Chapter 8

Formation of the Solar System

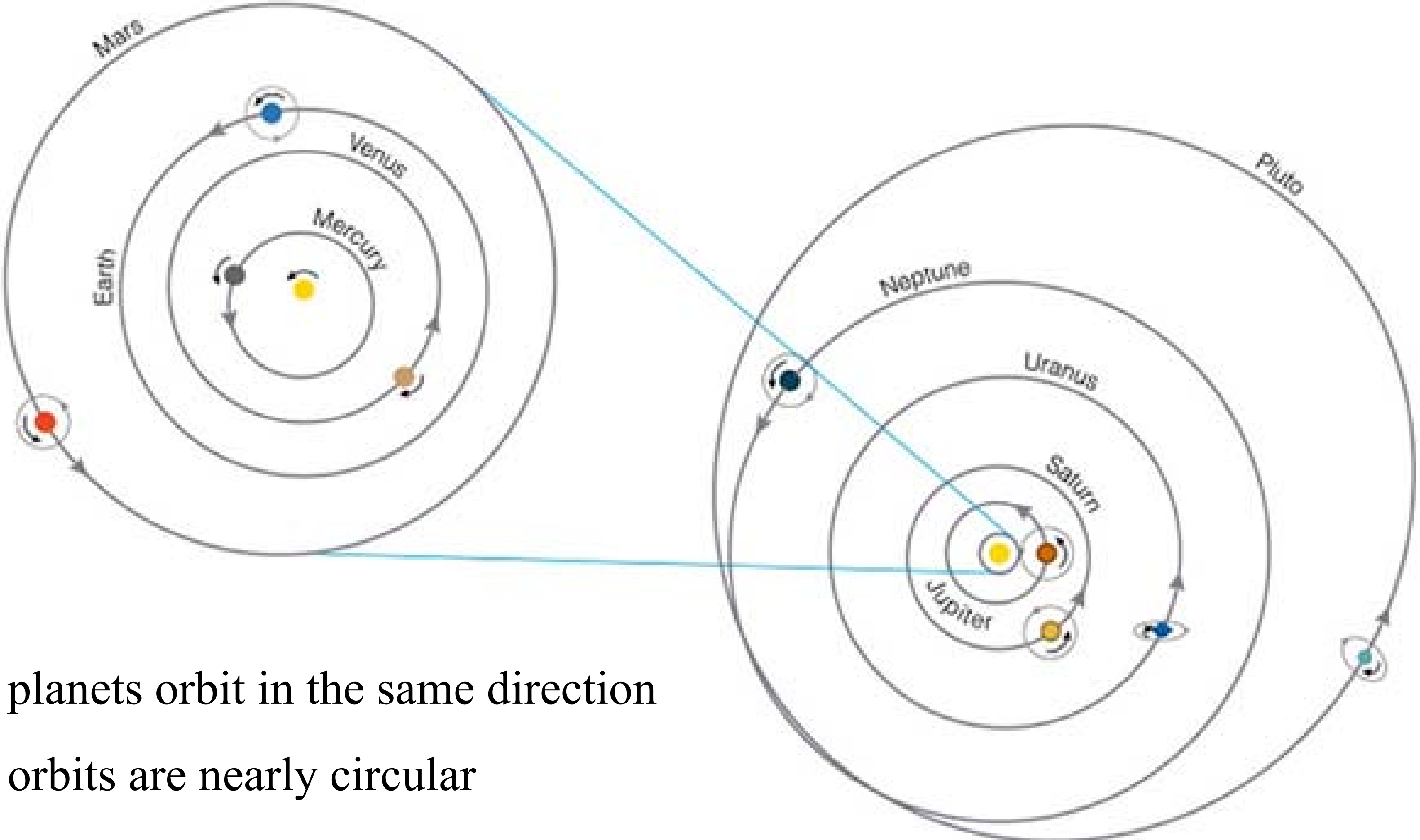
Big Picture

- The Earth, Sun, and rest of Solar System formed from a cloud of gas and dust some 4.6 billion years ago
- Properties of individual planets reflect their proximity to the hot proto-sun
- Some planets have experienced major perturbations and/or collisions
- Comets, asteroids, and Kuiper belt objects are debris leftover from SS formation
- We now have proof that other stars have planets; studying them will help us understand how the SS formed and evolved

Topics

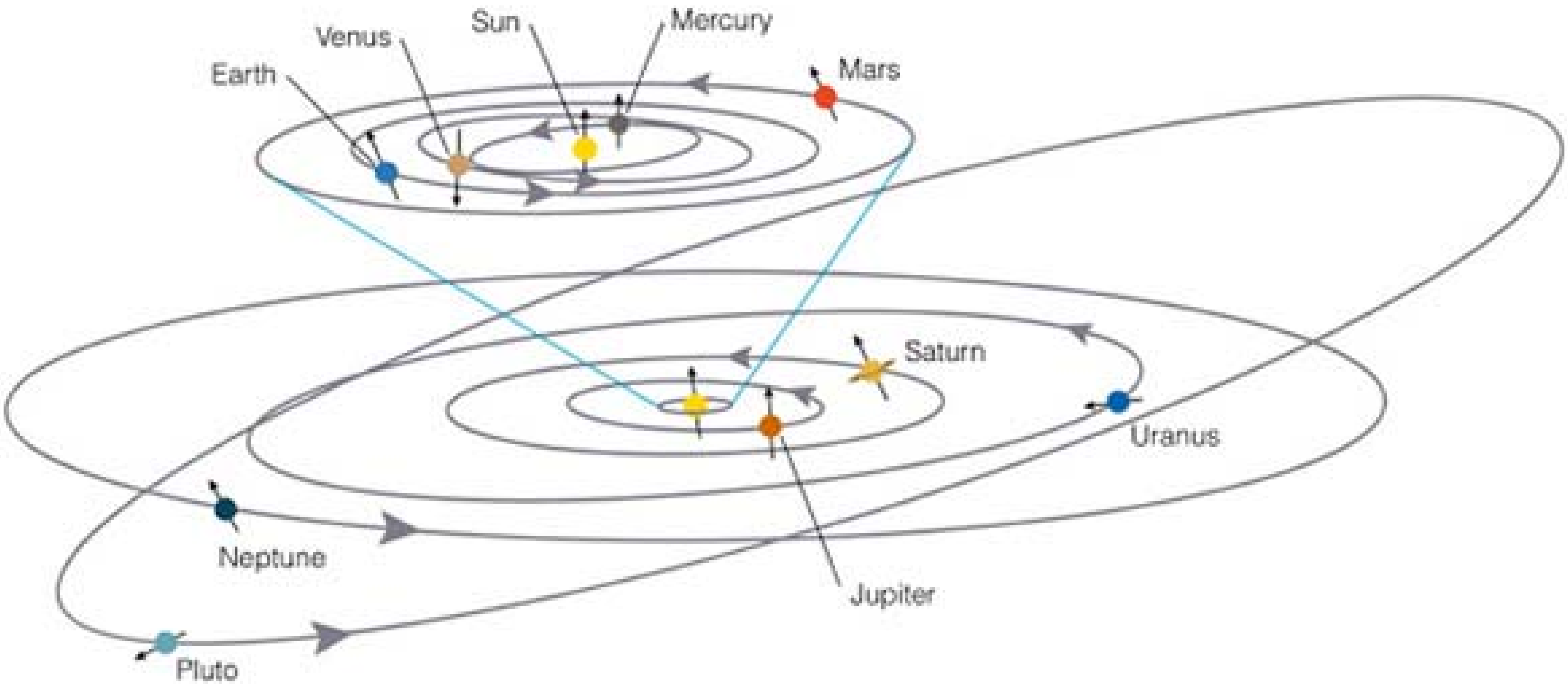
- Four Challenges to Theories
- The Nebular Theory
- How the Planets are Built
- Leftover Planetesimals
- Age of the Solar System
- Other Planetary Systems

Challenge 1: Patterns of Motion



- All planets orbit in the same direction
- All orbits are nearly circular
- Orbital separation increases with distance
- Spin of most planets and Sun same as orbital direction

Challenge 1: Patterns of Motion



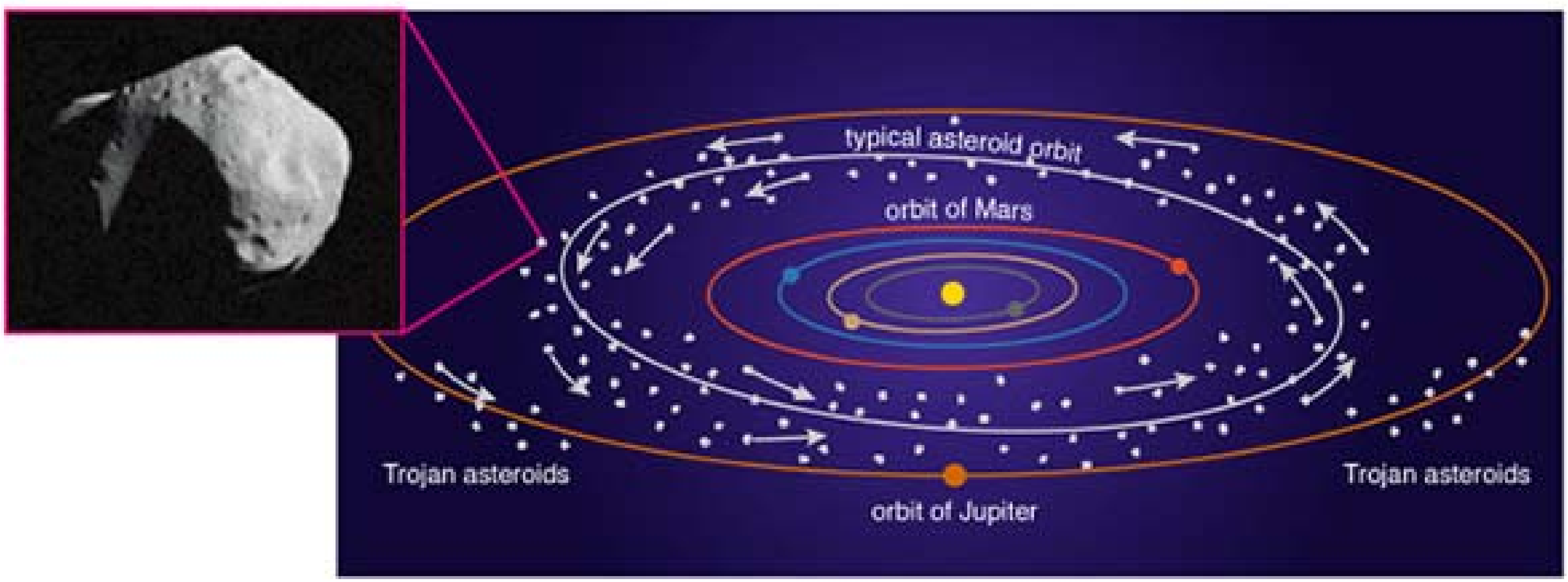
- All planets and moons lie nearly in the same plane
- Spin axis of most planets perpendicular to orbital plane

Planetary motions are quite orderly; theory must explain this!

Challenge 2: Two Planet Types

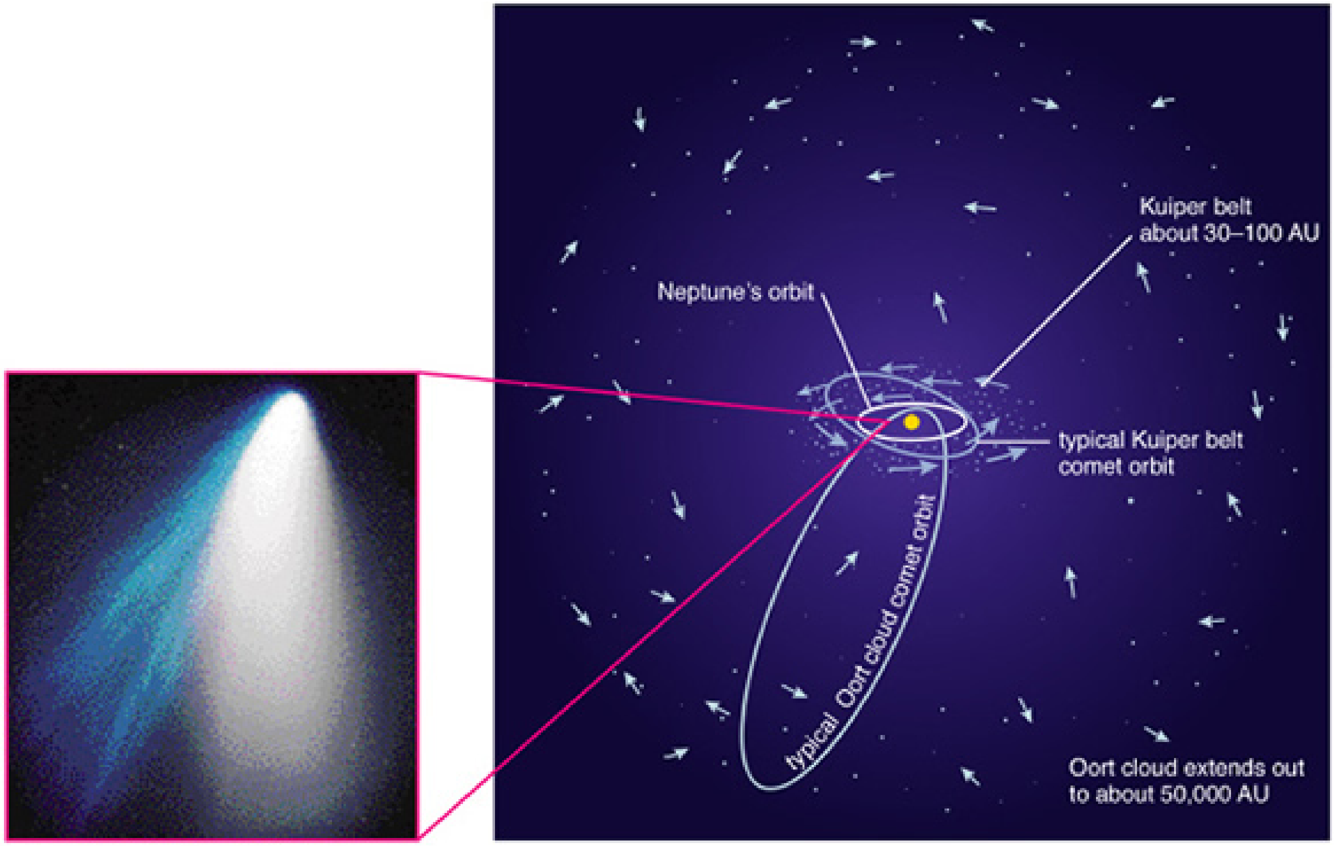
- Terrestrial planets
  - Rocky planets: Mars, Venus, Earth, Mars
  - Small, dense, close to the Sun ➔ warmer
  - Few or no moons
- Jovian planets
  - Gaseous (H, He) planets: Jupiter, Saturn, Uranus, Neptune
  - Large, low density, far from the sun ➔ cooler
  - Have rings and many moons

Challenge 3: Asteroids and Comets



- Asteroids are small, rocky bodies orbiting in the asteroid belt between Mars and Jupiter in same direction and plane
- Trojan asteroids lead and follow Jupiter in its orbit

Challenge 3: Asteroids and Comets



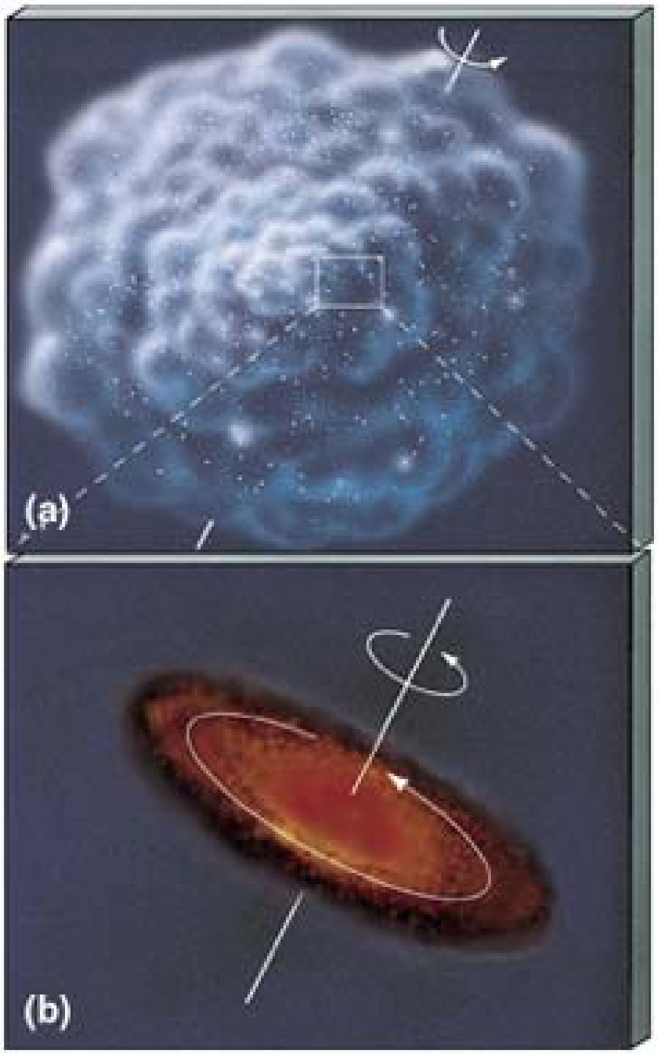
- Comets: small, icy bodies in highly eccentric orbits
- 2 reservoirs: Kuiper belt (30-100 AU), Oort cloud (to 50,000 AU)

Challenge 4: Exceptions to the Rules

- Mercury and Pluto have large orbital eccentricities and inclinations
- Rotation axis of Uranus and Pluto are tilted
- Venus rotates backwards
- Earth is only terrestrial with large moon
- Pluto has a moon almost its size
- A few jovian moons orbit backwards and on tilted and eccentric orbits

Nebular Hypothesis

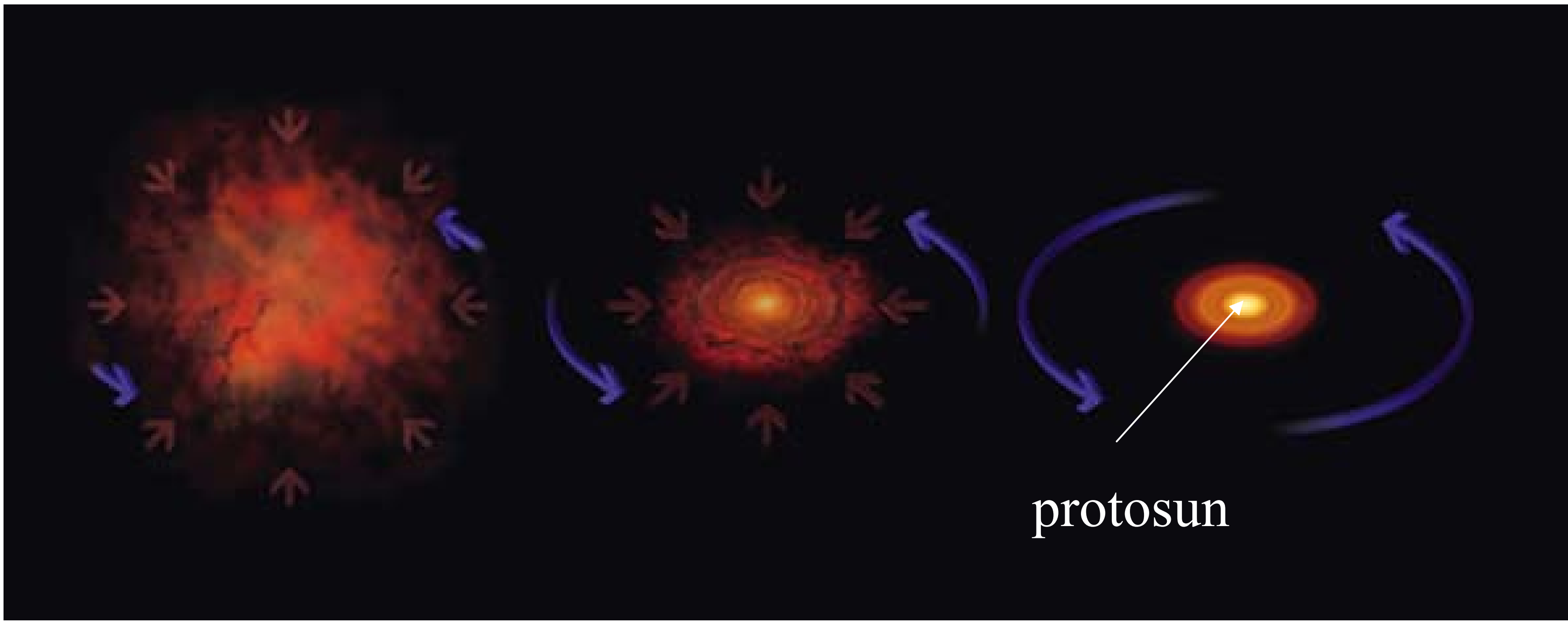
- Laplace (1796)
- slowly rotating interstellar gas cloud collapses due to self-gravity
- flattens to a disk due to centrifugal force
- “spins up” due to angular momentum conservation



Milky Way Galaxy

The Interstellar Medium: Birthplace of Stars

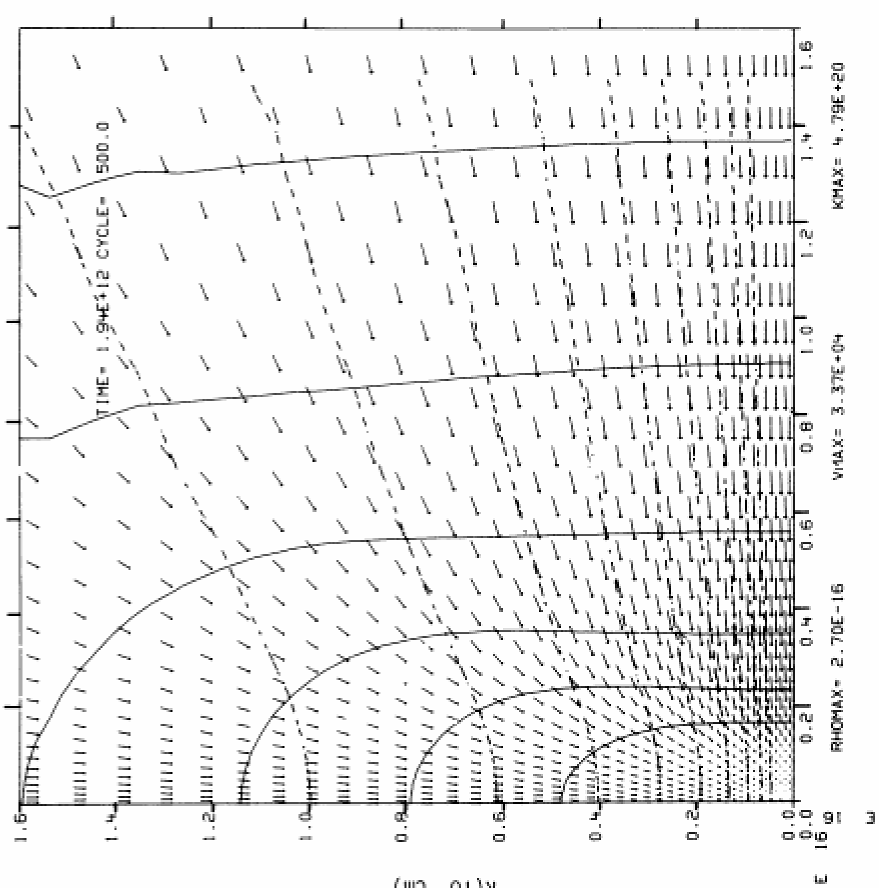
Nebular Contraction: Heating, spinning, flattening



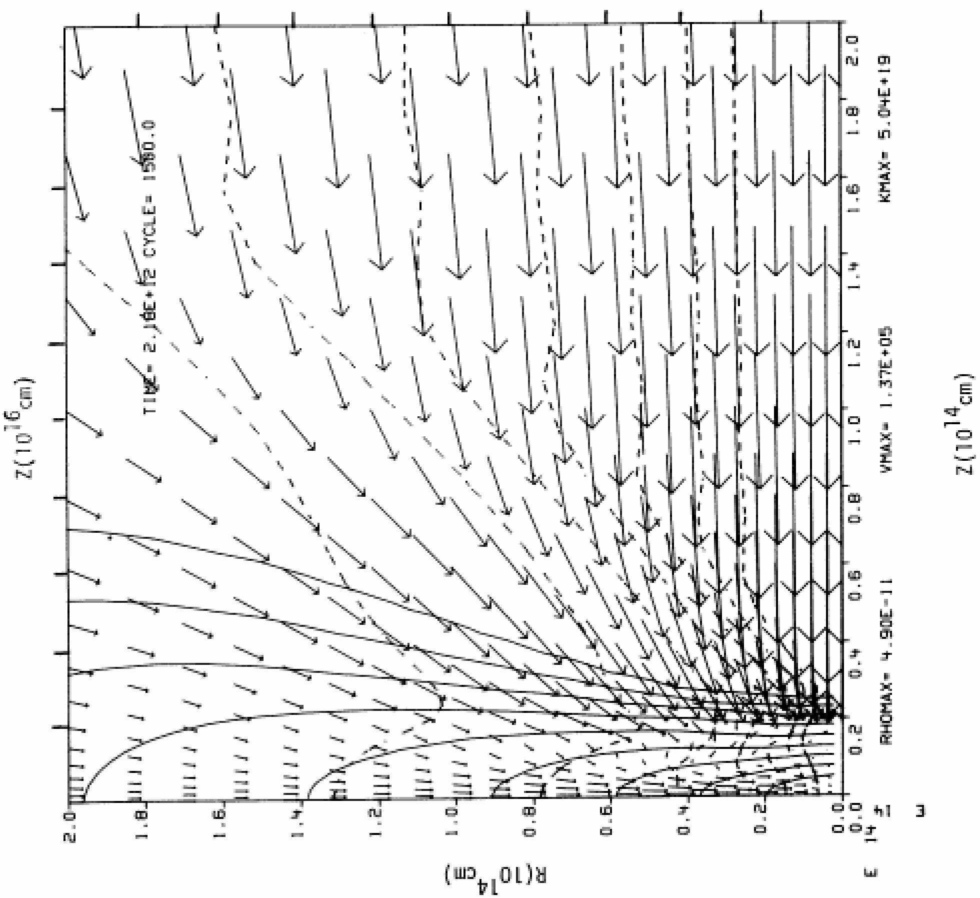
a) Interstellar cloud b) Collapsing cloud c) Protoplanetary disk

Computer Simulation of Rotating Cloud Collapse

early

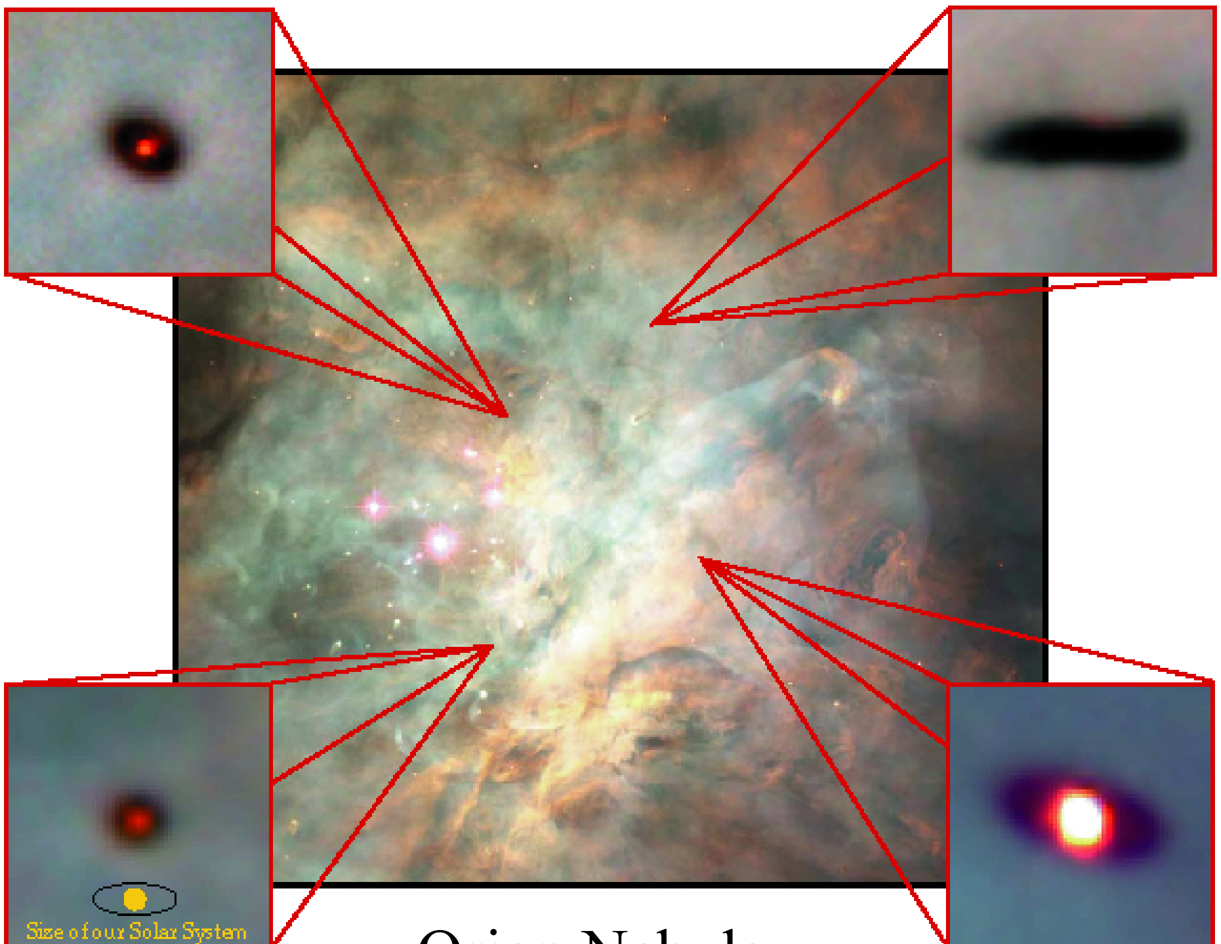


later

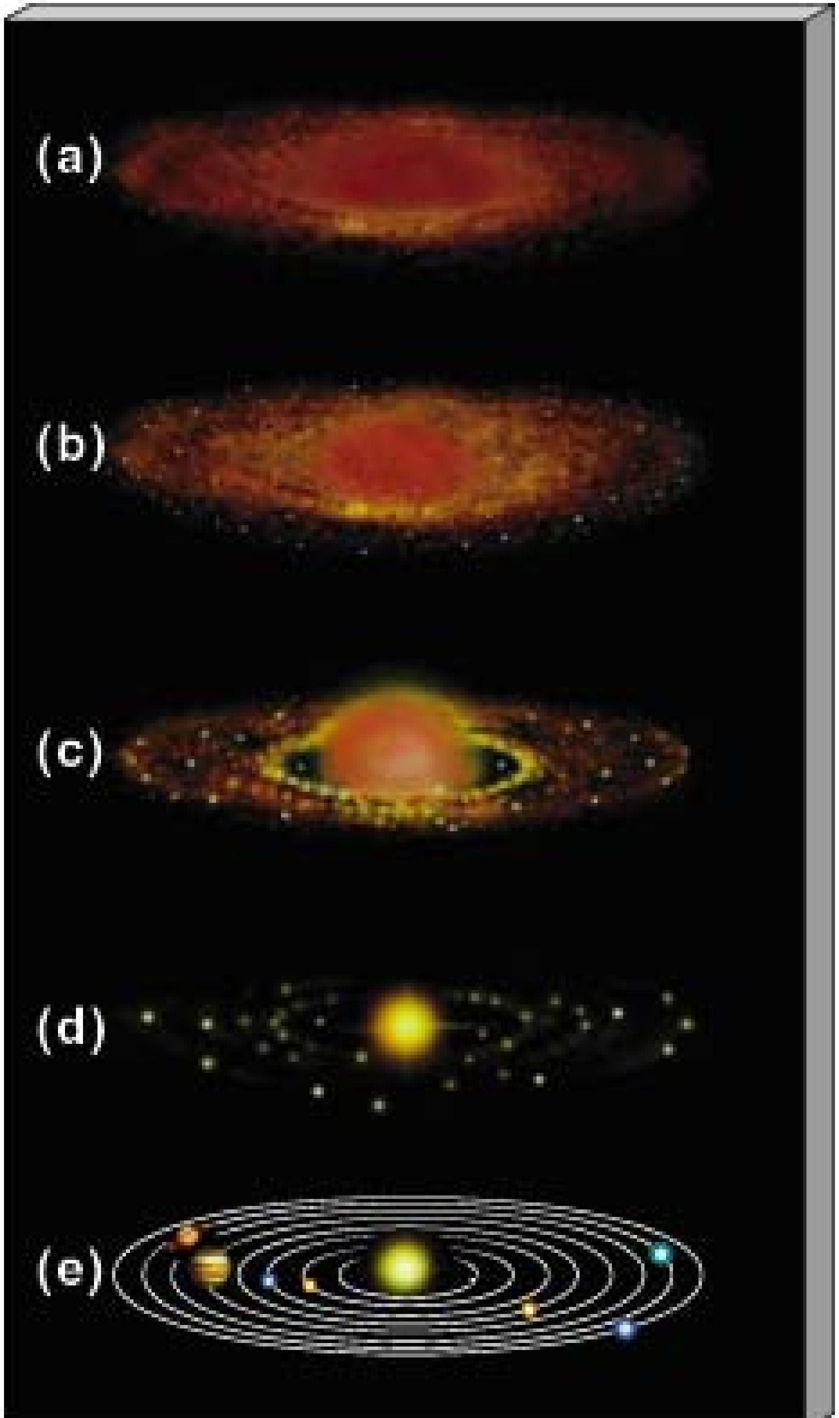


Norman et al. (1980)

Direct Evidence for Protoplanetary Disks (Proplyds)



Orion Nebula



Planet Formation

- a) flattened cloud of gas and dust
- b) dust settles to midplane and accumulates into planetesimals
- c) protosun heats up, wind blows gas away
- d) protoplanets grow by accretion
- e) modern solar system

Building Planets: Details

- Step 1: Condensation to grains and rocks
- Step 2: Accretion to planetesimals
- Step 3: Accumulation to protoplanets/cores
- Step 4: Nebular capture to gas giants
- Step 5: Solar wind clearing of nebula

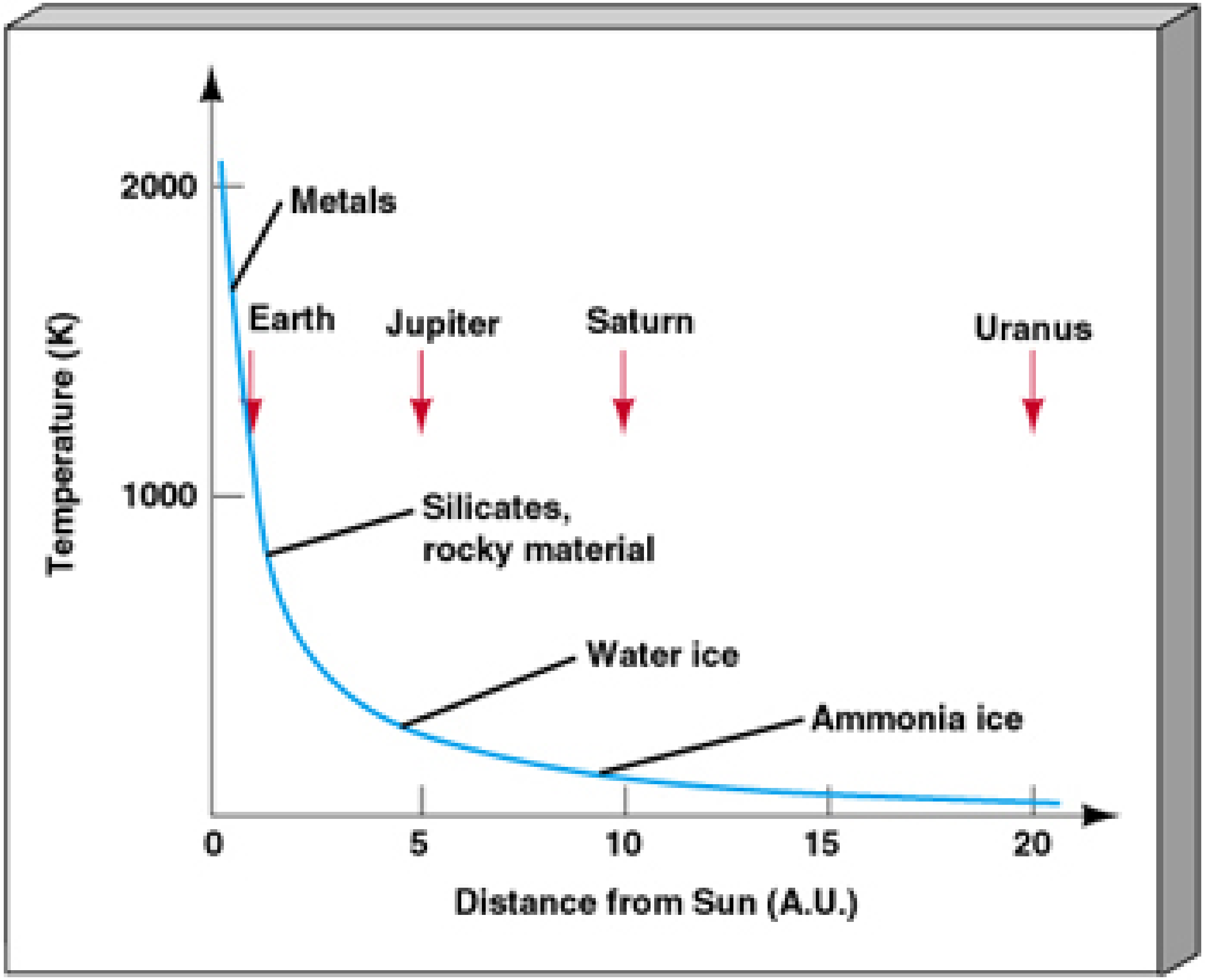
Step 1: Condensation

Composition of Solar Nebula

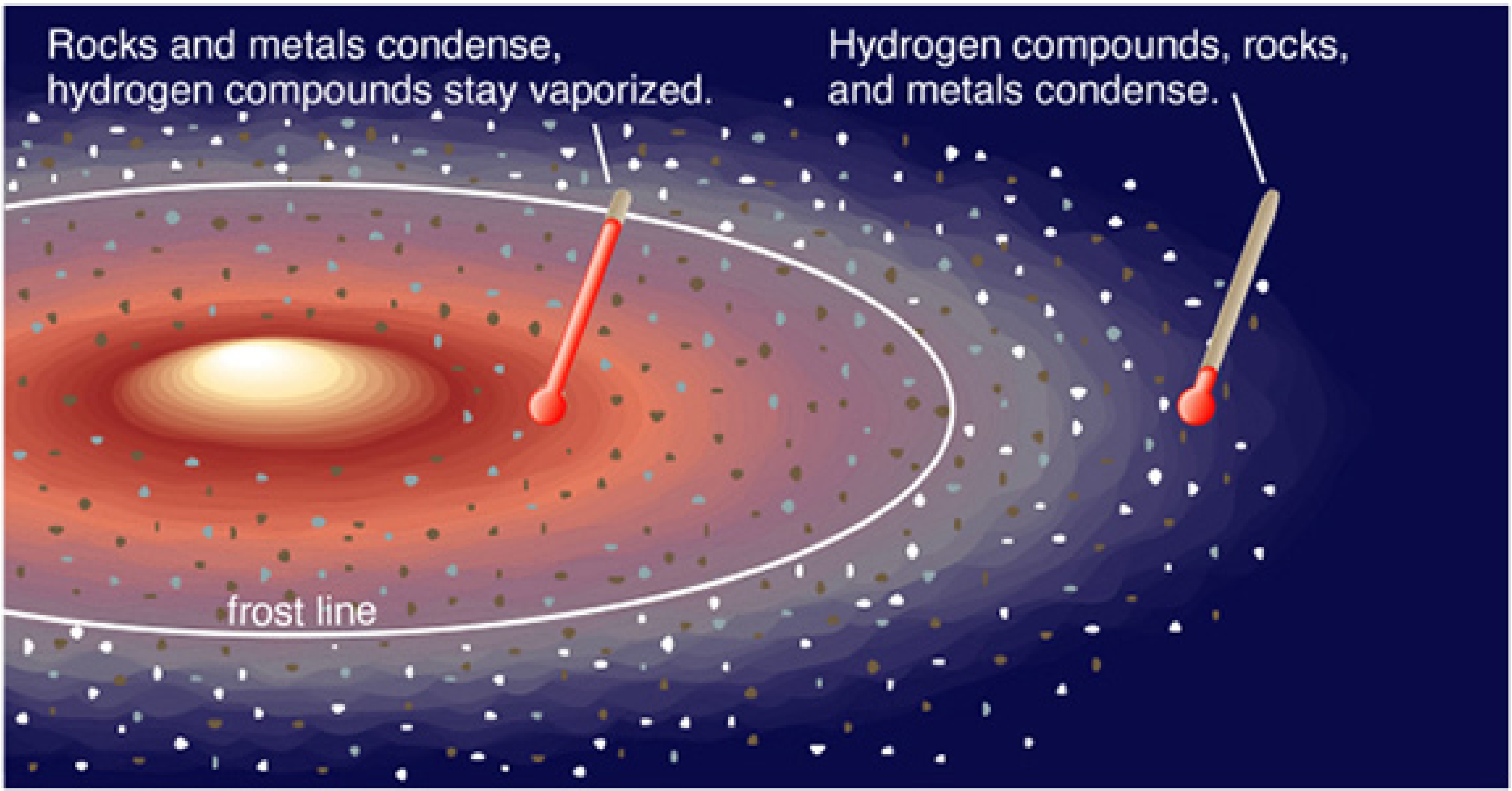
Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

Chemical Differentiation:
Condensation Sequence



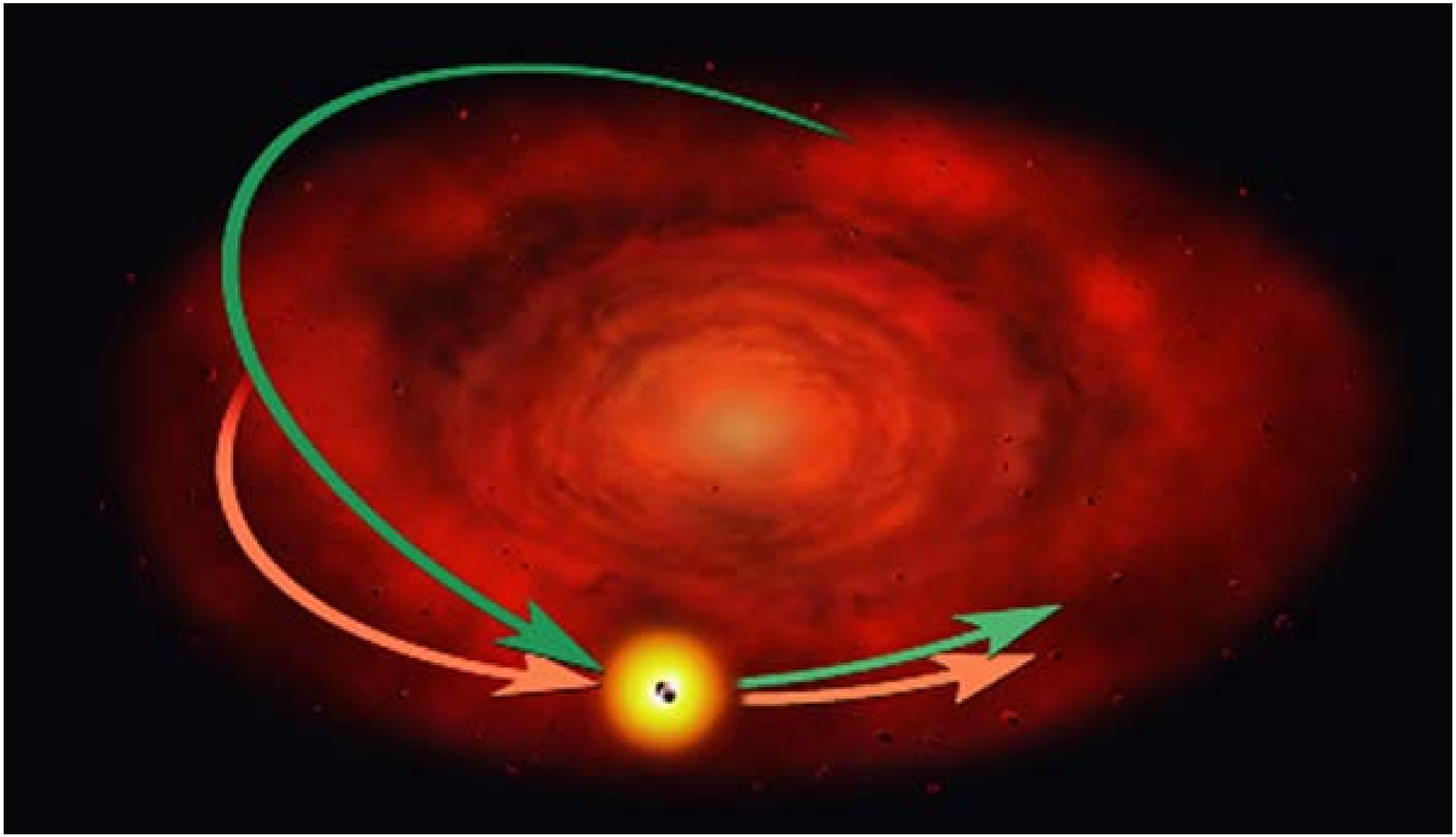
Temperature and Condensation: The Frost Line



Meteorites: Rocky Condensates

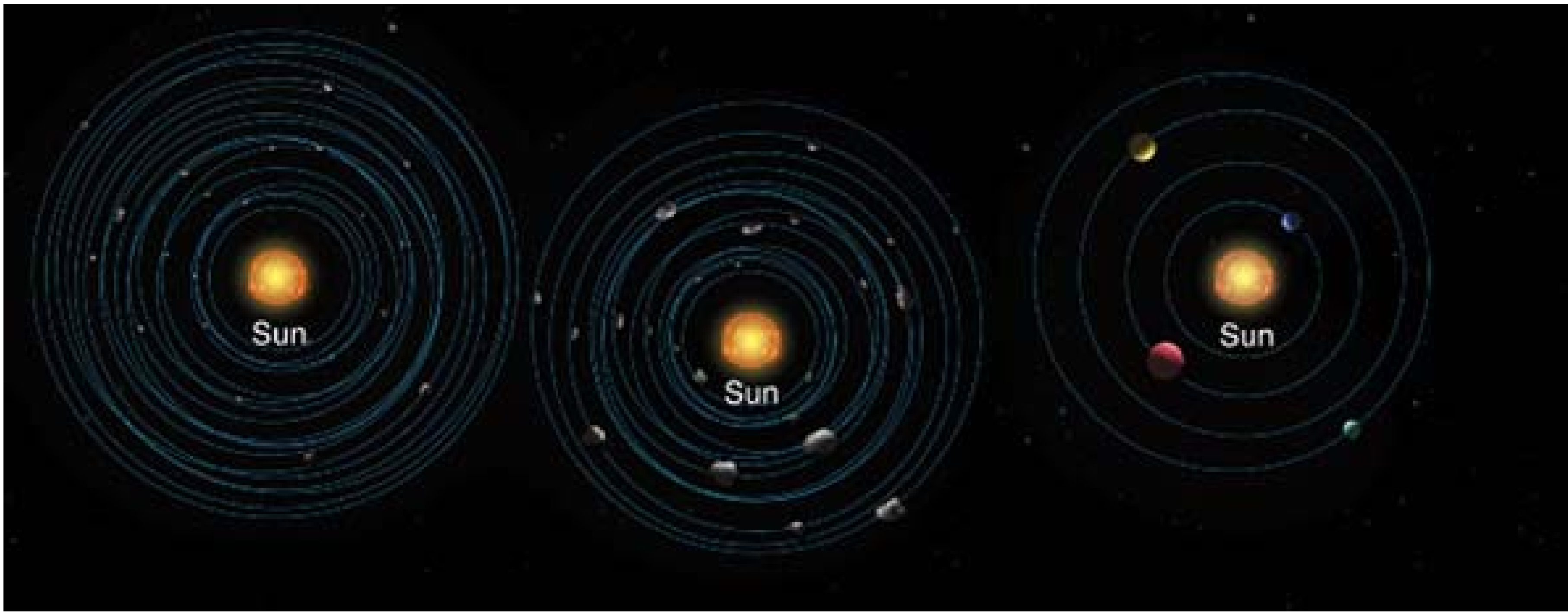
Ancient Relics of the Solar Nebula

Step 2: Accretion of Planetesimals



Collisions between grains and rocks cause them to *circularize orbits* and *settle to the midplane* of the disk where they grow by *accretion*

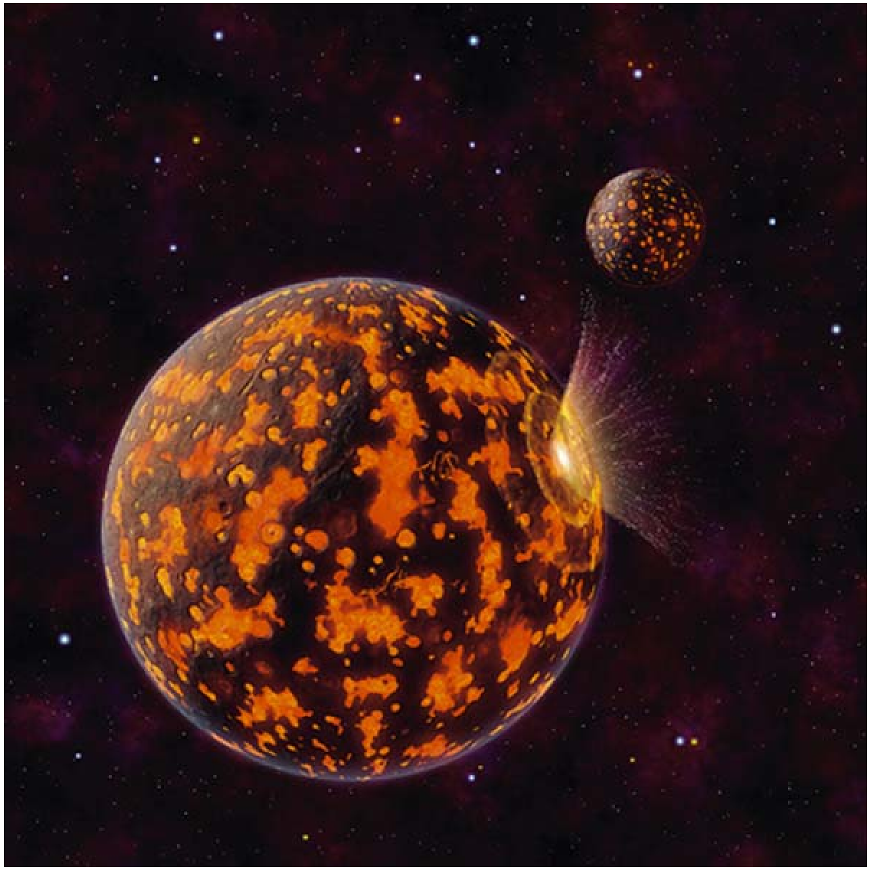
Step 3:
Accumulation of Protoplanets



Time
(< 1 billion years)

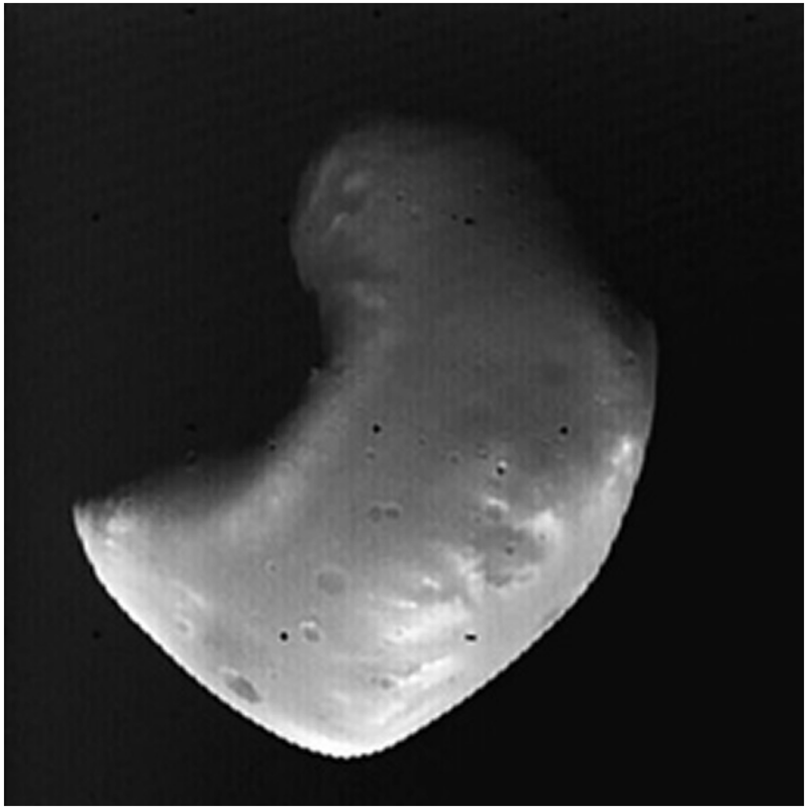
Leftover Planetesimals

- Early bombarded terrestrial planets (craters)
- Captured as Mars moons
- Collected into the asteroid belt and Trojans



Martian Moons: Survivors?

Phobos

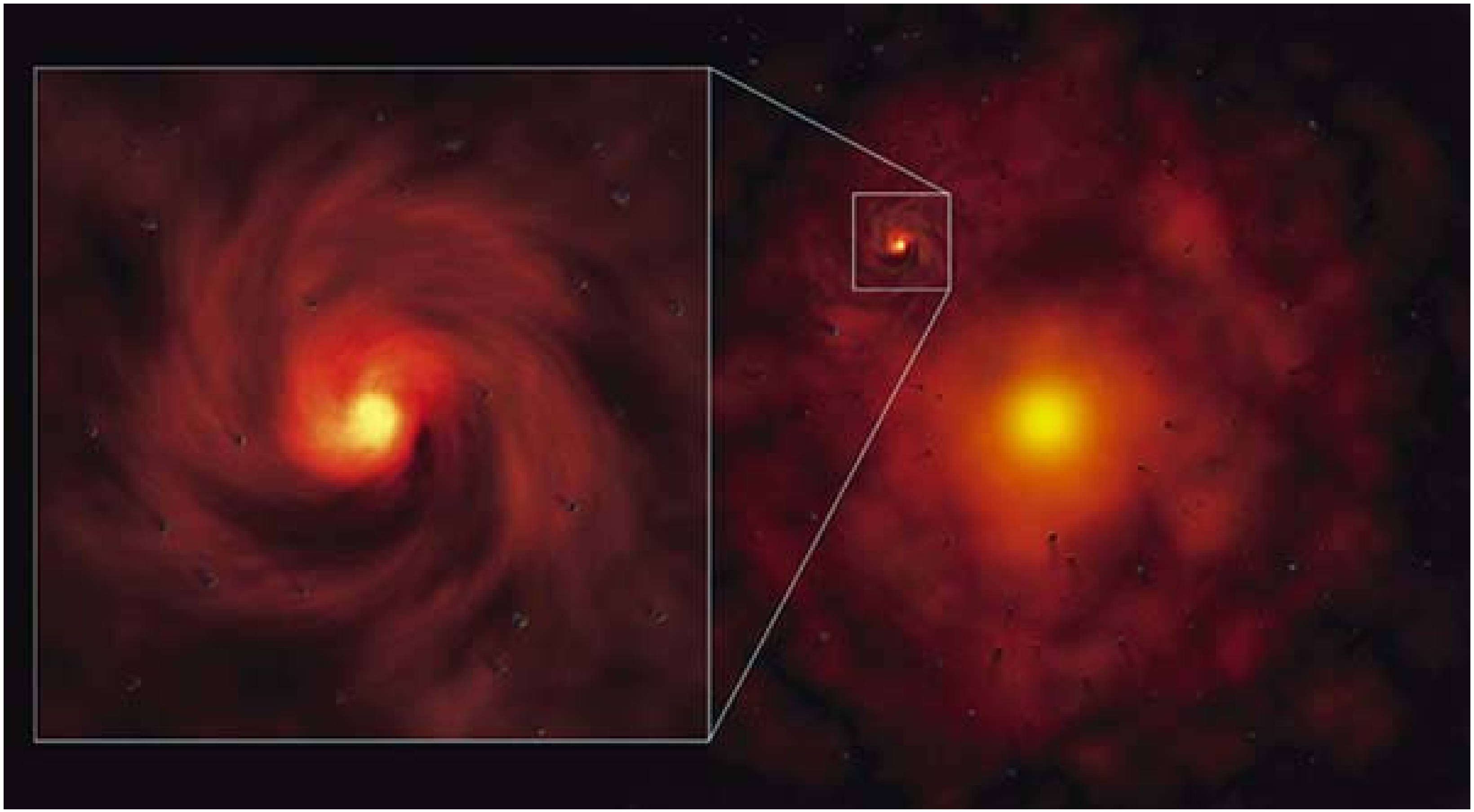


Diemos

Giant Impacts: Origin of the Moon?

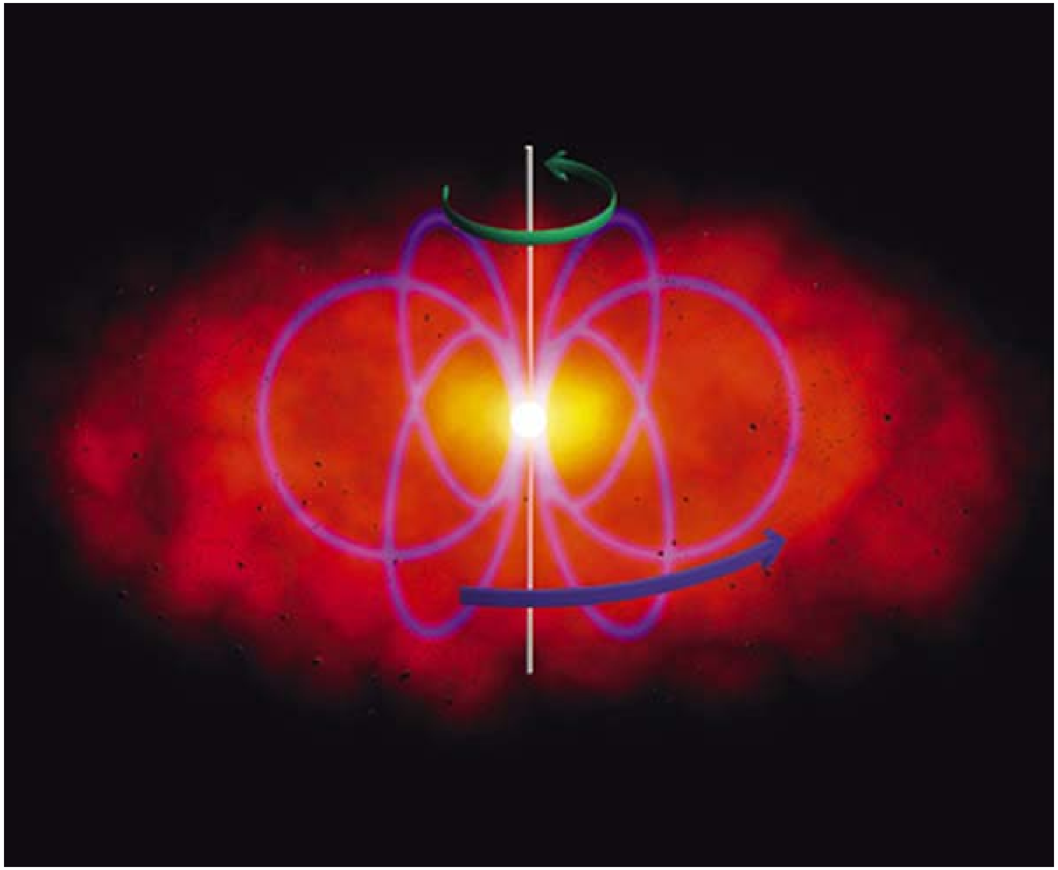
- Moon is the only large moon around a terrestrial planet
- Composition is identical to Earth's crust and mantle
- Theory: Mars-size planetesimal collided with Earth; Moon condensed from debris

Step 4: Nebular Capture: Making the Jovian Planets



Gas in the disk is gravitationally captured by rocky core

Step 5: Clearing the Solar Nebula

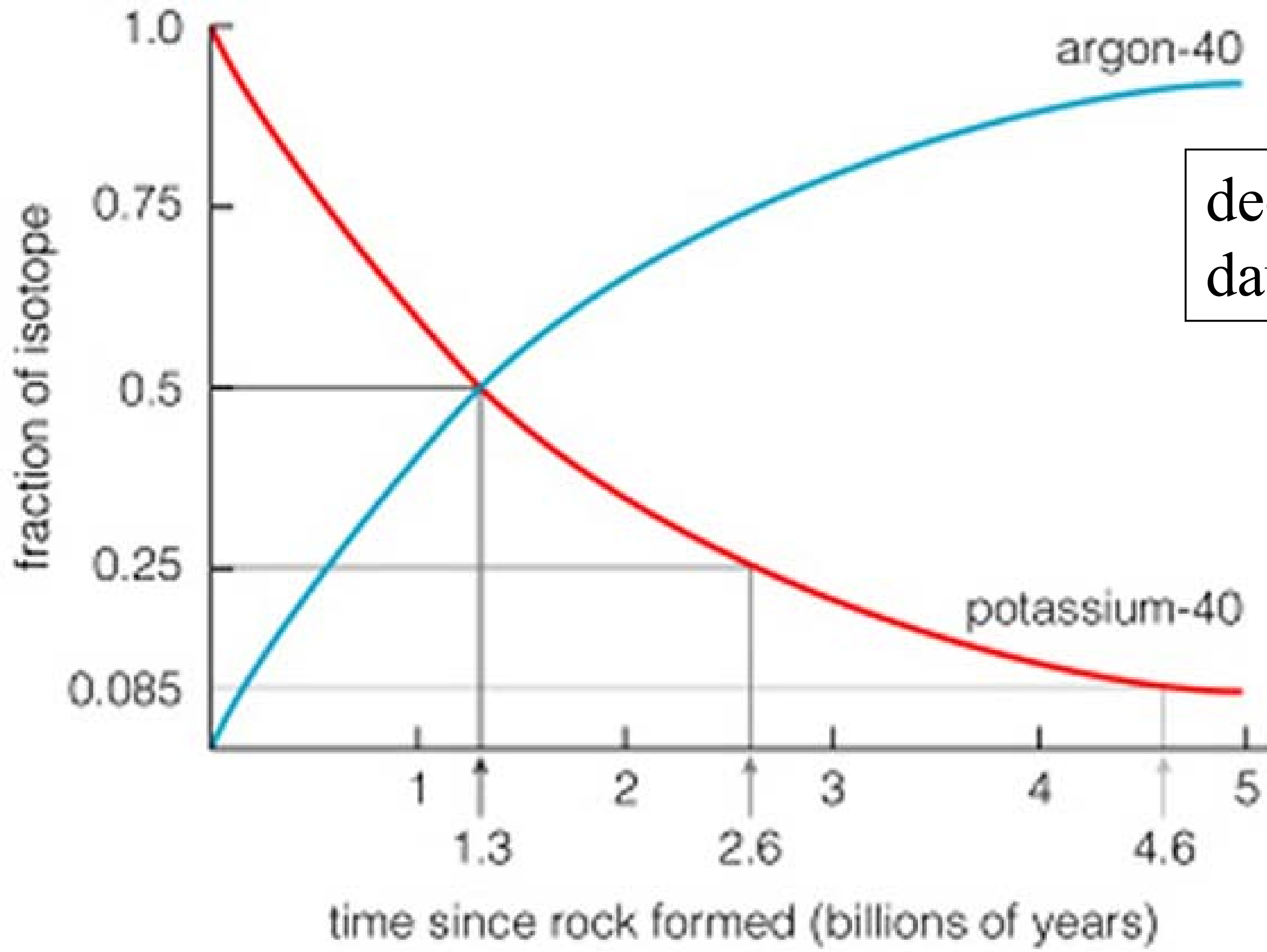


- Magnetic activity on the Sun drives the solar wind
- Wind was stronger when the Sun was born

Age of the Solar System

- Can measure the age of rocks using *radioactive dating*
- Age of the solar system is deduced from the age of the *oldest rocks* found on Earth and the *oldest meteorites*
- Result: about 4.6 billion years

Radioactive Dating

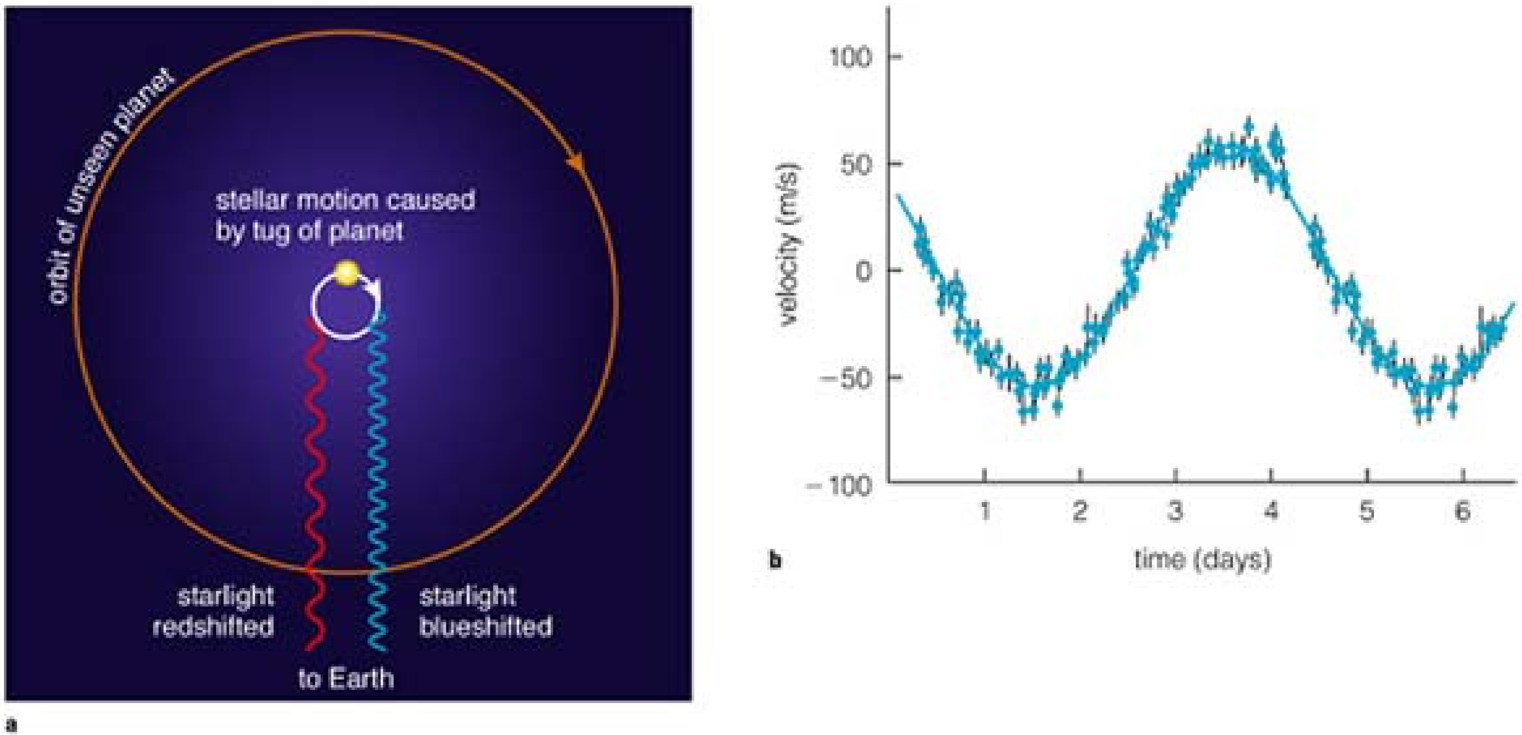


decay product: daughter

radioactive parent

Potassium-40 decays to Argon-40 with half-life of 1.3 Byr
Argon-40 is trapped in rocks/meteors containing P-40

Detecting Extrasolar Planets



- ❑Tug of massive planet causes parent star to wobble
- ❑Wobble is detectable as a Doppler shift of star’s spectrum
- ❑Planets mass and distance from star inferred from Kepler’s Laws

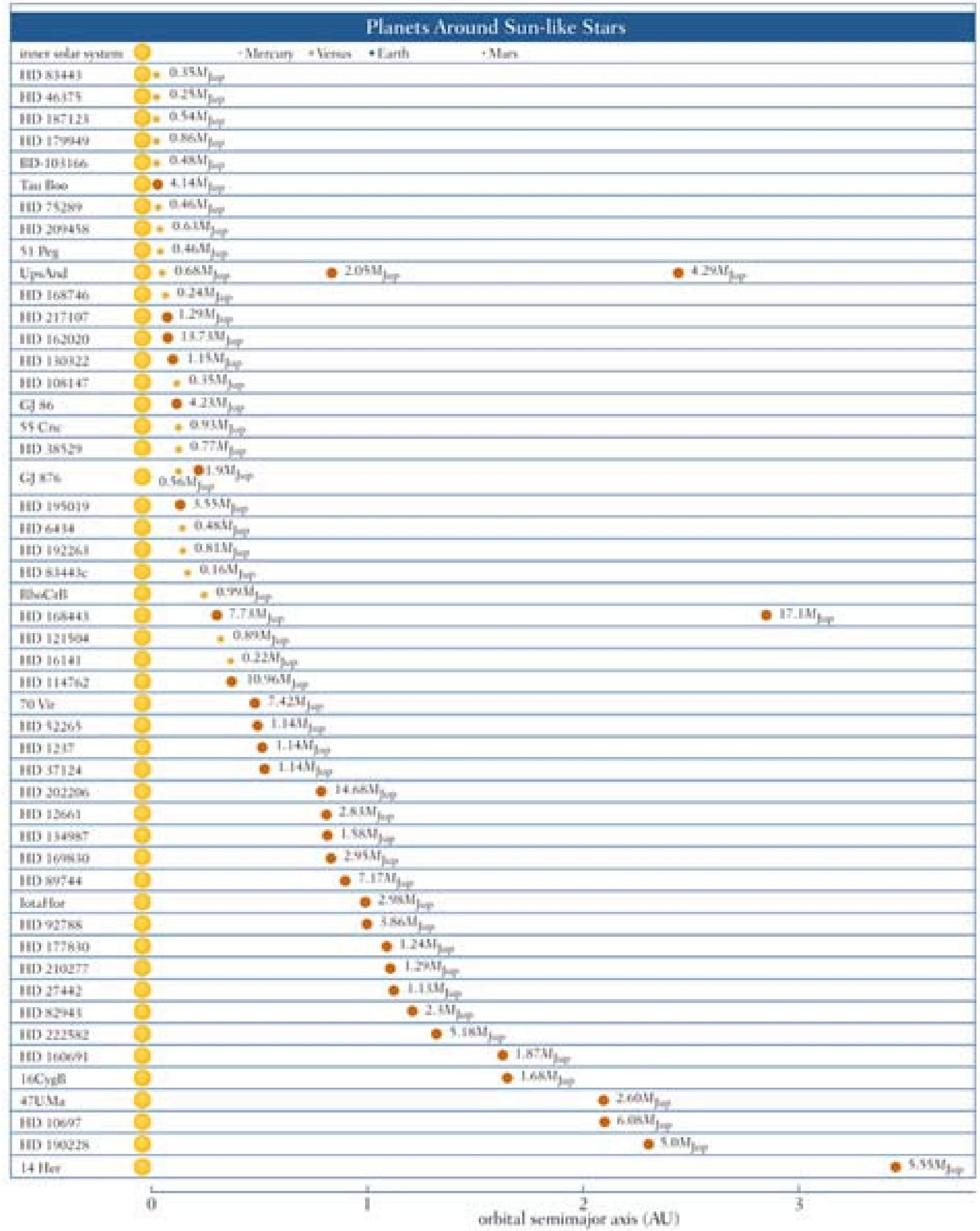
Current List

Over 100 exoplanets known

Only most massive planets detectable at present

Mysteries abound:

- Jupiter-mass planets closer than Mercury
- highly elliptical orbits



http://exoplanets.org/