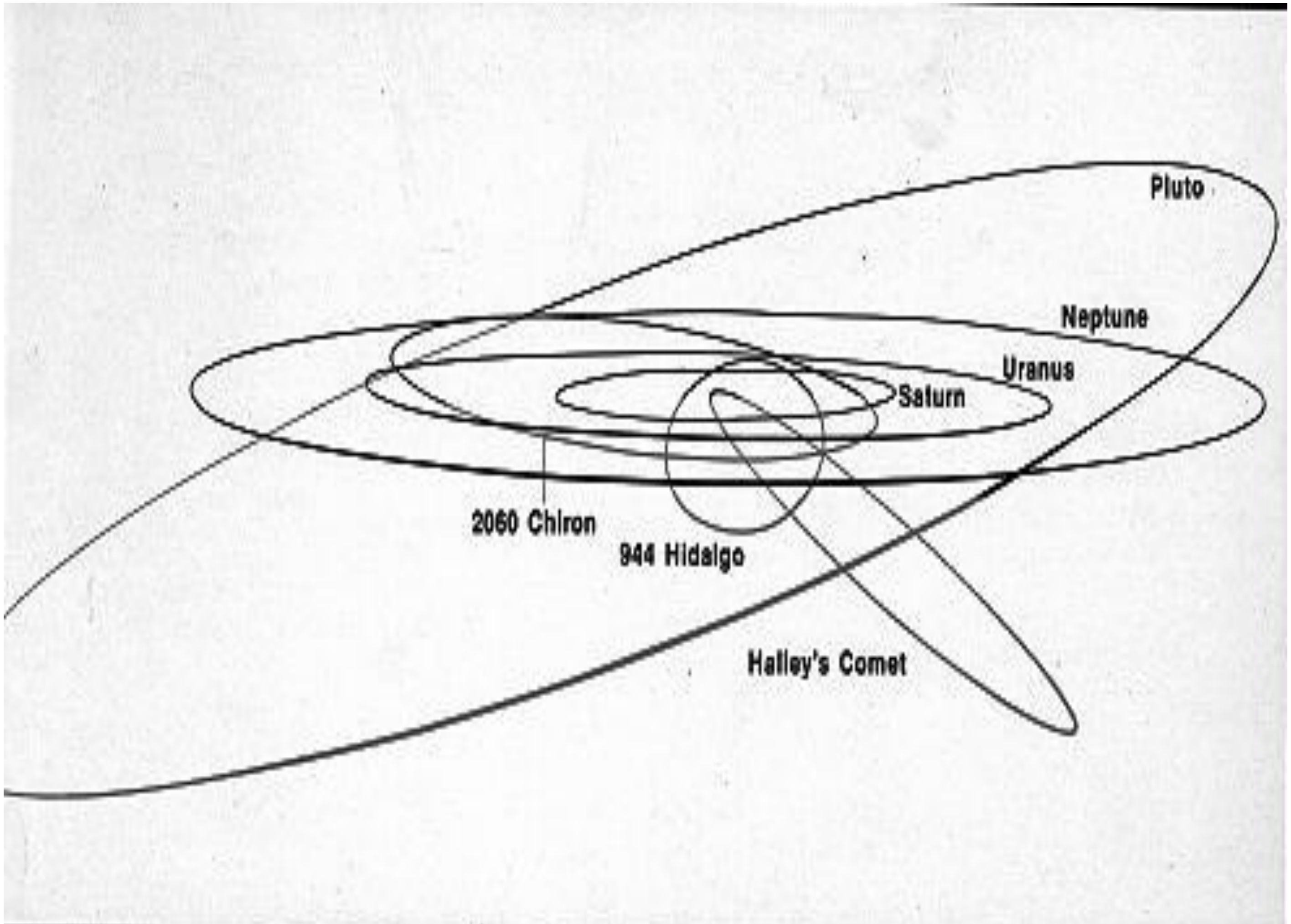
Figure 1. Cosmic Disks formed by the Interaction of Gravity and Centrifugal Force: **Panel A.** Saturn **NASA. Panel B.** An infrared (thermal) image of the dust surrounding the star b Pictoris with a warm preplanetary dust disc seen edge-on **NASA. Panel C.** The nearby spiral Andromeda galaxy (M31) viewed nearly edge-on. **The Electronic Universe Project.**

Introduction

- To ancients, the Solar System (along with a celestial sphere containing the stars) *was* the Universe.
- **In the last half of the twentieth century, scientists have finally been able to develop solid evidence bearing on the formation of the Solar System, including**
  - **returned lunar samples,**
  - **laboratory analyses of meteorites,**
  - **computer models of solar system formation,**
  - **and telescopic observations of star formation regions.** T
- led to a widely, but not universally, accepted broad hypothesis that the solar system **formed out of a collapsing interstellar cloud of gas and dust, triggered by a nearby supernova,** an exploding star : **the modern nebular theory for the formation of the Solar System**.
- evidence is still being gathered and weighed**; the jury is still out**

Three lines of evidence

- The first is the strikingly **systematic organization of the orbits and rotation of the Sun, planets and their satellites**.
- **The systematic nature of planetary composition, and**
- **The measured ages of terrestrial, lunar, and meteorite samples**.


Pluto
Neptune
Uranus
Saturn
2060 Chiron
944 Hidalgo
Halley's Comet

Evolutionary Theories are Fundamental

- **Since 1644, when René Descartes proposed that stars and planets condensed out of eddies in an interstellar gas**. Little observational evidence was available
- **Now, after sample return missions from the moon, modern geochemical studies of meteorites, and advanced computer models of possible solar system scenarios, dramatic progress has been made.**
- It is generally accepted by modern astronomers that **the solar system formed in the gravitational collapse of an interstellar cloud of gas and dust into a disk, about 4.6 billion years ago**.
- This agrees with most, but not all, of the observed age, composition, and orbital evidence.
- A major advantage of this modern nebular theory over the catastrophic theory is that the **same scenario invoked to describe the formation of the Sun is also used to explain the formation of the surrounding planets, comets, and asteroids. No special circumstances are needed for forming the planets..**

What any theory must address.

- **Why do the orbits of the planets lie in the same plane ?**
- **Why do the nine planets and asteroids all orbit the Sun with prograde revolution?**
- **Why does the Sun rotate in this prograde sense?**
- **Why are the orbits of the planets nearly circular?**
- **Why do six of the eight planets have prograde rotation? (With the exception of Venus and Uranus)**
- **Why does the rotational equator of the Sun and most planets (except for Uranus) lie close to the ecliptic plane?**
- **Why does Bode's Rule describe the nearly regular spacing of planetary orbits? (Each planet has approximately twice the distance to the Sun as its nearest inner neighbor.)**

Questions of Planetary Composition

- **Why do the planets vary systematically in composition and density, with the innermost planets tending toward high density and heavy elements, and the outermost planets tending toward low density and substances of low melting point (Table 1)?**

Gross Properties of the Planets

Table 1: Gross Properties of the Planets

Planet	**Distance AU**	**Diameter 10^3 km**	**Mass (Earth = 1)**	**Density (gm/cm^3)**	**Orbital Inclination**
Mercury	0.39	4.9	0.055	5.4	7.0°
Venus	0.72	12.1	0.82	5.25	3.6°
Earth	1.00	12.7	1.00	5.52	--
Mars	1.52	6.8	0.11	3.93	1.9°
Jupiter	5.20	143	318	1.33	1.3°
Saturn	9.54	120	95	0.71	2.5°
Uranus	19.2	51	15	1.27	0.8°
Neptune	30.1	50	17	1.70	1.8°
Pluto	39.4	2.4	0.03	1.99	17.2°

Radioactive Dating

- Meteorites have been dated by measuring the relative abundances of radioactively decaying isotopes and their decay products.
- Most meteorites have been dated at 4.6 billion years within a period of about 100 million years.
- The oldest rock samples returned from the Moon have also have been dated at 4.6 billion years, leading most scientists to the conclusion that the Moon, asteroid parent bodies, and the major planets solidified some 4.6 billion years ago over a cosmically short interval: only 100 million years.
- The oldest rocks on the Earth's surface are only 3.8 million years old, as weathering and plate tectonics have served to remove the primordial surface of the Earth and repave it with more recently formed rock.

Catastropic Theory

- Jeans and Jeffreys 1917
- Sun suffered a near-collision with another star. Extreme tides ripped matter out of the Sun in a gigantic arc (Figure 4). The matter in this arc subsequently condensed to form planets, like beads on a string.
- Generally accepted until 1930

Evolutionary Theories, having evolved from Renee Descartes, 1644

- generally accepted by modern astronomers that **the solar system formed in the gravitational collapse of an interstellar cloud of gas and dust into a disk, about 4.6 billion years ago**.
- **same scenario invoked to describe the formation of the Sun is also used to explain the formation of the surrounding planets, comets, and asteroids. No special circumstances are needed**

Flaws in Catastropic Theory

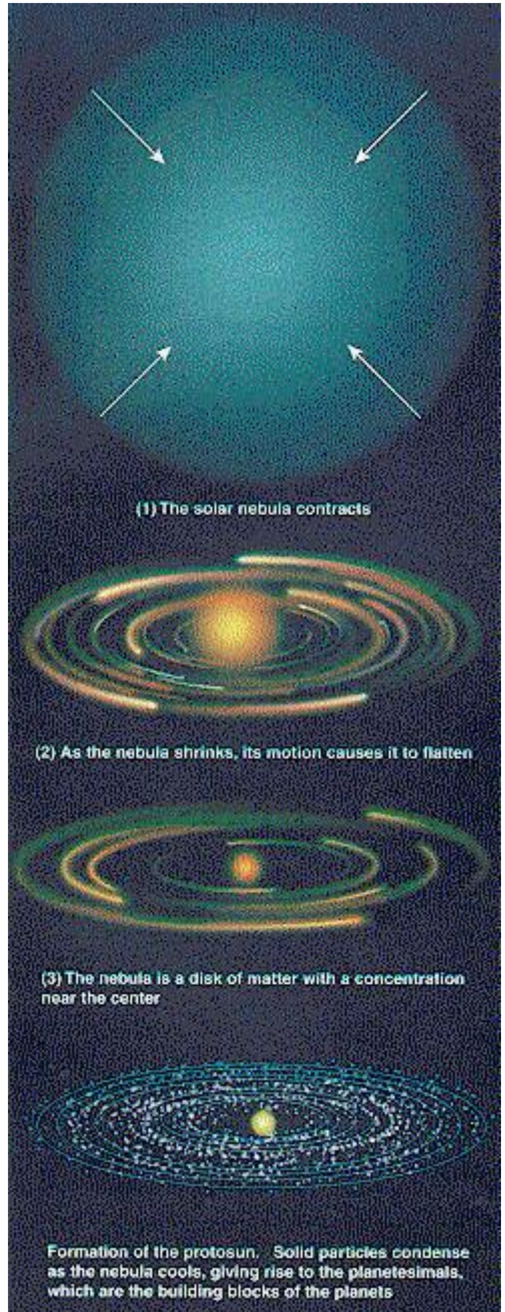
- **it did not satisfactorily explain the spin, or angular momentum, measured in the planets,**
- **it is improbable that the gas from the Sun would have cooled sufficiently to condense planets before**
- **it dispersed,it did not account for formation of planetary satellite systems, and**
- **close encounters between stars in our galaxy are extremely rare.**

Collapse of an Interstellar Cloud

collapse of an interstellar cloud of gas and dust into a lens-shaped disk, which eventually coalesced to form the planets.

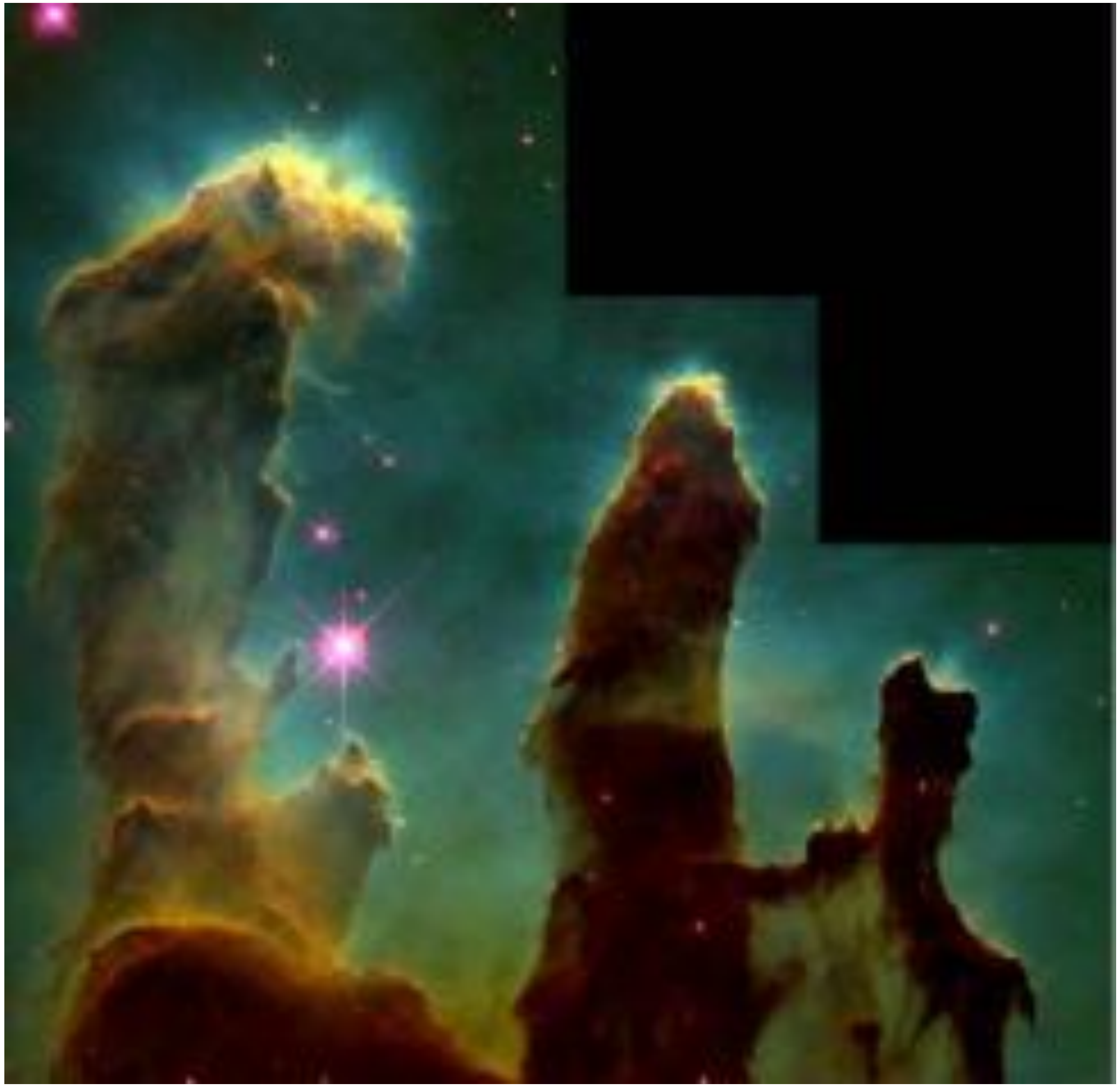
7 stages:

1. **the initial collapse and fragmentation of an interstellar cloud,**
2. **the free-fall of material in a cloud fragment to form a preplanetary disk,**
3. **the internal heating of the disk until pressure balances gravity,**
4. **the condensation of liquid droplets and/or solid grains,**
5. **the formation of the Sunthe coagulation of grains to form planetesimals,**
6. **the gravitational accumulation of planetesimals to form planets and**
7. **the early evolution of the protoplanets into the planets**


(1) The solar nebula contracts
(2) As the nebula shrinks, its motion causes it to flatten
(3) The nebula is a disk of matter with a concentration near the center
Formation of the protosun. Solid particles condense as the nebula cools, giving rise to the planetesimals, which are the building blocks of the planets

Evidence of Formation from Cloud Collapse

1. **the initial collapse and fragmentation of an interstellar cloud: star formation in interstellar clouds & meteorites**
2. **the free-fall of material in a cloud fragment to form a preplanetary disk: orbits and spins of planets, protoplanetary disks around other stars**
3. **the internal heating of the disk until pressure balances gravity: meteorite compositions**
4. **the condensation of liquid droplets and/or solid grains: density & composition of planets**
5. **the formation of the Sun the coagulation of grains to form planetesimals: T Tauri stars**
6. **the gravitational accumulation of planetesimals to form planets:**
7. **the early evolution of the protoplanets into the planets**



Star formation in a collapsing molecular cloud. HST image of the Eagle Nebula.

Continued

6. the gravitational accumulation of planetesimals to form planets:

- ***dust clouds of silicate composition are observed around recently formed stars,***
- ***the chemical composition of meteorites,***
- ***comets and asteroids appear to be planetesimals or fragments of planetesimals,***
- ***the extensive cratering on the surfaces of the terrestrial planets, satellites, and asteroids nearly circular orbits of the planets,***
- ***the regular spacing between the planets.***

Evidence for protoplanetary dust disks in the Orion Nebula.

Continued

7. the early evolution of the protoplanets into the planets

- **Planetary formation occurred about 4.6 billion years ago.**
- **First protoplanets formed by the accumulation of planetesimals in the solar nebula. As planetesimals collided forming larger masses, and were bombarded by smaller projectiles, these protoplanets were heated past the melting point for solid rock by these high-energy impacts.**
- **The resulting protoplanets were probably molten throughout. It may have been such a collision that literally knocked Uranus off its axis, leaving its pole in the ecliptic plane.**
- **After most of the larger debris in the solar system was incorporated into the protoplanets, they began to cool, forming solid surfaces.**
- **The planetesimals and smaller debris left in the solar system bombarded and cratered planetary surfaces for almost a billion years, leaving the surfaces scarred with craters, many that we still see today on the surfaces of the Moon and Mercury, and to a lesser extent Mars.**
- **Weathering has removed all but a few crater remnants on the Earth.**

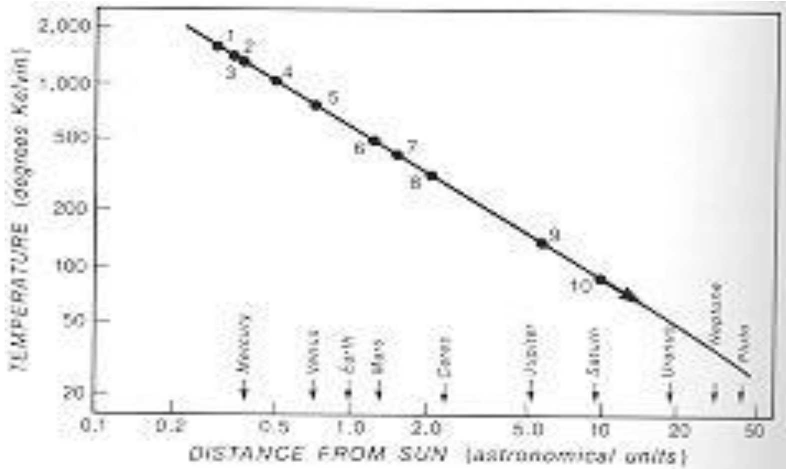
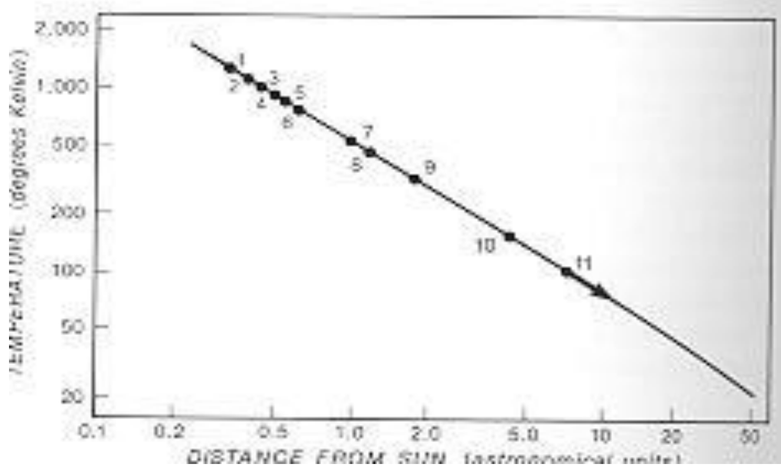


Fig. 6. Indicated in this diagram are the temperatures and locations at which major planetary constituents would be expected to condense from the primordial solar nebula (at a more evolved and cooler stage than in Fig. 3): *1*, refractory minerals like the oxides of calcium, aluminum, and titanium, and rare metals like tungsten and osmium; *2*, common metals like iron, nickel, cobalt, and their alloys; *3*, magnesium-rich silicates; *4*, alkali feldspars (silicates rich in sodium and potassium); *5*, iron sulfide; *6*, the lowest temperature at which unoxidized iron metal can exist; *7*, hydrated minerals rich in calcium; *8*, hydrated minerals rich in iron and magnesium; *9*, water ice; and *10*, other ices.



Evidence of Early Stages of Planet Formation

- ***ages of terrestrial rock samples, lunar return samples, and meteorites, the age of the solar system is estimated to be 4.6 billion years.***
- ***episode of extensive cratering has been recorded in craters on the Moon, other natural satellites, Mercury, Venus, Mars, asteroids, and the Earth.***
- ***The effects of weathering via wind and water are seen on the surfaces of the Earth and the other terrestrial planets. Differentiation has caused the Earth to separate into a dense core, a mantle, and a crust floating on the mantle.***
- ***Differentiation is also supported by the composition of meteorites, which appear to be fragments of shattered planetesimal/parent body.***
- ***The densities of the gas giants are consistent with a rocky/metallic core surrounded by volatiles in solid, liquid, and gaseous form.***

Formation of Natural Satellites

- larger planetary satellites have prograde spin and prograde, circular orbits in the equatorial plane of their primary planet, and are regularly spaced in their distance from their primary planet as the planets/Sun
- Two formation theories
  - Satellites formed along with their mother planet.
  - Satellites formed elsewhere in the solar system and were later captured by their primary planet.
- The first theory is thought to explain the larger satellites. The second theory would explain those smaller satellites that have irregular orbits.

Evidence of Satellite Formation

- **inner satellites of Jupiter and Saturn have regular** (circular, prograde, and low inclination) orbits and exhibit a regular increase in orbit spacing with distance from the primary planet.
- **regular satellites of Jupiter exhibit a decreasing density with increasing distance from Jupiter**
- Nearly all of satellites of the gas giant planets can probably be explained by **capture of rogue solid bodies in the early solar system**

Formation of other Small Bodies

- Lunar formation: capture, daughter, and co-formation theories
- Asteroids
  - proximity of the huge planet Jupiter served to collect much of the available matter near the asteroid belt, starving the region of planetesimals
- Comets
  - Comets formed in the outer solar system and were ejected into the Oort comet cloud by the gravitational influence of the gas giants.
  - Comets formed outside the solar system but were swept into it as it traveled through space.