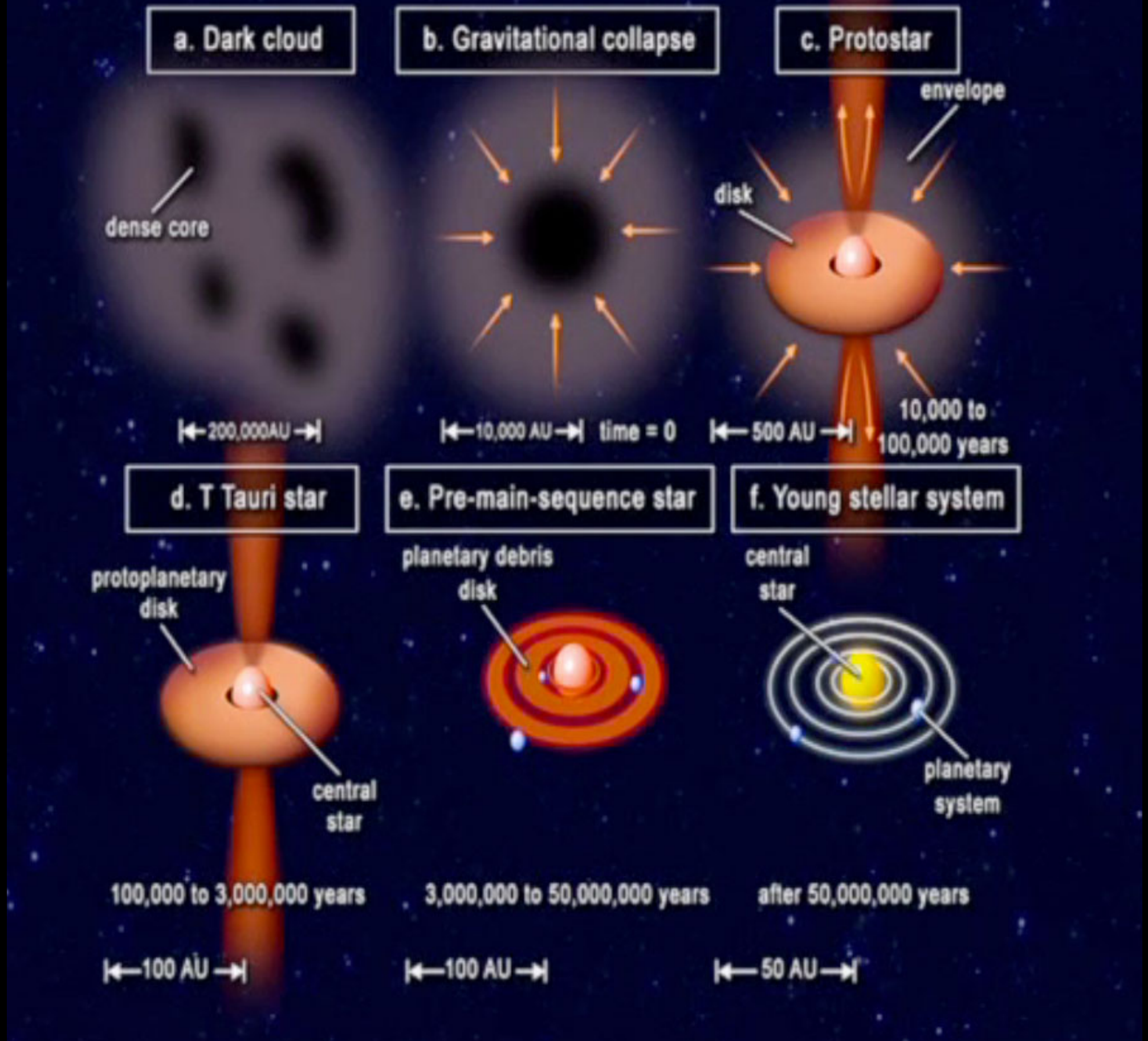

a. Dark cloud
b. Gravitational collapse
c. Protostar
envelope
disk
dense core
200,000AU
10,000 AU
time = 0
500 AU
10,000 to
100,000 years
d. T Tauri star
e. Pre-main-sequence star
f. Young stellar system
protoplanetary
disk
central
star
planetary debris
disk
central
star
planetary
system
100,000 to 3,000,000 years
3,000,000 to 50,000,000 years
after 50,000,000 years
100 AU
100 AU
50 AU

How did our solar system come to be?

National Aeronautics and Space Administration

NASA

4.6 Billion Years Ago

It all began about 4.6 billion years ago in a wispy cloud of gas and dust.

At some point, part of the cloud collapsed in on itself—possibly because the shockwave of a nearby supernova explosion caused it to compress.

The result: a flat spinning disk of dust and gas.

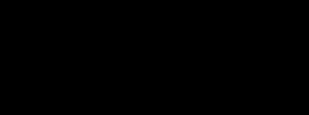
When enough material collected at this disk's center, nuclear fusion began. Our sun was born. It gobbled up 99.8% of all the material.

These clumps became planets, dwarf planets, asteroids, comets, and moons.

This cloud was a small part of a much bigger cloud.

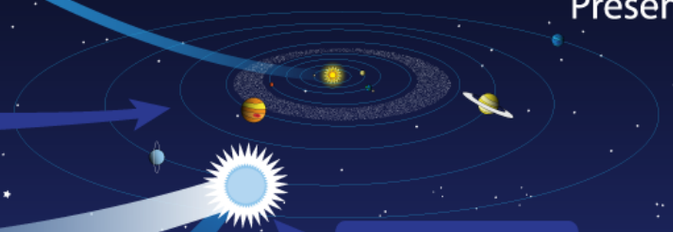
Nuclear fusion occurs when hydrogen atoms fuse into helium.

The material left behind by the sun clumped together into bigger and bigger pieces.



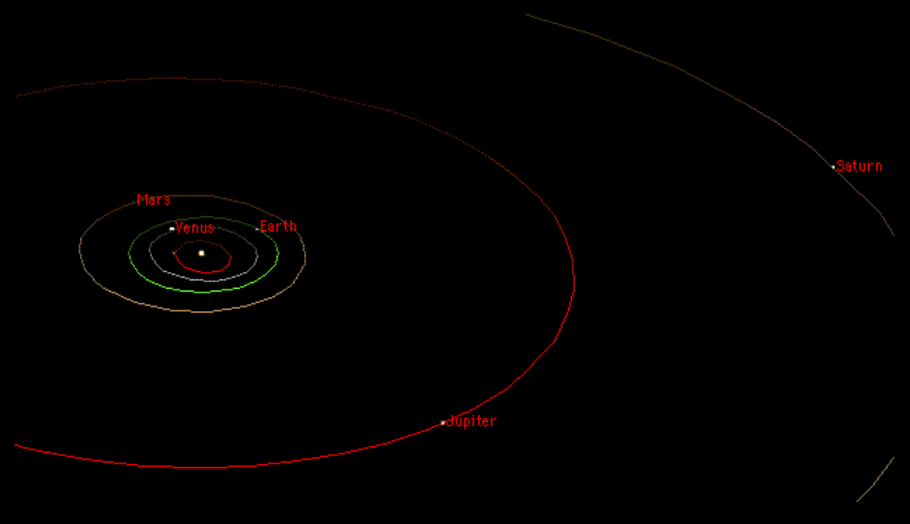
Only rocky things could survive close to the sun, so gaseous and icy material collected further away. That's how our solar system came to be the place it is today!

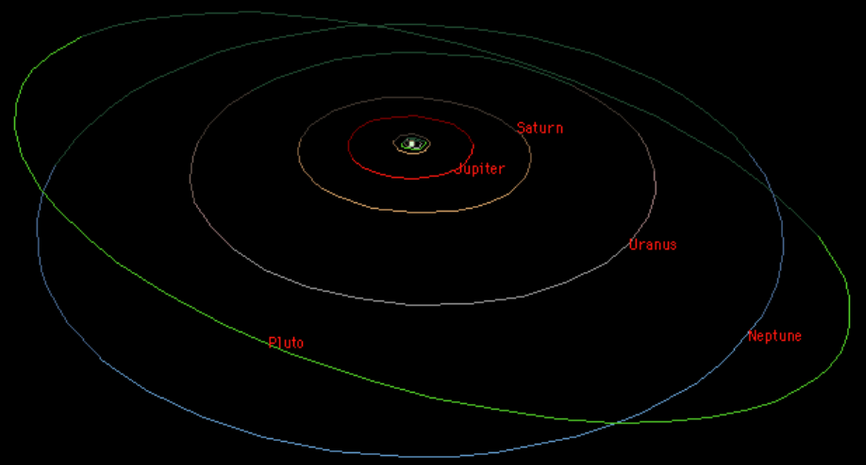
Present



Comets and asteroids are the left over remains of the solar system's formation.

Not to Scale





Any model or theory for the formation of the Solar System must have a set of explanations for large-scale and small-scale properties.

Large-Scale:

the planets are isolated in orderly intervals
orbits are nearly circular
orbits are in the same plane
all planets revolve prograde

Small-Scale:

most planets rotate prograde

the systems of moons can be divided into regular objects (spherical) with direct orbits versus irregular objects with eccentric orbits

terrestrial planets have

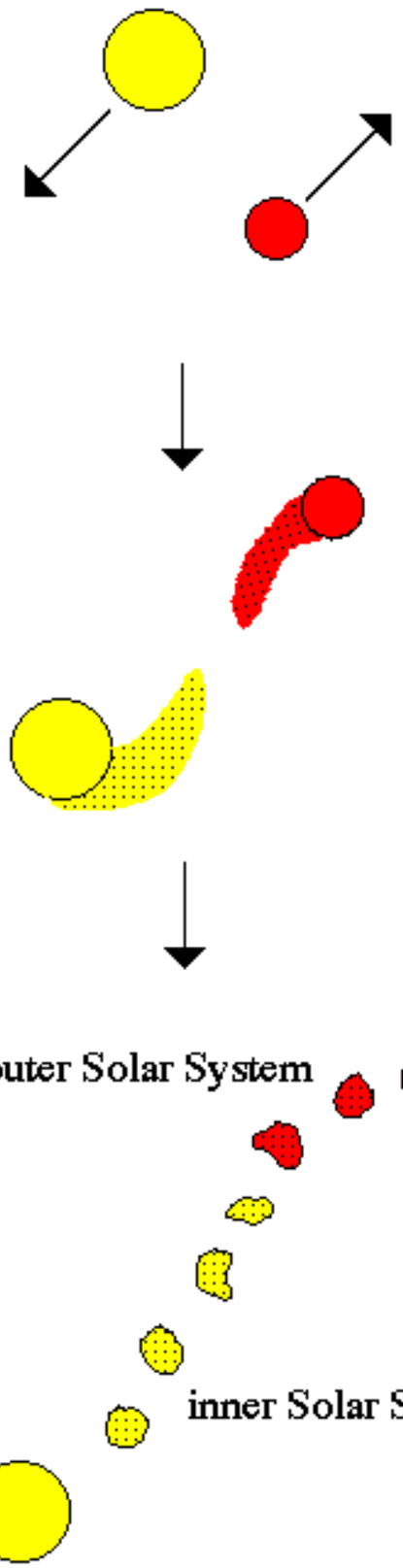
1) high densities
2) thin or no atmospheres
3) rotate slowly
4) rocky, poor in ices and H/He

jovian worlds have

1) low densities
2) thick atmospheres
3) rotate rapidly
4) many moons
5) fluid interiors, rich in ices, H/He

most of outer SS objects (not just jovian worlds) are ice-rich

Encounter Hypothesis



rogue star passes close to the Sun

gas is tidally removed from both rogue star and Sun

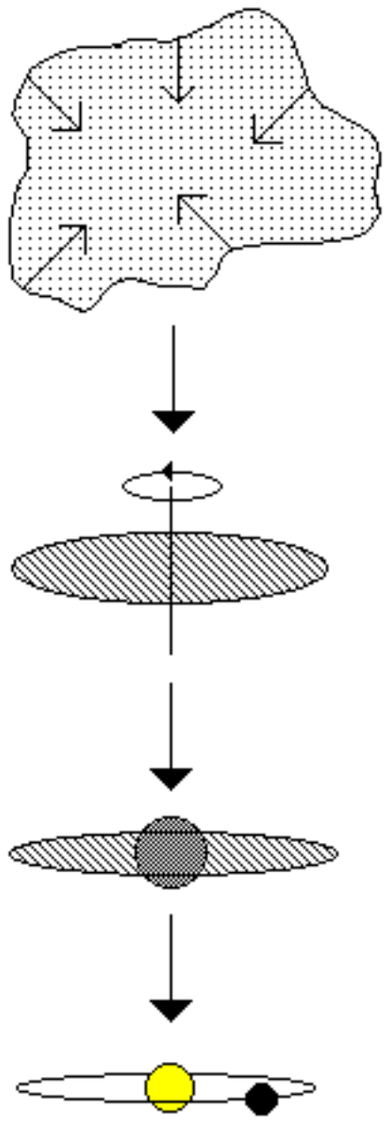
outer Solar System

rogue star material is less dense and becomes outer Solar System planets

inner Solar System material is more dense and becomes terrestrial planets

inner Solar System

Nebular Hypothesis



self–gravity contracts a gas cloud

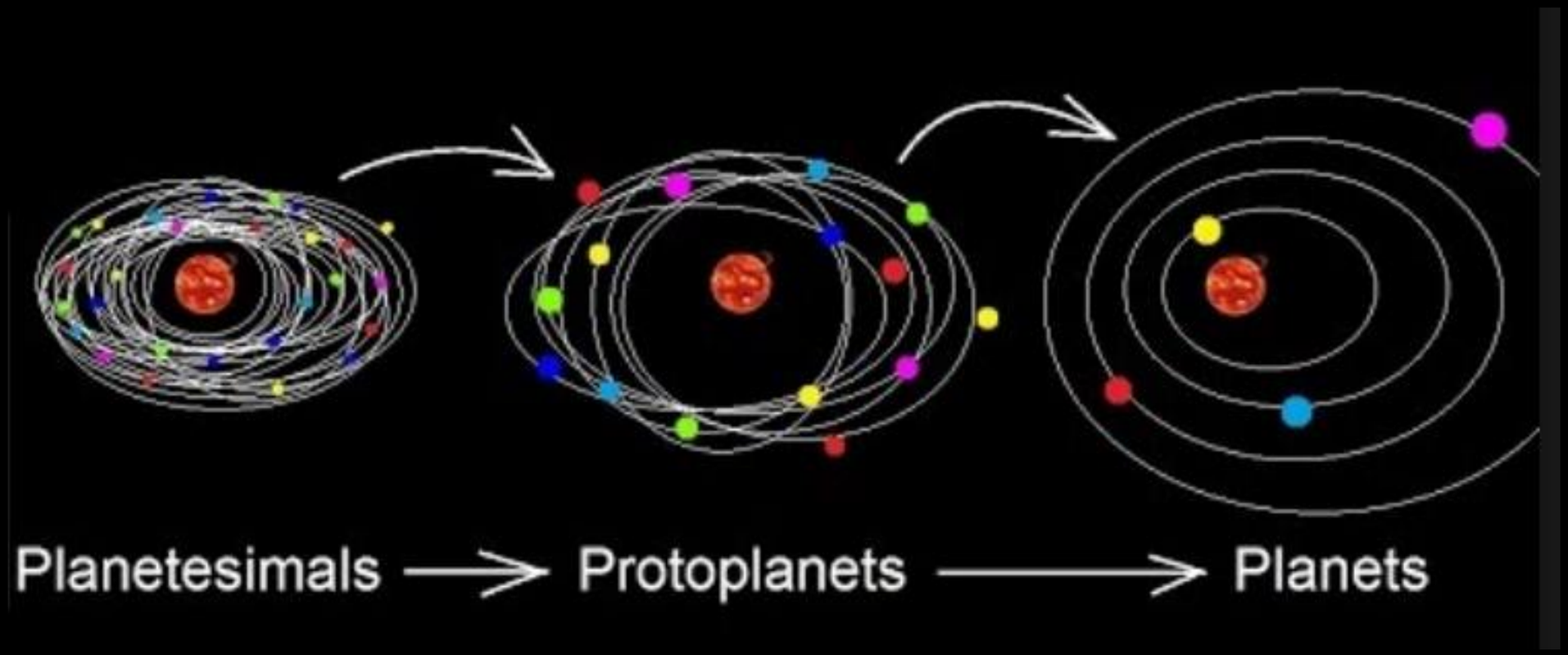
conservation of angular momentum pulls cloud into a disk

disk begins to rotate

central mass forms (proto–Sun)

centrifugal force balances gravitational forces and a ring forms

ring forms into a planet


Planetesimals
Protoplanets
Planets

Protoplanet Hypothesis

Milky Way galaxy is filled with cold (10 K) clouds of molecular hydrogen gas, also filled with dust

↓

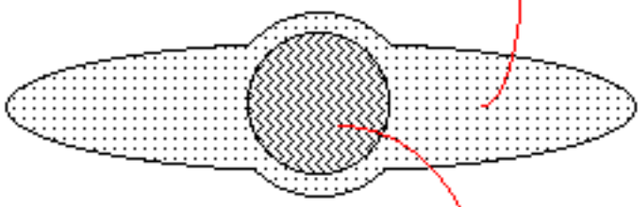
dust provides sites for condensation of gas → ice–covered dust

↓

cloud begins to collapse under self–gravity
dust begins to accrete

↓

cloud collapse to a rotating disk

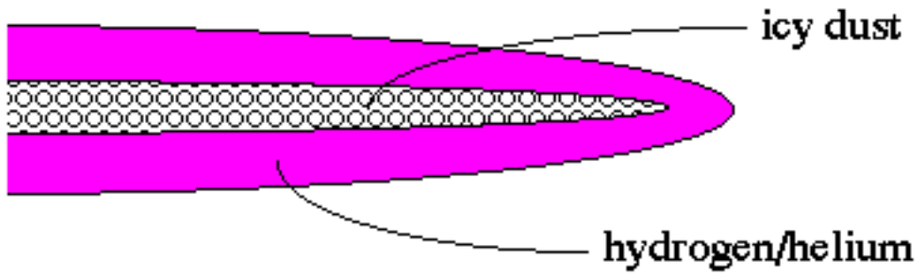


↙ inner region

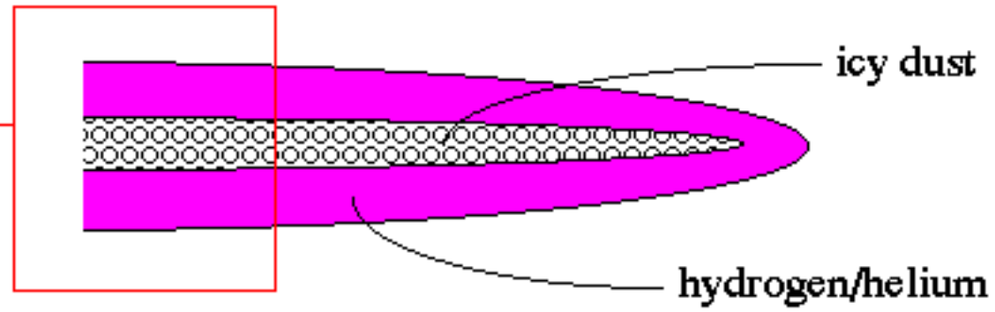
denser, collapses faster
proto–Sun forms before planets

↘ outer region

evolves slower into thin disk of particles
and a thicker outer disk of gases



early solar system disk

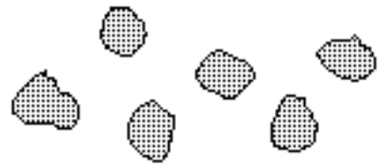


inner disk

closer to proto–Sun, warmer

warm enough to vaporize lighter compounds (H_2O, CO_2, NH_4)
metals and silicates stay as solids

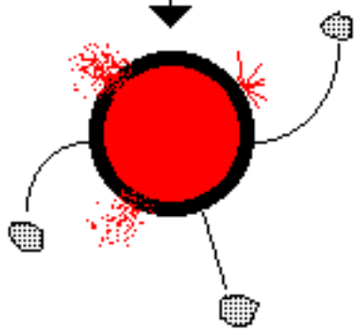
small planetesimals form



planetesimals collect to
form the terrestrial planets

infall of particles produces molten spheres

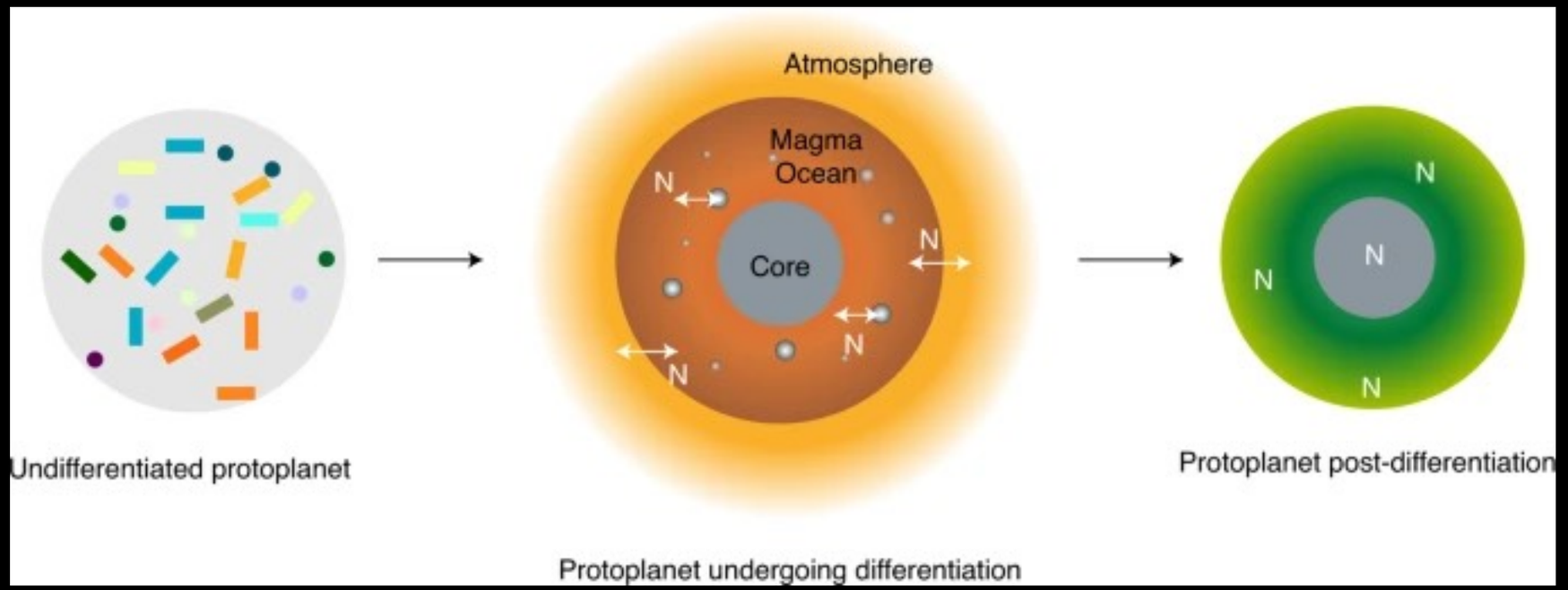
sphere's cool, early crusts form

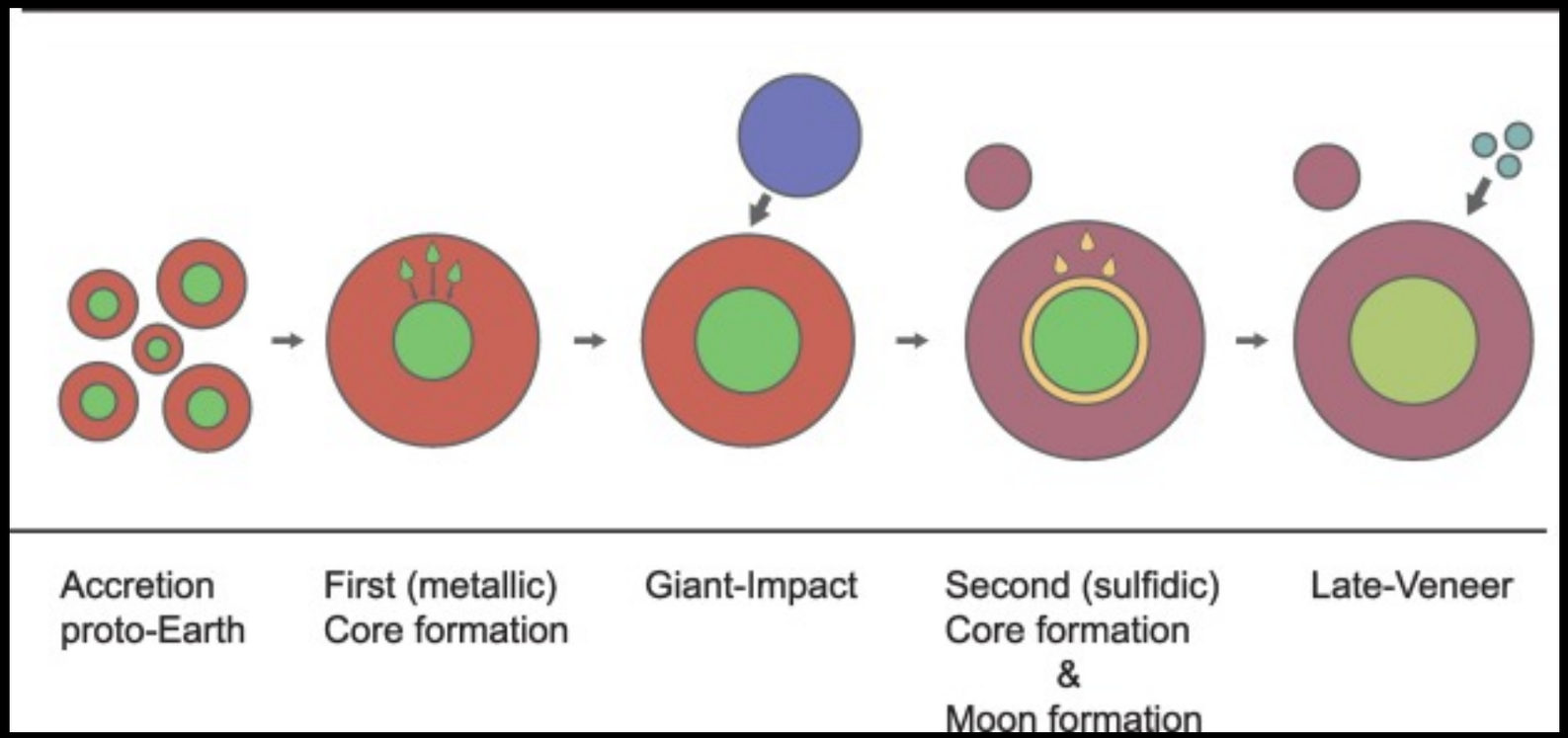


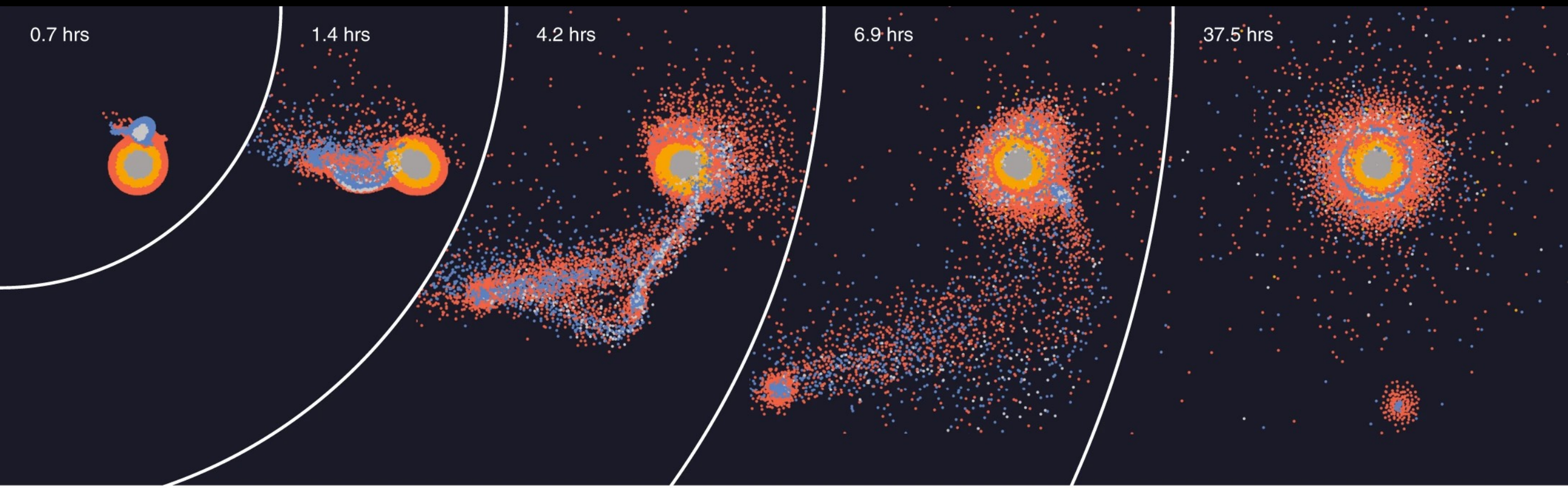
bombardment by remaining planetesimals

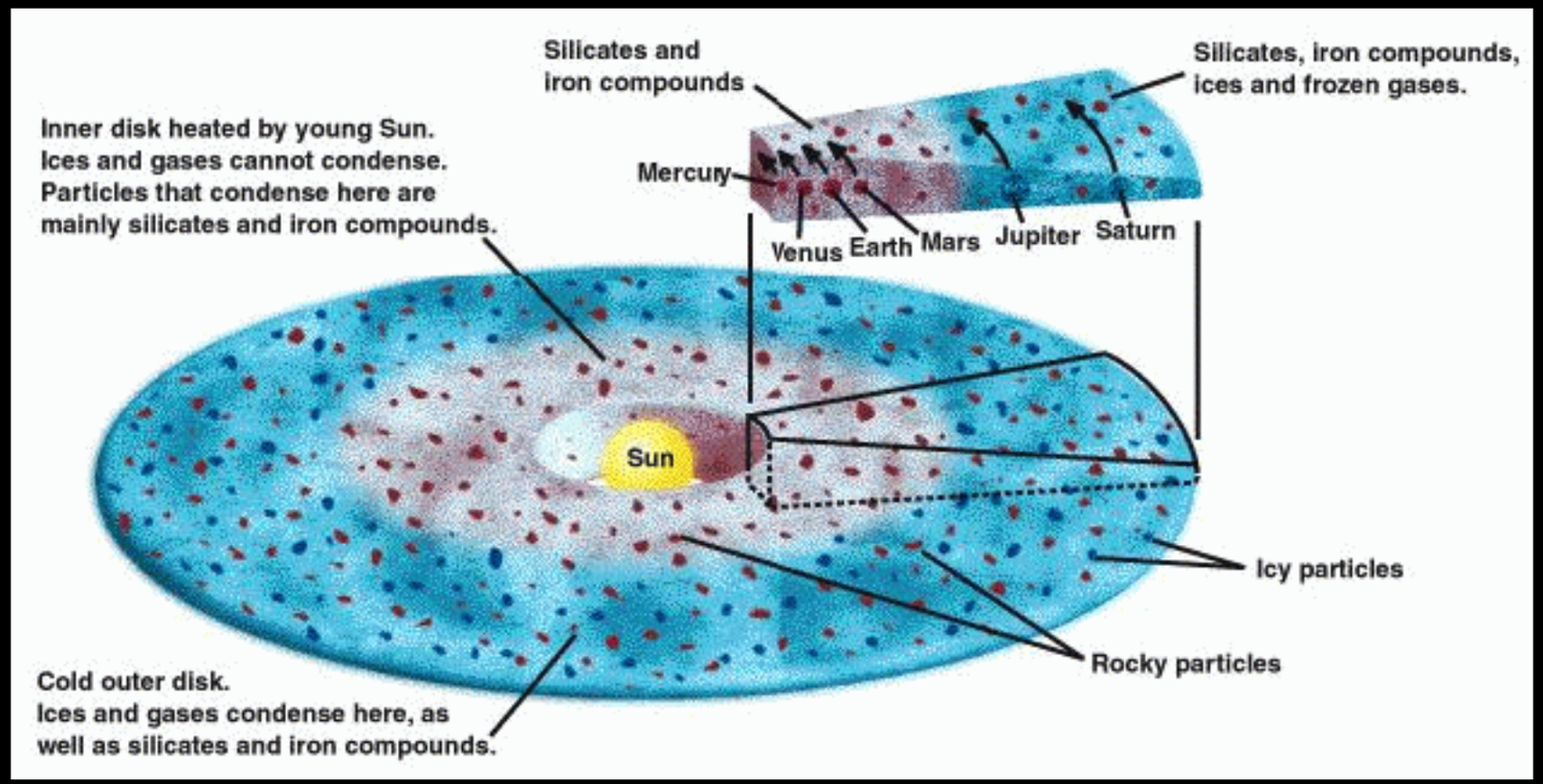
chemical differentiate interiors (core, mantle, crust)

outgassing from hot interiors


Atmosphere
Magma Ocean
Core
N
N
N
N
N
N
N
N
Undifferentiated protoplanet
Protoplanet undergoing differentiation
Protoplanet post-differentiation

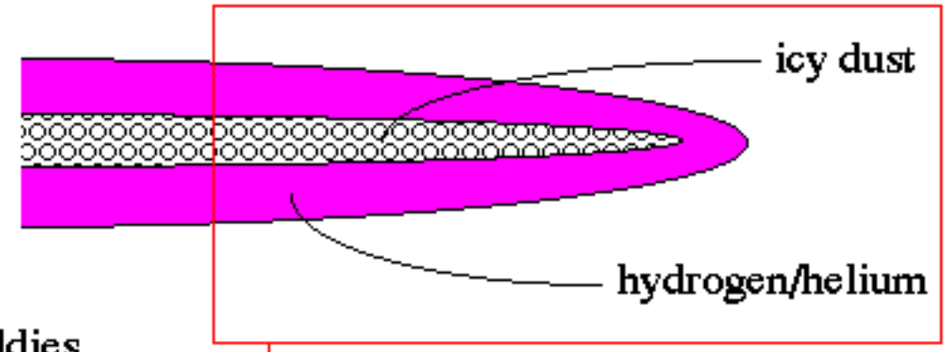

Accretion
proto-Earth
First (metallic)
Core formation
Giant-Impact
Second (sulfidic)
Core formation
&
Moon formation
Late-Veneer


0.7 hrs
1.4 hrs
4.2 hrs
6.9 hrs
37.5 hrs
Target core
Target mantle
Target magma ocean
Impactor core
Impactor mantle


Silicates and
iron compounds
Silicates, iron compounds,
ices and frozen gases.
Inner disk heated by young Sun.
Ices and gases cannot condense.
Particles that condense here are
mainly silicates and iron compounds.
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Sun
Icy particles
Rocky particles
Cold outer disk.
Ices and gases condense here, as
well as silicates and iron compounds.

early solar system disk

turblence in outer disk
= eddies



build–up of large bodies in eddies

outer regions colder, more volatile ices and gases = more mass

icy planetesimals form, lower condensation temperature = more accretion

growth to few Earth masses

inner edge

balance point between where temperature allows build–up of ice–rich planetesimals

lack of material plus disruption from proto–Jupiter's gravitational field produces asteroid Belt

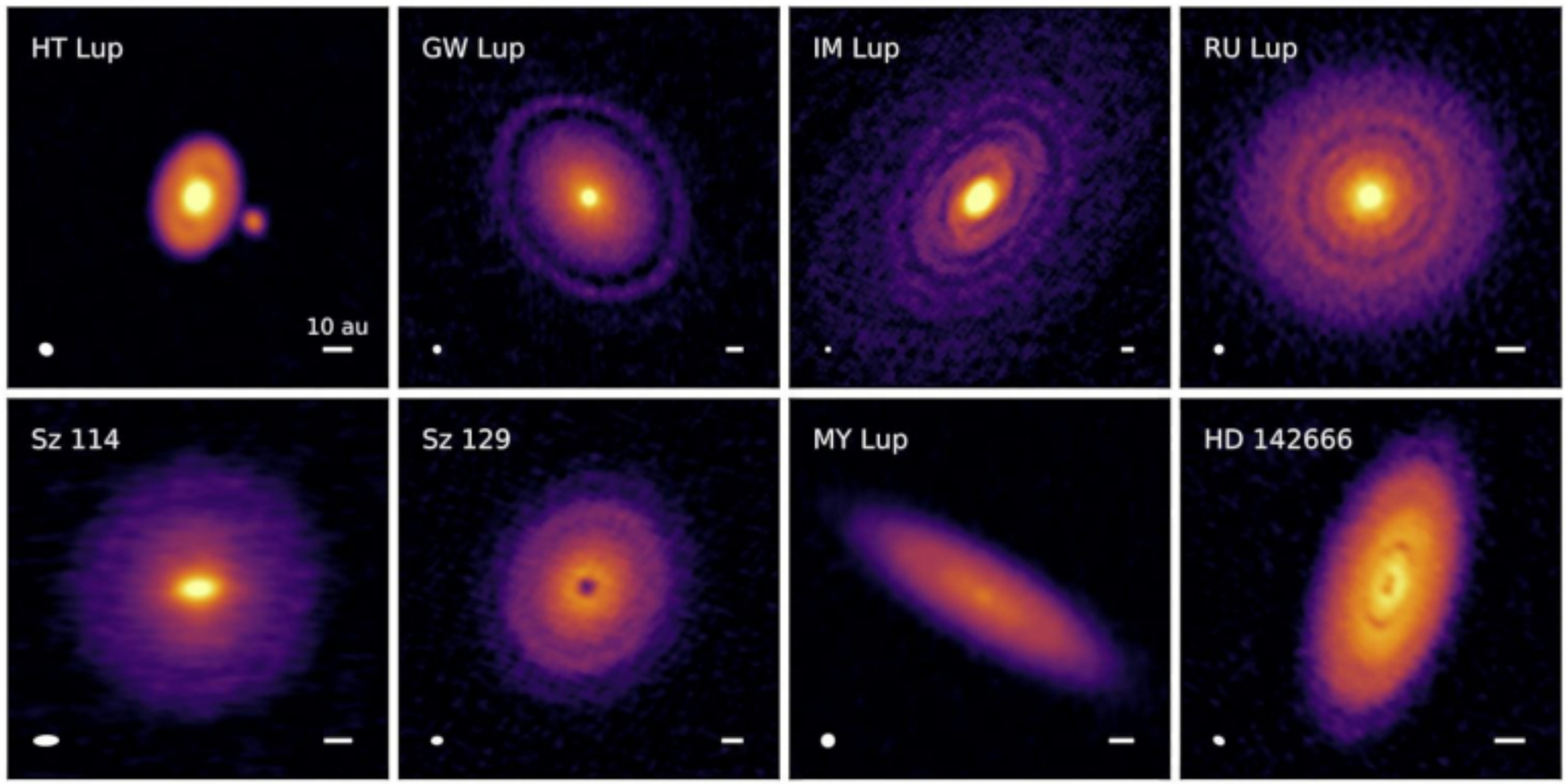
outer edge

seed cores accrete free hydrogen and helium

proto–Jupiter and Saturn more massive, more H/He

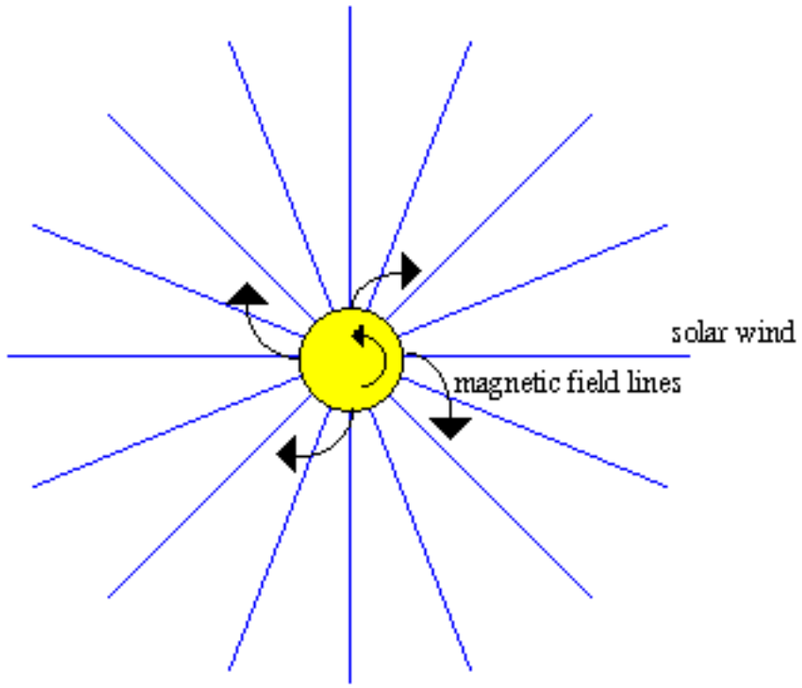
proto–Uranus and Neptune not as massive, more rich in CNO compounds

comets = fossil relics of icy planetesimals, tossed into Oort cloud by Jovian worlds

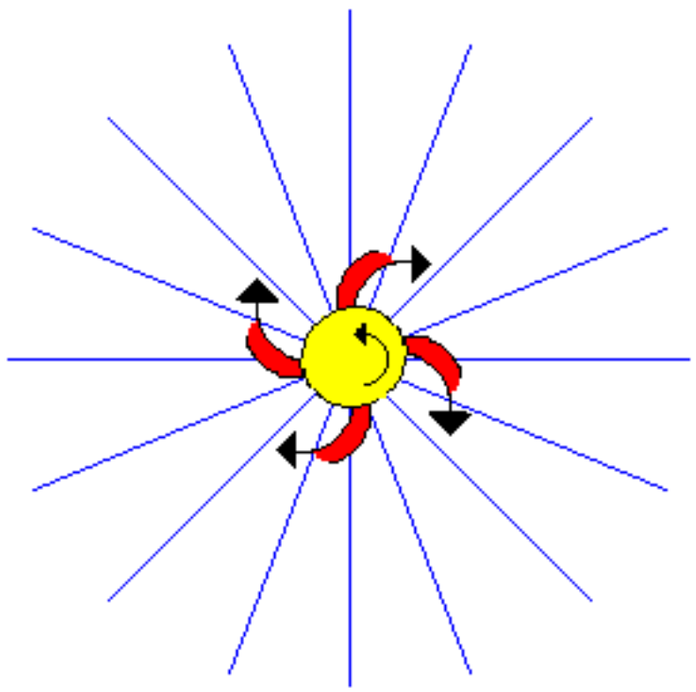

HT Lup
10 au
GW Lup
IM Lup
RU Lup
Sz 114
Sz 129
MY Lup
HD 142666

Magnetic Braking

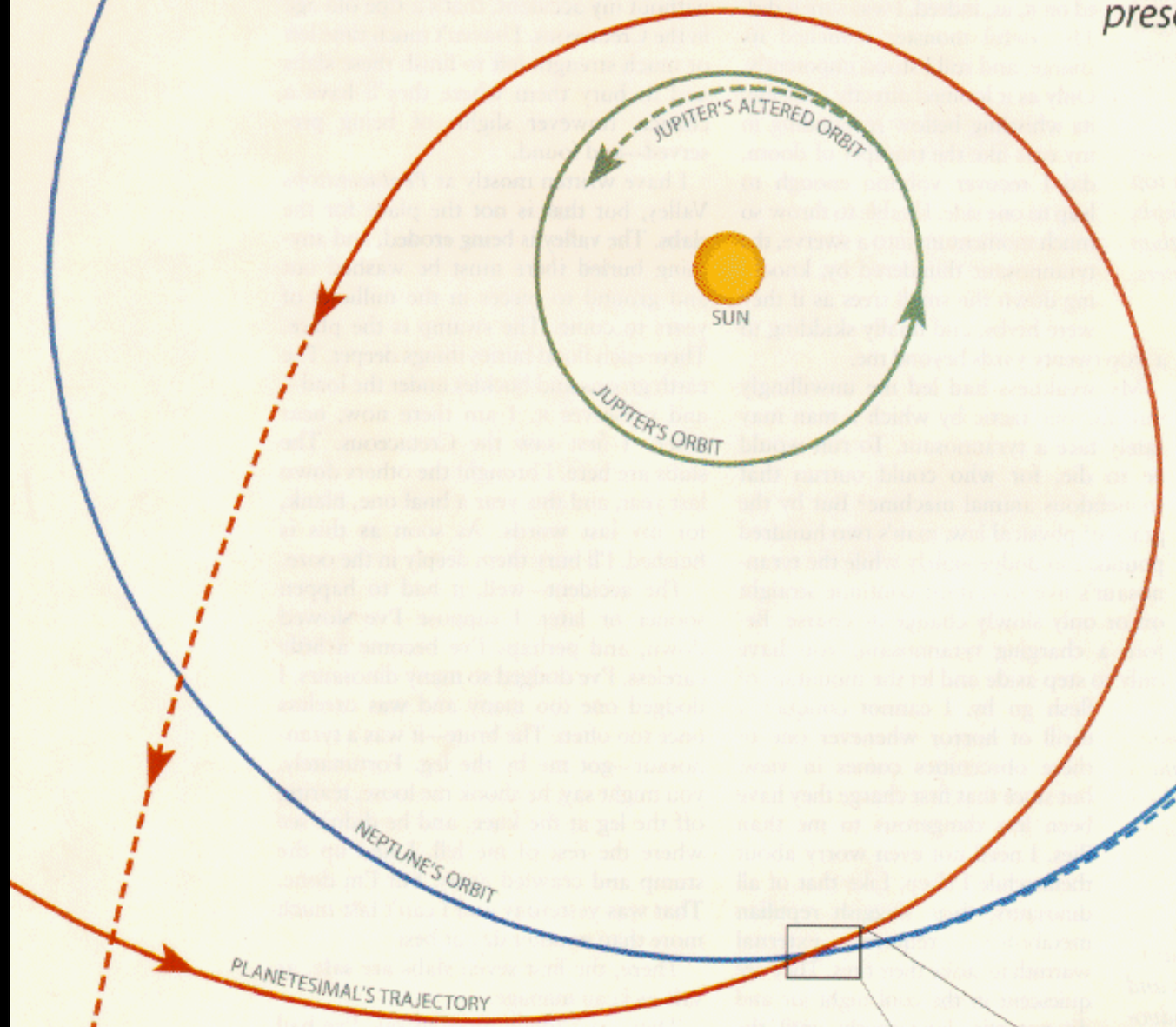
The solar wind, a stream of charged particles, moves outward from the Sun in a radial direction. The magnetic field of the Sun also reaches outward, but is twisted due to the rapid rotation of the Sun.

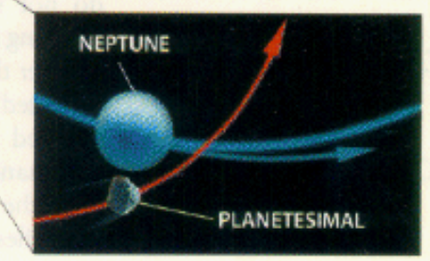


Charged particles in the solar wind become trapped in the Sun's magnetic field and are 'dragged' along the field lines. The result is angular momentum is transfered from the Sun by the magnetic field to the charged particles.



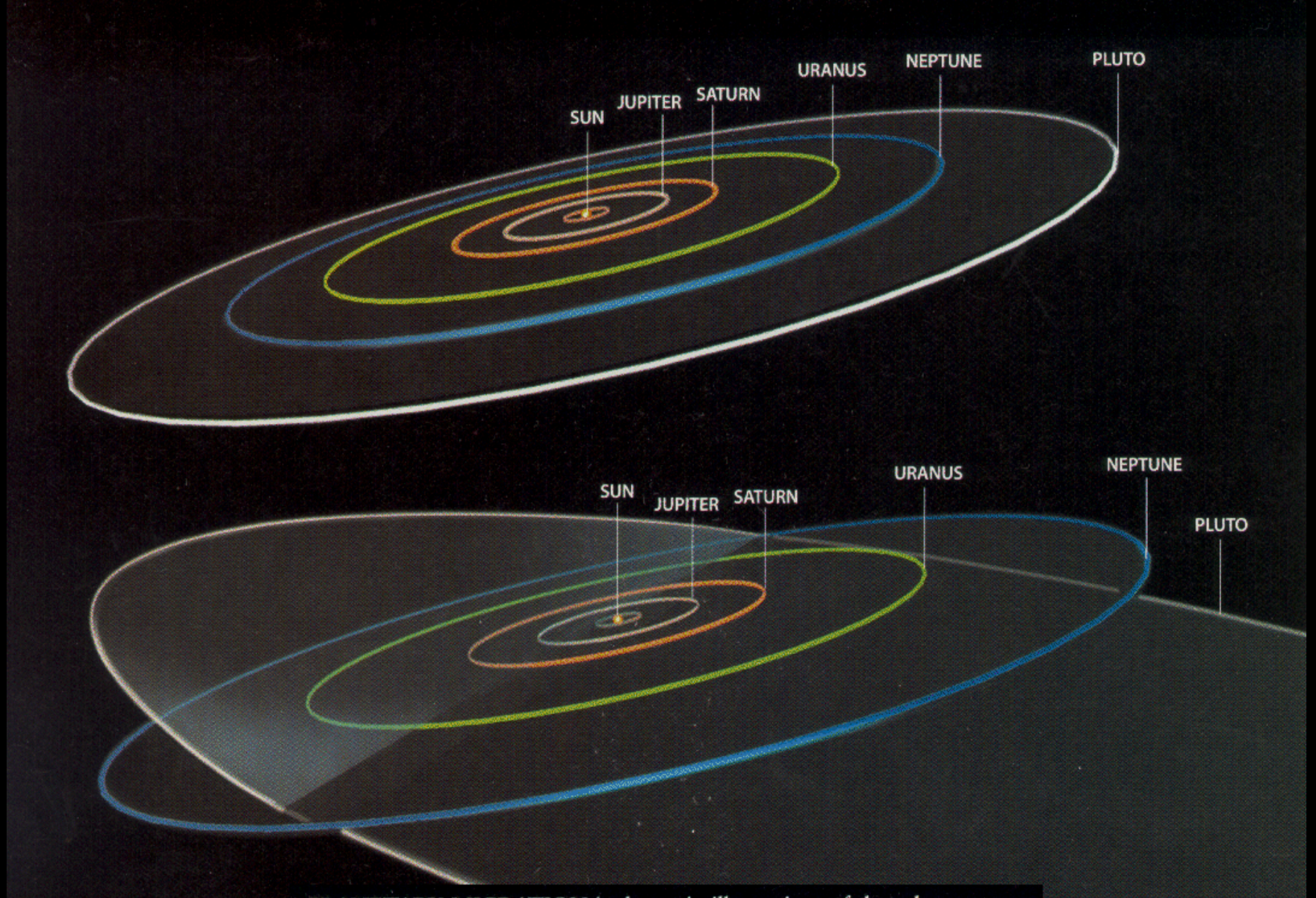
Did the solar system always look the way it does now? New evidence indicates that the outer planets may have migrated to their present orbits



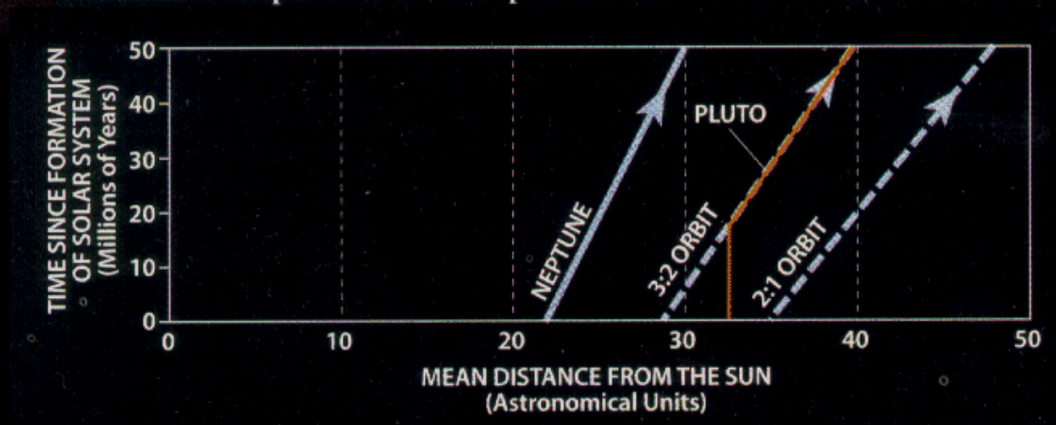


NEWLY FORMED NEPTUNE traveled amid a swarm of small rocky and icy bodies called planetesimals (*opposite page*). Some hit the planet but most were scattered by Neptune's gravity toward Jupiter, which ejected them from the solar system (*above*). In a typical scattering, Neptune gained energy, and its orbit spiraled outward very slightly. Billions of such encounters may have caused the planet to migrate to its current orbit.

JANA BRENNING; (DON DIXON (inset)



PLANETARY MIGRATION is shown in illustrations of the solar system at the time when the planets formed (*top left*) and in the present (*bottom left*). The orbit of Jupiter is believed to have shrunk slightly, while the orbits of Saturn, Uranus and Neptune expanded. (The inner planetary region was not significantly affected by this process.) According to this theory, Pluto was originally in a circular orbit. As Neptune migrated outward, it swept Pluto into a 3:2 resonant orbit, which has a period proportional to Neptune's (*above*). Neptune's gravity forced Pluto's orbit to become more eccentric and inclined to the plane of the other planets' orbits.



One of the main ingredients for life as we know it is liquid water. Water exists as a liquid between 273K and 373K (unless the pressure is too low, in which case the water sublimates into gaseous water vapor). The region on the solar system (or any planetary system) where the temperature is in this range, is called the habitable zone.