Formation of the Solar System (Chapter 8)

Based on Chapter 8

- This material will be useful for understanding Chapters 9, 10, 11, 12, 13, and 14 on "Formation of the solar system", "Planetary geology", "Planetary atmospheres", "Jovian planet systems", "Remnants of ice and rock", "Extrasolar planets" and "The Sun: Our Star"
- Chapters 2, 3, 4, and 7 on "The orbits of the planets", "Why does Earth go around the Sun?", "Momentum, energy, and matter", and "Our planetary system" will be useful for understanding this chapter

Goals for Learning

- Where did the solar system come from?
- How did planetesimals form?
- How did planets form?

Patterns in the Solar System

- Patterns of motion (orbits and rotations)
- Two types of planets: Small, rocky inner planets and large, gas outer planets
- Many small asteroids and comets whose orbits and compositions are similar
- Exceptions to these patterns, such as Earth’s large moon and Uranus’s sideways tilt

Help from Other Stars

- Use observations of the formation of other stars to improve our theory for the formation of our solar system
- Use this theory to make predictions about the formation of other planetary systems

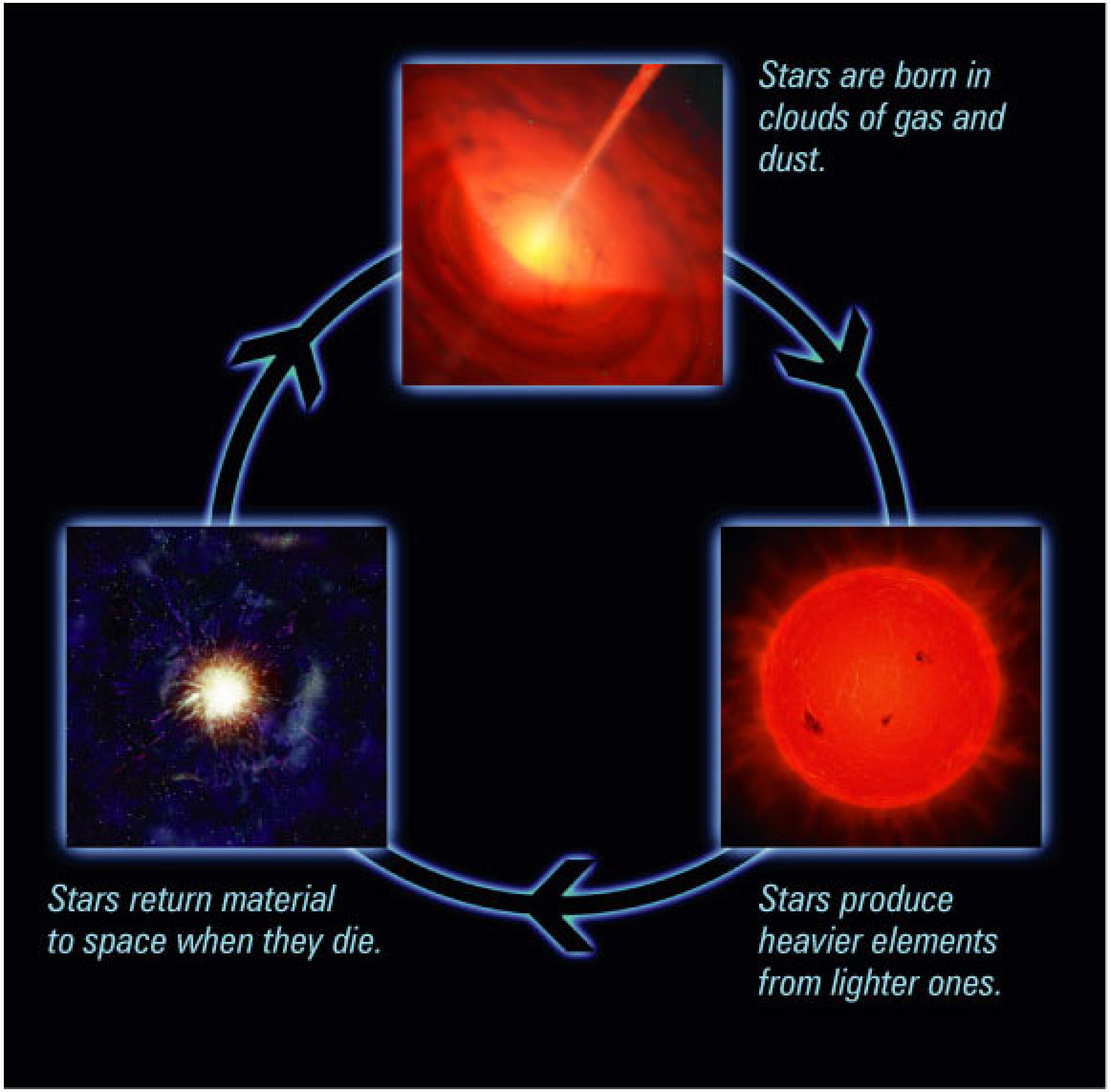
Nebular Theory of Solar System Formation

- A cloud of gas, the “solar nebula”, collapses inwards under its own weight
- Cloud heats up, spins faster, gets flatter (disk) as a central star forms
- Gas cools and some materials condense as solid particles that collide, stick together, and grow larger

Where does a cloud of gas come from?

- Big Bang -> Hydrogen and Helium
- First stars use this to generate other heavier elements
- Stars die, explode, spread these elements into space

- Galactic Recycling



Metal, rock, and ice could not have been present in the first stars or their accompanying stellar systems

Our solar system must be younger than the Universe

Orion Nebula

Young stars are always found within clouds of gas

Thousands of stars are forming within this cloud

So our Sun was born within a cloud of gas too

The first step

- A cloud of gas forms
- It starts to collapse under its own gravity
  - Textbooks are vague on exactly how gas cloud formed and why it started to collapse because this process isn’t very well understood today
- What happens next?

Does the shrinking cloud stay spherical?

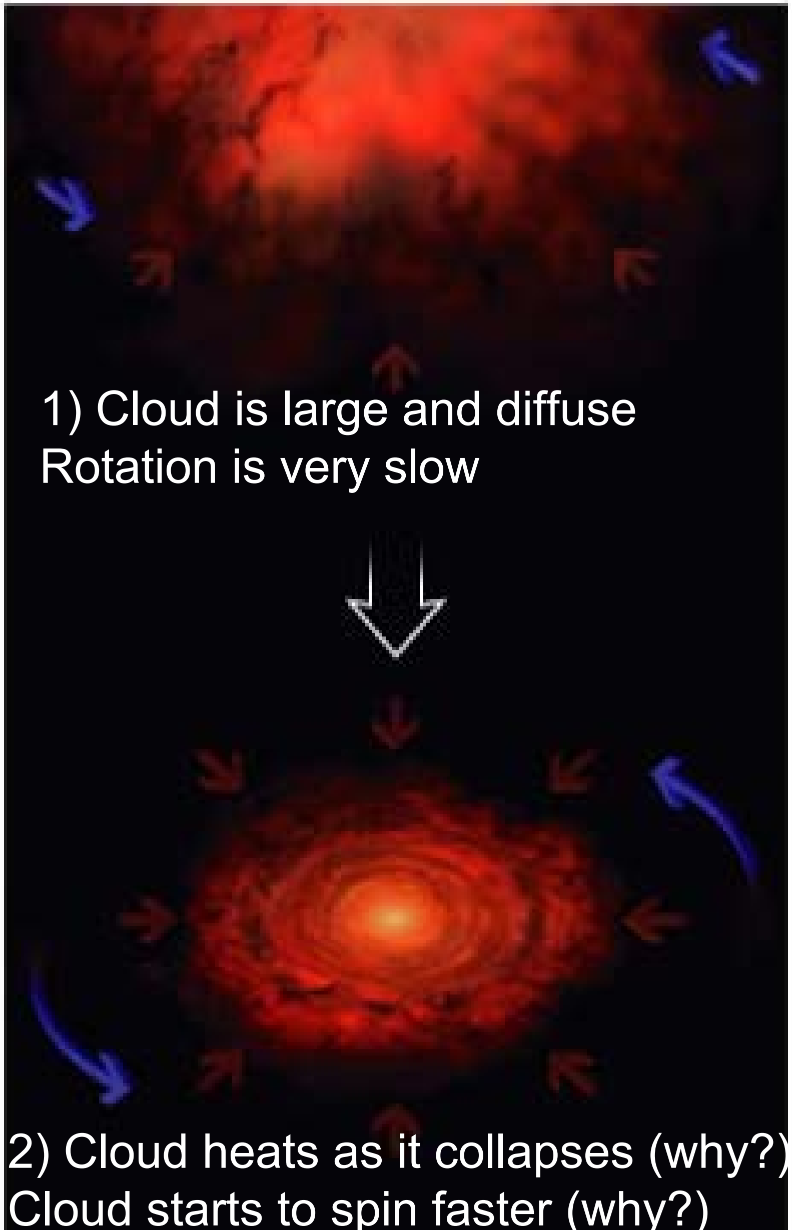
- $F = GM_1M_2 / r^2$
- As cloud shrinks, gravitational forces get stronger and it collapses faster
- Gravity pulls inwards in all directions, it's not weaker in some directions than others
- So it looks like the cloud of gas should stay spherical as it shrinks

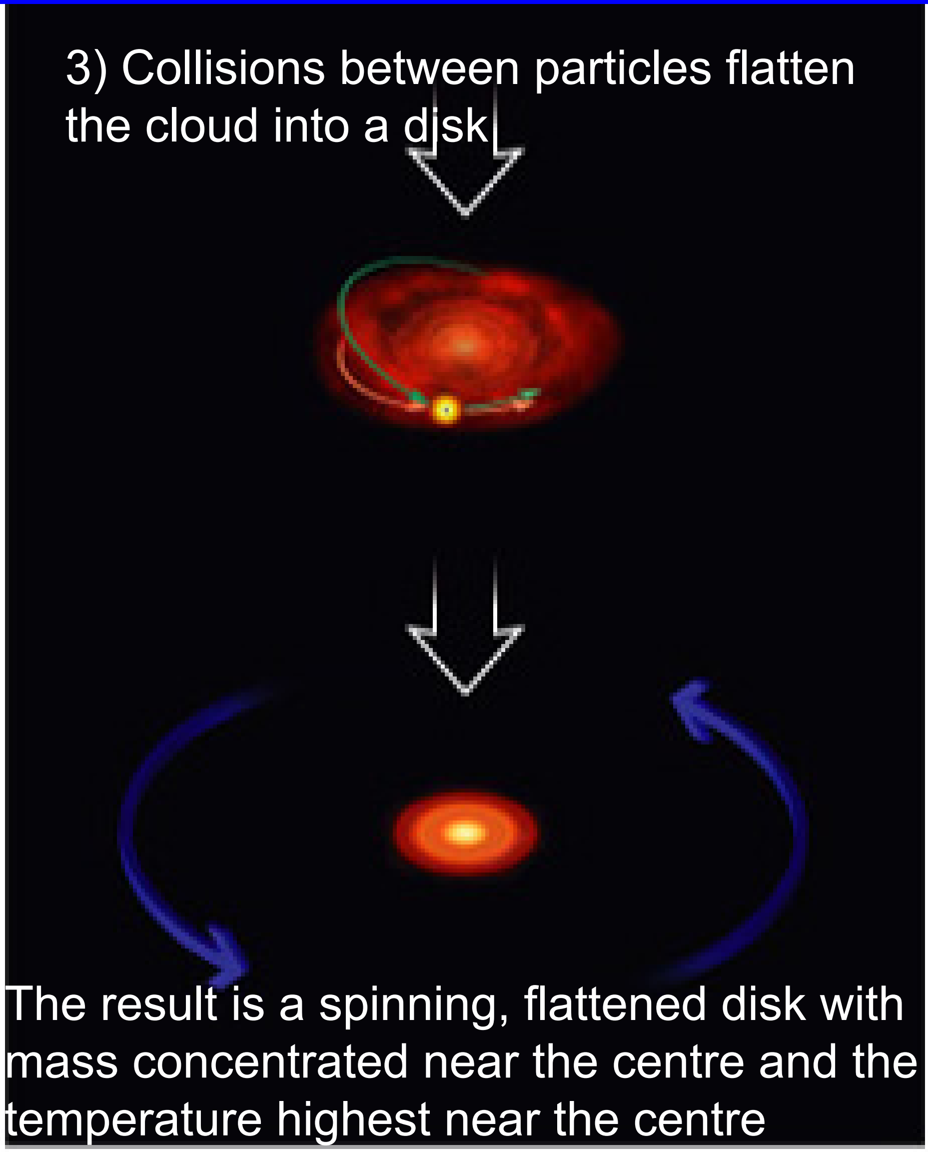
Three Conservation Laws

- These three properties are conserved as the cloud collapses
- Energy
  - Gas particles speed up as they are pulled inwards, collisions convert inward kinetic energy into randomly directed thermal energy
- Momentum
  - Gas cloud doesn't suddenly start moving along
- Angular Momentum

Angular Momentum

- Gas cloud has some angular momentum when it starts to collapse
- Cloud starts to spin faster as it collapses, like an ice-skater pulling in her arms
  - Interactive Figure 8.3
- Collisions between particles flatten the cloud into a disk
  - Interactive Figure Why does the disk flatten?


1) Cloud is large and diffuse
Rotation is very slow
2) Cloud heats as it collapses (why?)
Cloud starts to spin faster (why?)


3) Collisions between particles flatten the cloud into a disk
The result is a spinning, flattened disk with mass concentrated near the centre and the temperature highest near the centre

Conservation of energy

- A – Turns spherical cloud into flat disk
- B – Heats the cloud as it collapses
- C – Makes the cloud/disk rotate
- D – Explains why the cloud of gas forms

Conservation of momentum

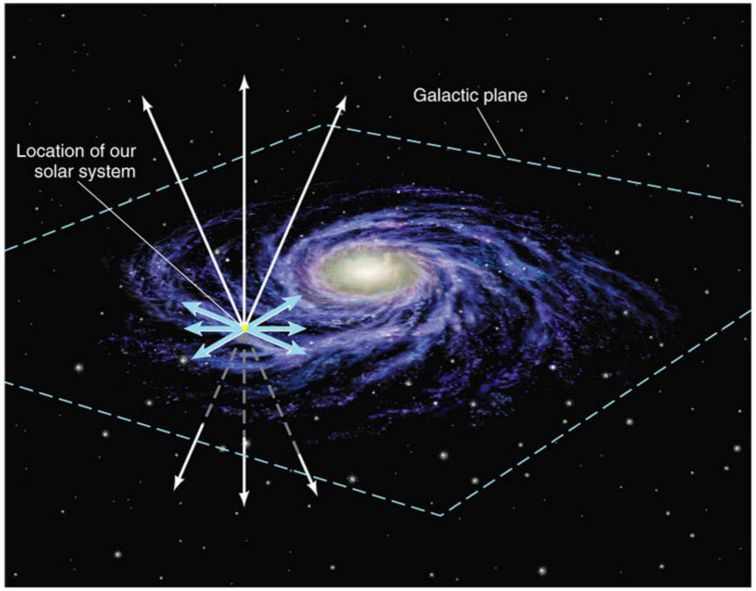
- A – Isn’t very important here
- B – Makes the cloud rotate
- C – Turns the spherical cloud into a flat disk
- D – Affects the condensation of gas into solids

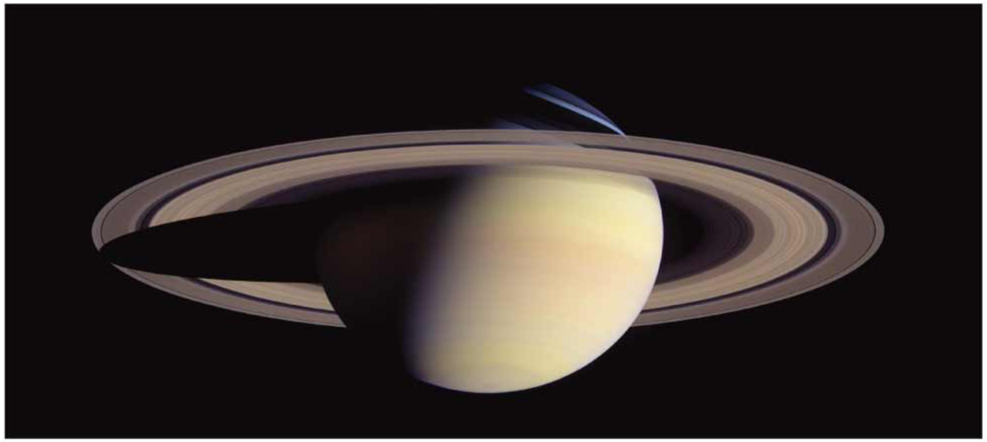
Conservation of angular momentum

- A – Heats the gas as the cloud collapses
- B – Affects whether atoms form larger molecules or not
- C – Isn’t very important here
- D – Makes the cloud rotate

Other Disks

- Spiral galaxies are disks
- Saturn's rings are a disk
- Disks of material form around black holes
  - Evidence for how disks form





Cloud Collapse Summary

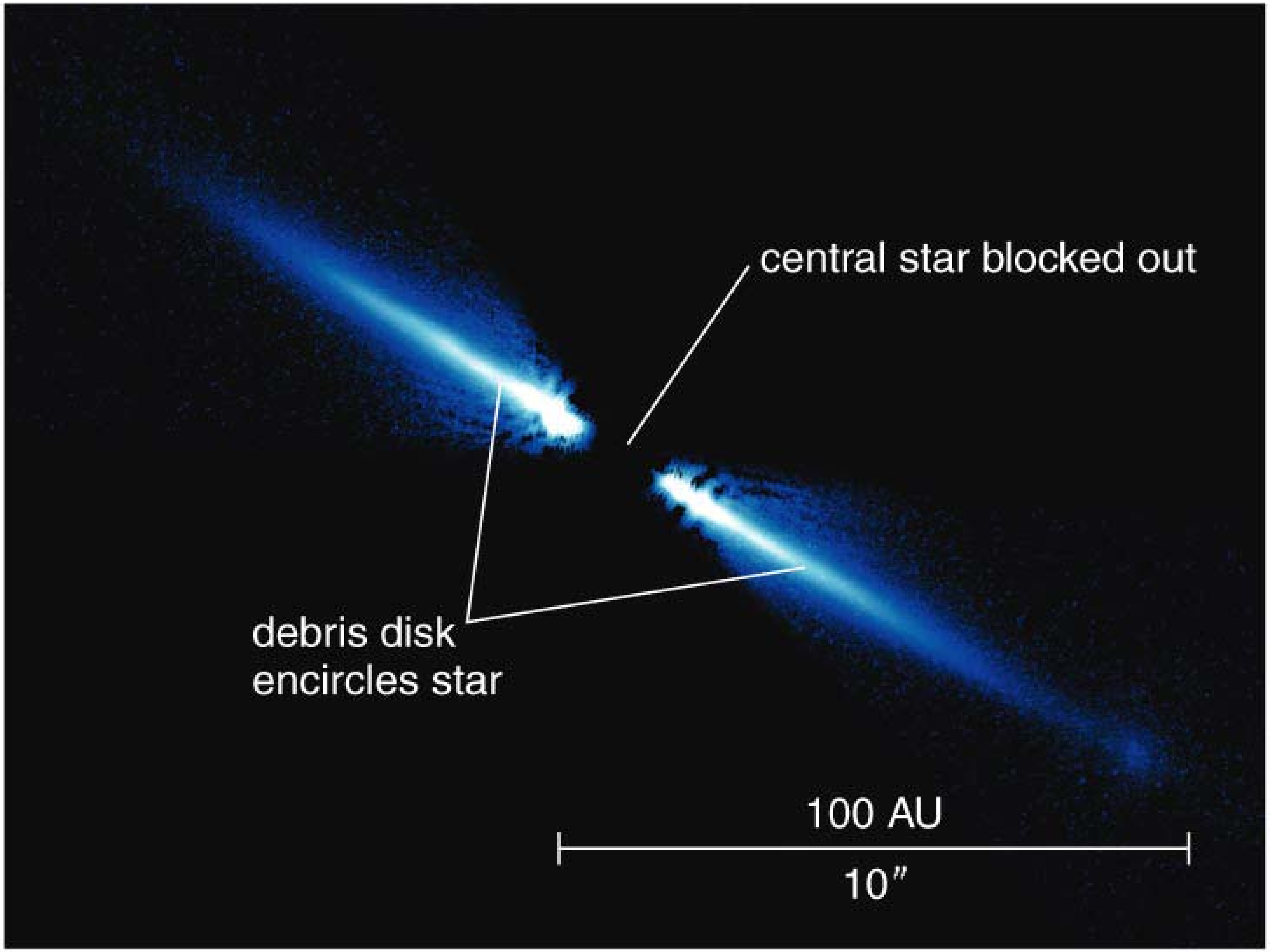
- Hot because of conservation of energy, gravitational potential energy has become heat
- Spinning because of conservation of angular momentum. Moving so much mass to the centre of the cloud causes the rest to spin much faster
- A flat disk because collisions in a spinning cloud prevent particles from orbiting in other directions (conservation of momentum)

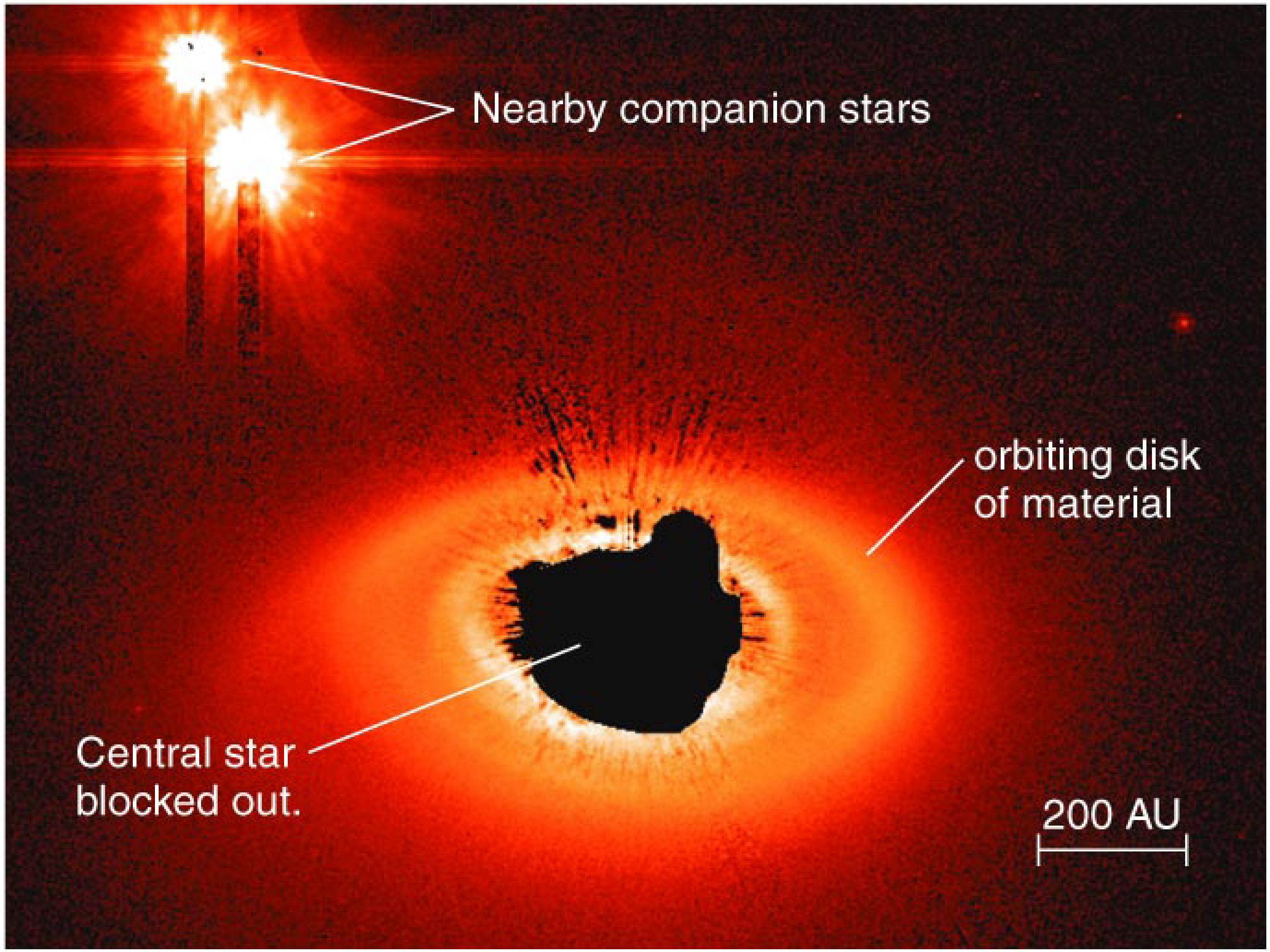
Calculation Exercise

- A 1 gram dust grain moving upwards at 10 m/s hits another 1 gram dust gram moving downwards at 30 m/s.
- What is the momentum of the first dust grain before the collision? The second?
- The dust grains stick together. How fast do they move and in what direction?

Observational Evidence

- Hot clouds/disks should emit lots of infra-red radiation
  - Many regions where stars appear to be forming emit infra-red radiation
- The shapes of these hot regions should be flat disks
  - Disks have been observed in star-forming regions and around young stars


central star blocked out
debris disk
encircles star
100 AU
10″


Nearby companion stars
orbiting disk
of material
Central star
blocked out.
200 AU

The Formation of Planets

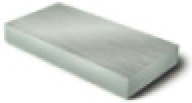
- The solar nebula had collapsed into a flattened disk about 200 AU in diameter, twice as large as Pluto’s orbit today before planets started to form
- Nebula’s composition was 98% hydrogen and helium, 2% everything else
- How did two classes of planet form?
  – Small, rocky, innermost terrestrial planets
  – Large, gas, outermost jovian planets

Gas or Dust?

- Low density of collapsing gas cloud means that all materials start off as isolated atoms of gas, not liquid or solid
- As cloud collapses, atoms start bumping into each other. Do they stick together as a solid (condense) or stay separated as a gas?
- Condense if cold, stay as gas if hot
- How hot is hot?

Table 8.1 Materials in the Solar Nebula

A summary of the four types of materials present in the solar nebula. The squares represent the relative proportions of each type (by mass).

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

Solid water, ammonia, or methane are all called "ice" in this context

Very near the Sun, nothing could condense

Near Mercury's present orbit, metals and some rocks could condense

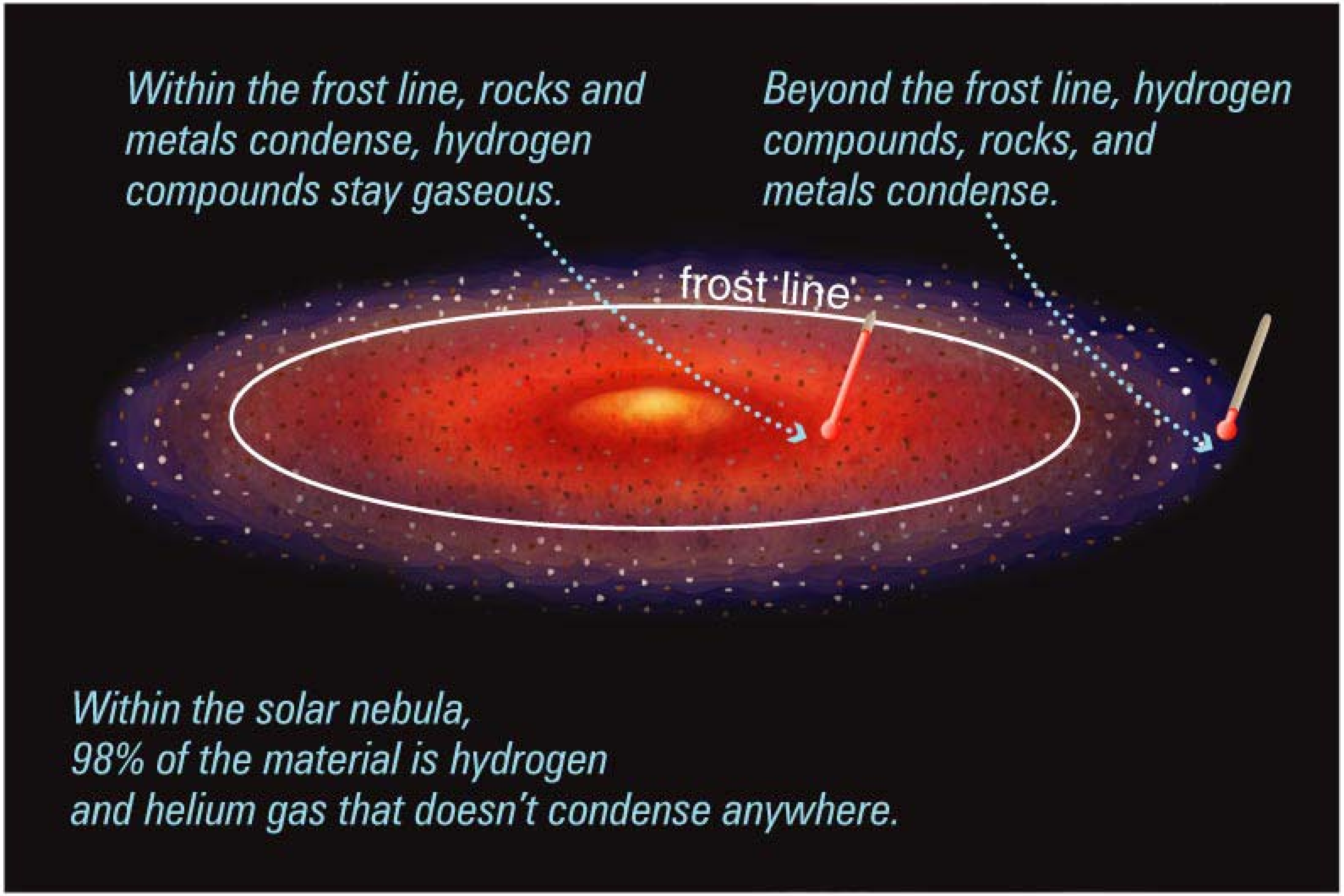
Near Earth's present orbit, metals and all rocks could condense

Near Jupiter's present orbit, metals, rocks, and ices could condense

Rocks could only condense outside 0.3 AU

Ices could only condense outside 3.5 AU
the "Frost Line"

Show summary of interactive figure 8.5


Within the frost line, rocks and metals condense, hydrogen compounds stay gaseous.
Beyond the frost line, hydrogen compounds, rocks, and metals condense.
frost line
Within the solar nebula, 98% of the material is hydrogen and helium gas that doesn't condense anywhere.

Inner/Outer Differences

- Inner solar system (<3.5 AU)
  - small amounts of condensed metal and rock
  - tiny flakes or “seeds” of material

- Outer solar system
  - large amounts of condensed ices
  - small amounts of condensed metal and rock
  - tiny flakes or “seeds” of material

The frost line is important because

- A – It affects the chemical composition of planets
- B – It affects the size of planets
- C – It affects the speed and direction of planetary rotation
- D – It affects the eccentricity of planetary orbits

Dust into Boulders, Boulders into Planets

- The early inner solar system contained many tiny flakes of metal/rock like dust grains
- The inner solar system today contains several large metal/rock planets

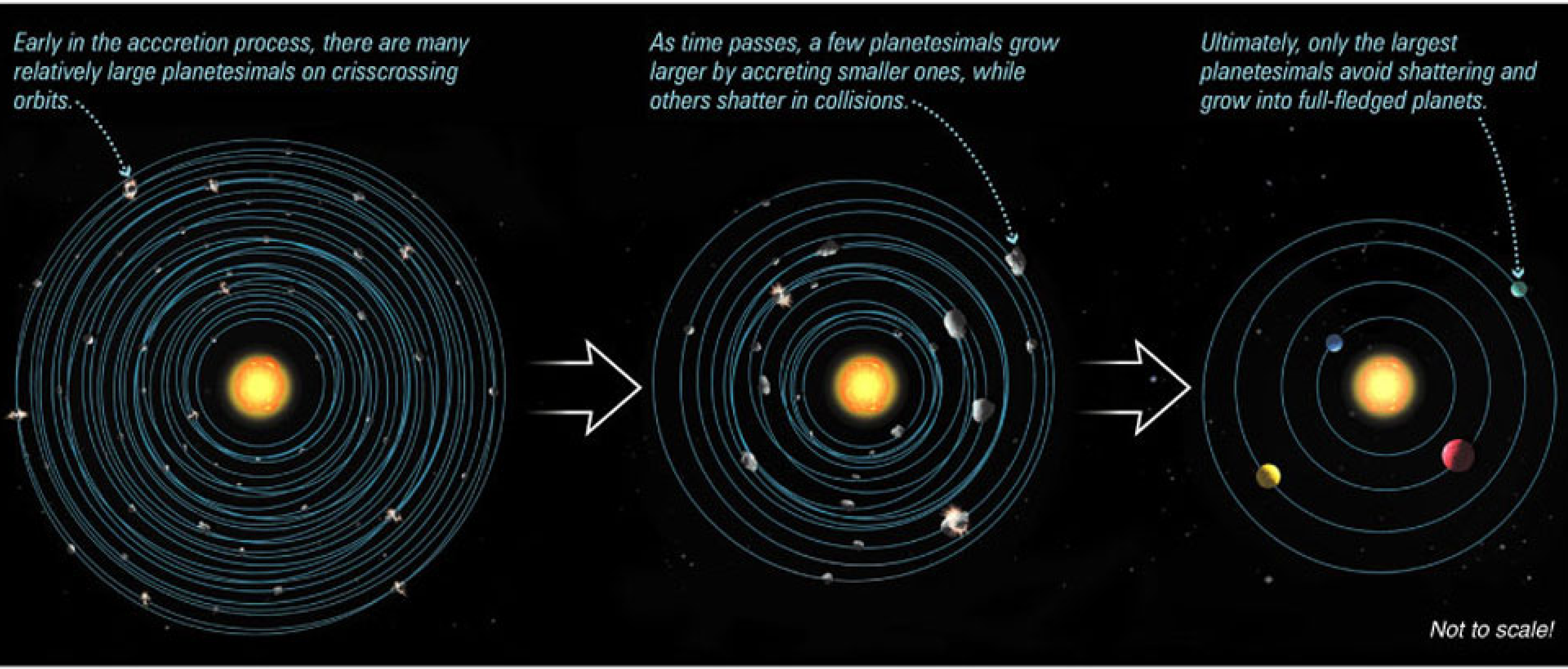
- The process of turning dust into planets (accretion) involved two stages

Dust into Boulders

- Many tiny flakes orbiting the Sun in nearly-identical circular orbits at nearly the same speeds
- Orbits criss-cross each other, so collisions occur, but collisions are very gentle
- Static electricity causes colliding flakes to stick together and grow larger
- Gravity does not play a major role

Boulders into Planets

- Gravitational forces between boulders alter their orbits, so relative speeds are much faster
- Collisions are violent
- Colliding boulders either fragment into small pieces or join together into one larger boulder
- Size matters
  - Larger boulders gravitationally attract smaller ones, experience more collisions
  - Larger boulder have a large surface area to make contact with other boulders, experience more collisions
  - Larger boulders are more likely to survive a collision intact
- Large boulders become very large, trend towards a small number of large objects (planets), not many small objects (boulders)
- Fancy name for these boulders = planetesimal


Early in the acccretion process, there are many relatively large planetesimals on crisscrossing orbits.
As time passes, a few planetesimals grow larger by accreting smaller ones, while others shatter in collisions.
Ultimately, only the largest planetesimals avoid shattering and grow into full-fledged planets.
Not to scale!

Calculation Exercise

- $g = GM/R^2$ $G = 6.67 \times 10^{-11}\ m^3/(kg\ s^2)$
- What is the acceleration due to gravity on the surface of a 10 m radius boulder whose mass is 10^7 kg?

A meteorite

Rocks in planets have been heated and squished so that they've lost any memory of early condensation

Rocks in small asteroids haven't been altered like that

This meteorite contains small (few cm) flakes of metal mixed into a rocky material

Consistent with our condensation theory

Accretion in the Outer Solar System

- Planetesimals contained lots of ice, as well as metal and rock
- Once these baby planets exceeded a few Earth masses in size, their gravitational pull was able to capture and hold hydrogen/helium gas from the surrounding nebula
- Bigger planets capture more gas, get big fast
- A mini-nebula around each baby planet

Jovian Satellites

- Heating, spinning, and flattening affected the solar nebula
- They would also have affected the mini-nebulas around each baby jovian planet
- Just as planets formed around the Sun, satellites formed around the jovian planets
- Orbits in direction of planet's rotation, circular orbits, same plane for orbits, moon's rotation in same sense as the orbit

Nebular Theory of Solar System Formation

- A cloud of gas, the “solar nebula”, collapses inwards under its own weight
- Cloud heats up, spins faster, gets flatter (disk) as a central star forms
- Gas cools and some materials condense as solid particles that collide, stick together, and grow larger

Why did accretion stop?

- Early solar system = hot. Today = cold
- Why didn’t water condense in the inner solar system later on?

- Mass of Jupiter << Mass of gas in solar nebula. Where did all that gas go?

Goals for Learning

- Where did the solar system come from?
- How did planetesimals form?
- How did planets form?

Goals for Learning

- Where did the solar system come from?
  - A cloud of gas collapsed inwards due to its own gravity
  - It heats up due to conservation of energy and becomes a flat, spinning disk due to conservation of angular momentum
  - This is called the solar nebula

Goals for Learning

- How did planetesimals form?
  - The first solids condensed as the nebula become more dense and cooler
  - Small grains stuck together due to static electricity, eventually forming boulder-sized objects called planetesimals

Goals for Learning

- How did planets form?
  - Metal and rock could condense at all distances from the Sun, but ices could only condense far from the Sun, beyond the frost line
  - Heavy ice/rock/metal objects in the outer solar system could capture lots of gas and became the jovian planets
  - Less heavy rock/metal objects in the inner solar system became the terrestrial planets

Formation of the Solar System (Chapter 8)

Goals for Learning

- How did asteroids and comets form?
- Can we explain those “exceptions”?
- What is radioactivity?

Solar Wind

- A wind of protons and electrons continuously pours off the Sun
- Very strong winds are seen around young stars
- This strong wind eventually swept the remains of the solar nebula, hydrogen and helium gas, out of the solar system
  - Nebula gas leaves before inner solar system cools enough for ices to condense
  - Nebula gas leaves outer solar system before Jupiter can capture all of it

What if solar wind blew early and hard? What if solar wind blew late and gently?

The Aftermath

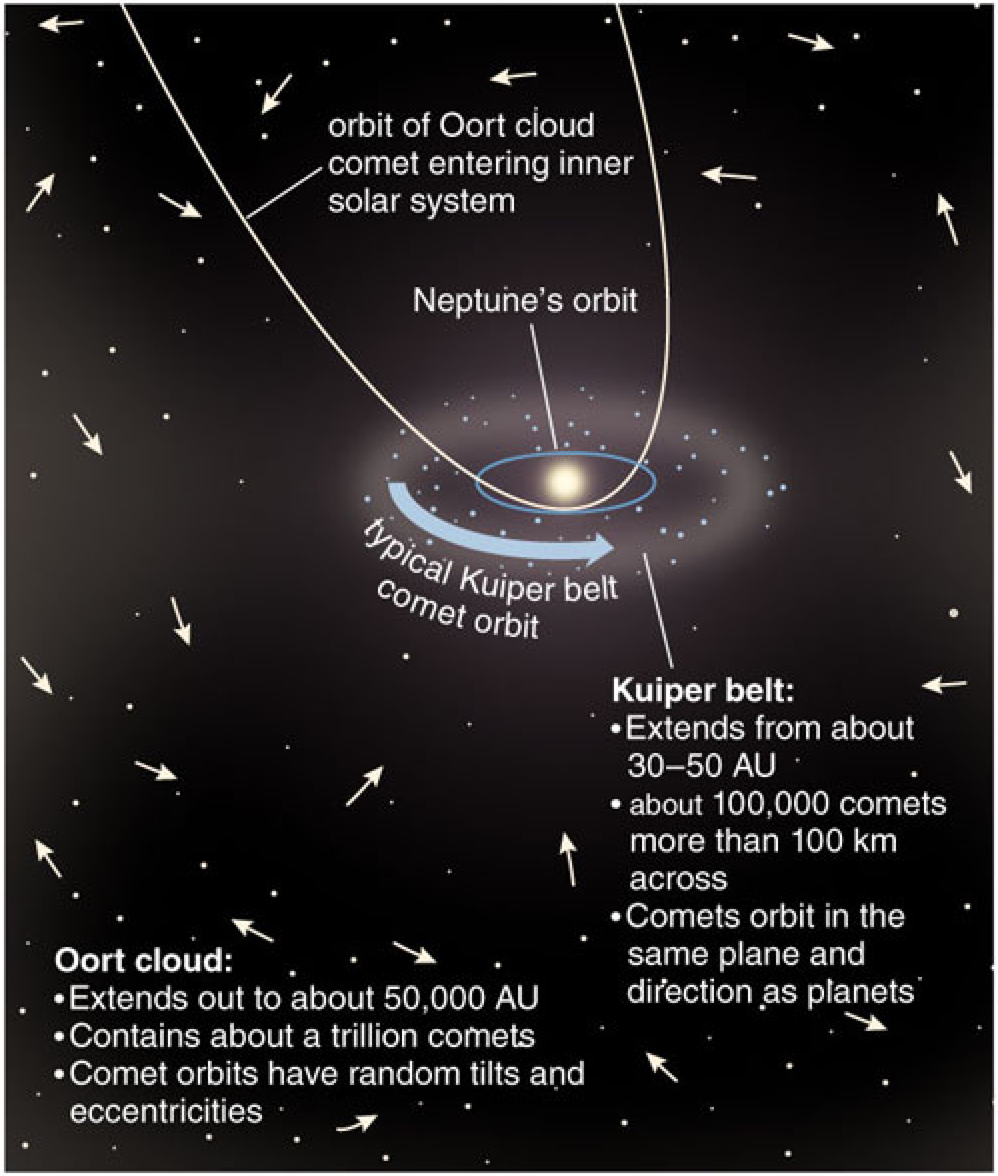
- The planets exist in their present sizes and orbits
- Jovian satellites exist in their present sizes

- Two classes of planet exist
- Patterns of motion for the planets and large satellites exist
  - Asteroids/Comets?
  - Exceptions to rules?

- Many small planetesimals remain after solar wind clears nebular gas away – what happens?

Asteroids

- Asteroids are leftover rocky planetesimals that were formed in the inner solar system
- Gravitational forces from Mercury, Venus, Earth, and Mars make any asteroids orbiting between them either hit a planet or fly out of the solar system
- Only planetesimals orbiting between Mars and Jupiter could survive as asteroids
- Jupiter's gravity plays a major role in deciding which orbits are safe and stable



Comets fall into two categories:
short-period (tens of years)
long-period (millions of yrs)

S-P = Kuiper Belt Comet
L-P = Oort Cloud Comet

The Nebular Theory accounts for these characteristics

Comets

- Leftover icy planetesimals that orbited between Jupiter and Neptune were flung almost all the way out of the solar system by a jovian planet’s gravity – Oort Cloud
  - Far from the Sun, random inclinations and eccentricities
- Leftover icy planetesimals that orbited beyond Neptune stayed in their orbits – Kuiper Belt
  - Just beyond Neptune, in same plane as the planets, orbiting in same direction

List as many similarities and differences between asteroids, Kuiper Belt objects, and Oort Cloud objects as you can

Similarities

- Leftover planetesimals, so their chemistry hasn’t been changed much
- Affected by the gravity of other solar system objects, especially Jupiter
- Can collide with planets

Differences

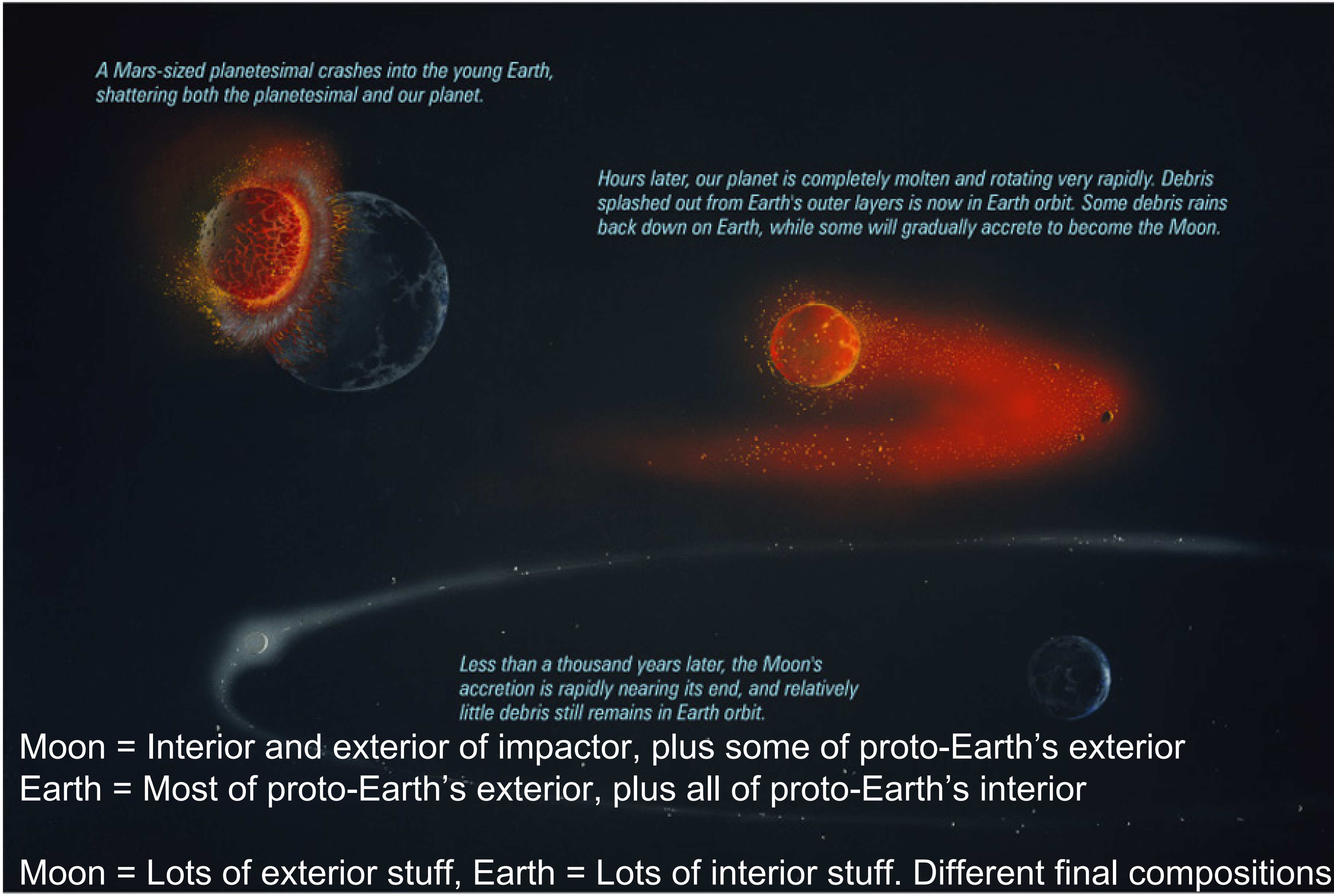
- Asteroids are rocky, Kuiper Belt and Oort Cloud objects are icy
- Asteroids and Kuiper Belt objects formed in their present orbits, Oort Cloud objects did not
- Asteroids and Kuiper Belt objects have smaller inclinations and eccentricities than Oort Cloud objects

“Exceptions”

- Some small moons of the jovian planets orbit the “wrong” way around their planet or in very “inclined” orbits
  - These couldn’t have formed in the mini-nebula
- Capturing a moon by gravity is difficult
  - The moon must lose energy somehow
- Planetesimal passes through the dense gas around a baby jovian planet, “air resistance” causes it to lose energy
  - Planetesimal gets captured by planet’s gravity

Exceptions

- Earth is much too small to have captured the Moon in this way
- Since the compositions of the Moon and Earth are different (Earth has more iron, less rock), they couldn't simply have formed together
- Have to explain why such a large body of non-Earth-like composition is orbiting Earth
  - GIANT IMPACT!



Moon = Interior and exterior of impactor, plus some of proto-Earth’s exterior
Earth = Most of proto-Earth’s exterior, plus all of proto-Earth’s interior

Moon = Lots of exterior stuff, Earth = Lots of interior stuff. Different final compositions
Solid debris re-accretes into Moon, gases do not. Water vapour doesn’t condense quickly enough to form Moon, so Moon rocks are very dry

Calculation Exercise

- What is the kinetic energy of a planetesimal as heavy as Mars ($m = 6 \times 10^{23}$ kg) hitting Earth at 10 km/s?
- It takes about 3×10^{6} Joules of energy to melt 1 kg of rock. How much rock could have been melted by this impact?

Other Giant Impacts

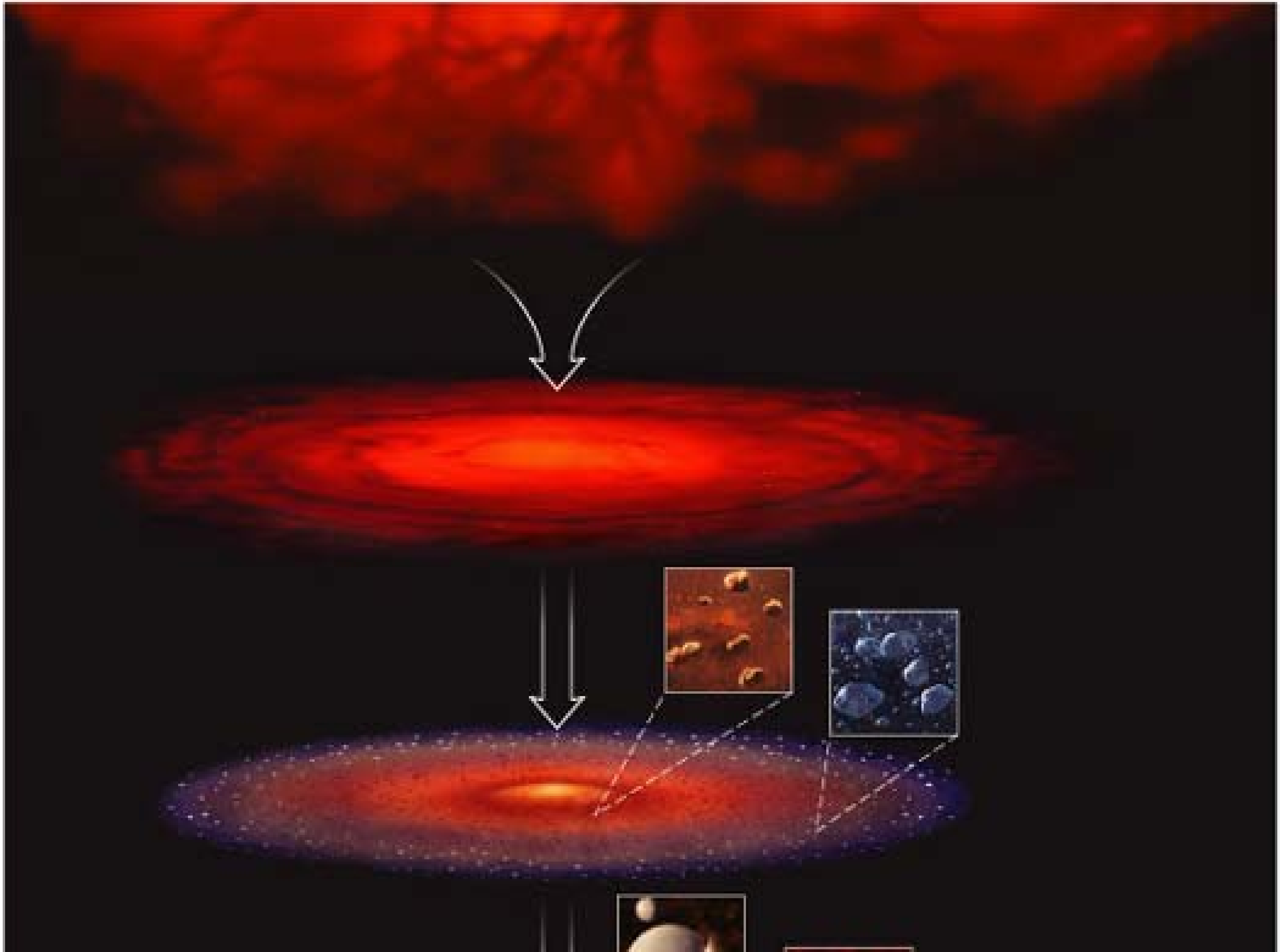
- Tilt of Uranus
- Capture of Charon by Pluto

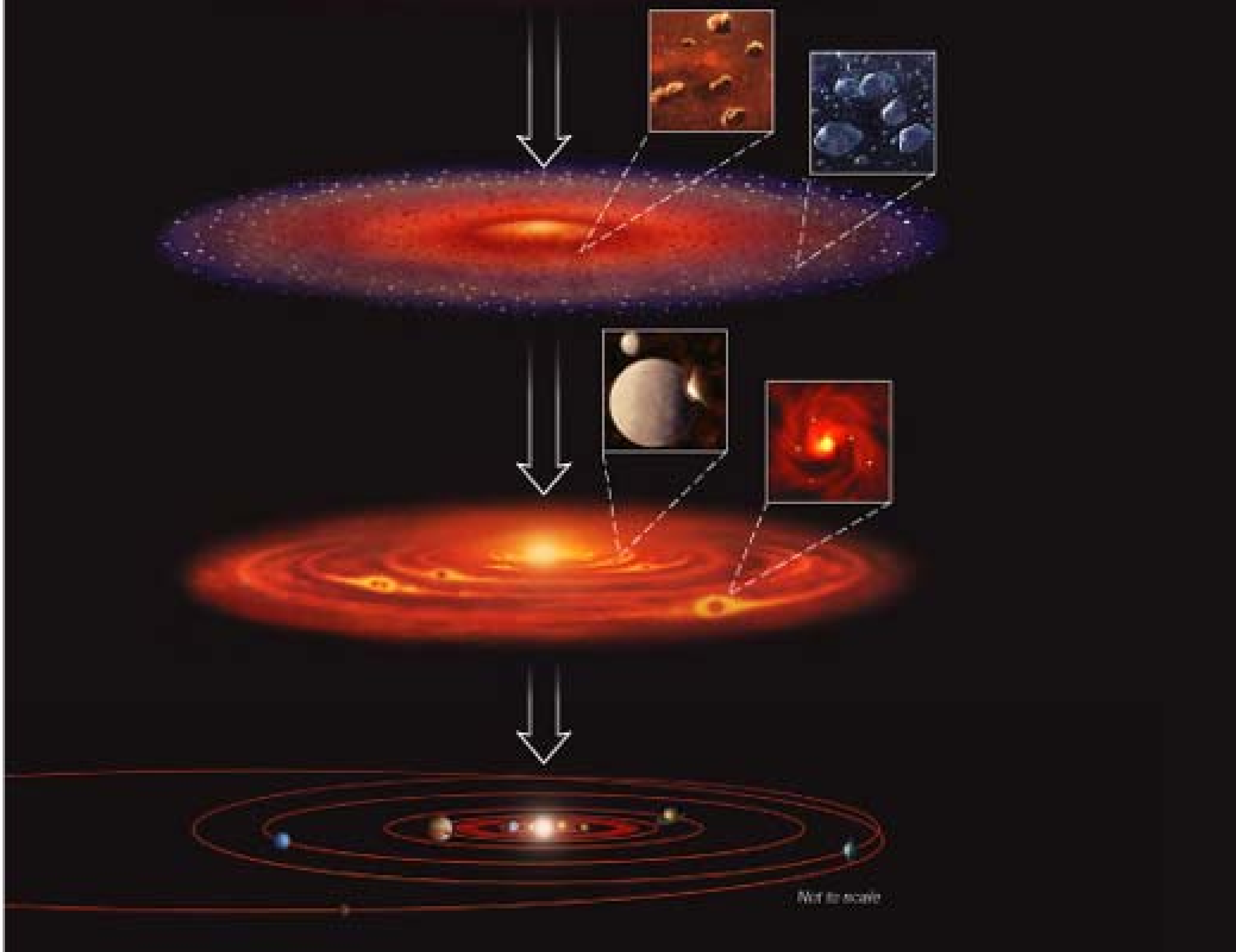
- Strong chemical evidence for Earth/Moon giant impact
- Weaker evidence for Uranus, Pluto’s giant impacts

Timescales

- Solar System = 4.6 billion years old
- Process of solar system formation as described here took few tens of millions of years

- Things could have happened differently
  - Number, orbits, sizes of terrestrial planets
  - Number, orbits, sizes of jovian planets
  - Which bodies experienced giant impacts and what happened in those impacts?




Not to scale

The Young Solar System

- Lots of leftover planetesimals
- Some remain today as asteroids/comets
- Many flung out of solar system
- Many impacted into planets
  - Lots of planetesimals, some small, some large impacted all of the planets
  - This “heavy bombardment” lasted several hundred million years
  - Formed lots of impact craters (Moon, Mars)
  - Possibly brought water compounds from outer solar system to Earth (oceans and atmosphere)

The Age of Things

- How old is an atom? Unknown
- Atoms sometimes spontaneously change into other atoms in a process called radioactive decay
- This decay process has a steady timescale
  - This gives us a clock to measure time

Parent and Daughter Isotopes

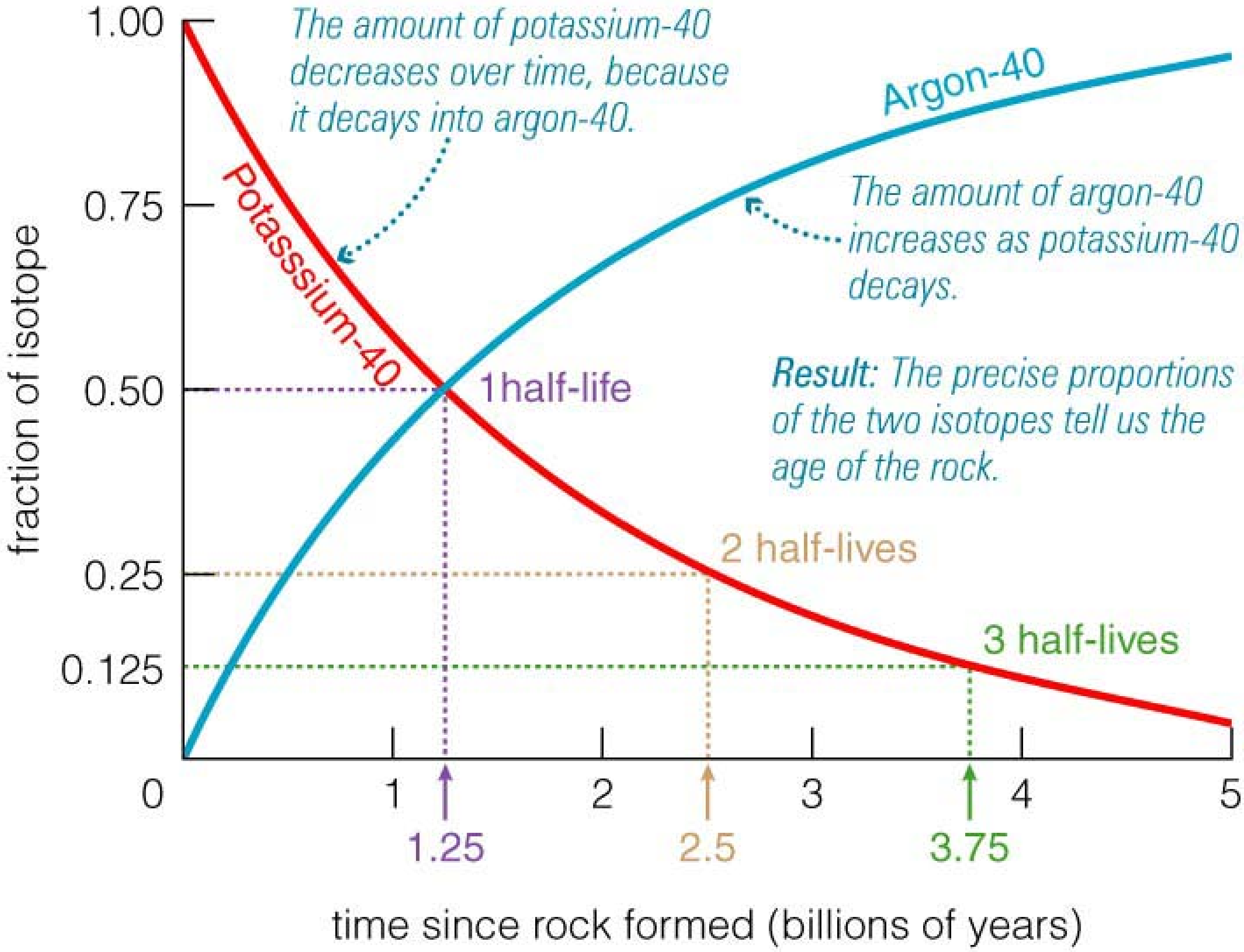
- Electrons aren’t important here, only the protons and neutrons in the nucleus
- Since the number of both protons and neutrons affects the radioactivity of a nucleus, different isotopes of the same element can have different radioactivies
- Some isotopes are radioactive, but many are not
- “Parent isotopes” change into “daughter isotopes”

What Happens Exactly?

- Nucleus just splits into two pieces – nuclear fission, like in nuclear power stations
  - One heavy atom becomes two lighter atoms
- A proton turns into a neutron after effectively eating an electron
  - One element changes into a different element
- Many different processes can occur

Example Process

- Potassium-40 = 19 protons, 21 neutrons
  - This parent isotope turns into this daughter isotope…
- Argon-40 = 20 protons, 20 neutrons
- Random, spontaneous decay for any individual nucleus, but a well-defined timescale for a group of many atoms
- Get a collection of potassium-40 atoms. Wait. 1.25 billion years later, half of the atoms will be potassium-40 and half will be argon-40
  - Half-life = 1.25 billion years



1.00
0.75
0.50
0.25
0.125
0
fraction of isotope
The amount of potassium-40 decreases over time, because it decays into argon-40.
Argon-40
Potassium-40
The amount of argon-40 increases as potassium-40 decays.
1half-life
Result: The precise proportions of the two isotopes tell us the age of the rock.
2 half-lives
3 half-lives
1
2
3
4
5
1.25
2.5
3.75
time since rock formed (billions of years)

Rocks keep atoms locked up

- Atoms were mixed a lot in the gas of the solar nebula
- Atoms also get mixed a lot in liquids, like lava or magma
- But atoms stay fixed in rocks, new atoms don't join the rock, existing atoms don't leave the rock
- Radioactive decay can find the time since the rock last solidified
  - If we know how much potassium-40 or argon-40 was in the rock when it solidified

Half-Lives

- There are many radioactive isotopes, with half-lives from fractions of seconds to billions of years
- Rocks can often be dated using more than one parent/daughter pair. Hopefully the ages agree…

$$\frac{\text{current amount}}{\text{original amount}} = \left(\frac{1}{2}\right)^{(\text{t/halflife})}$$

Calculation Exercise

- A rock contains 16 grams of a radioactive isotope whose half-life is 12 million years. How many grams of that isotope will it contain after 36 years? After 60 years?
- Fifty years ago, another rock contained 48 grams of a radioactive isotope. Now it contains 12 grams. What is the half-life of the radioactive isotope?

The Oldest Rocks

- Many rocks on Earth are young, tens-hundreds of millions of years old
- The oldest rocks on Earth are 4 billion years old
- The oldest rocks found on the Moon by Apollo are 4.4 billion years old
  - Why are Earth rocks younger?
  - When did the giant impact occur?
- The oldest pieces of meteorites are 4.55 billion years ago, the start of the accretion of the solar nebula
- The solar system is about 4.5-4.6 billion years old

Goals for Learning

- How did asteroids and comets form?
- Can we explain those “exceptions”?
- What is radioactivity?

Goals for Learning

- How did asteroids and comets form?
  - Jupiter's gravity prevented planetesimals between Mars and Jupiter forming a planet. Some of them still remain there today as asteroids
  - Leftover ice-rich planetesimals in the outer solar system were either flung into the Oort cloud, almost out of the solar system, and left undisturbed in the Kuiper Belt beyond Neptune

Goals for Learning

- Can we explain those “exceptions”?
  - Small moons orbiting “backwards” were captured by gas around the forming planet
  - Earth’s large Moon was formed by a giant impact
  - Uranus’s strange tilt and Pluto’s large moon Charon MAY have been formed by giant impacts as well
  - Pluto is part of the Kuiper Belt, not a lone oddball

Goals for Learning

- What is radioactivity?
  - Isotopes sometimes spontaneously change into other isotopes
  - This occurs at a fixed rate, expressed as a half-life
  - The ages of rocks can be found using measurements of the products of radioactive decay