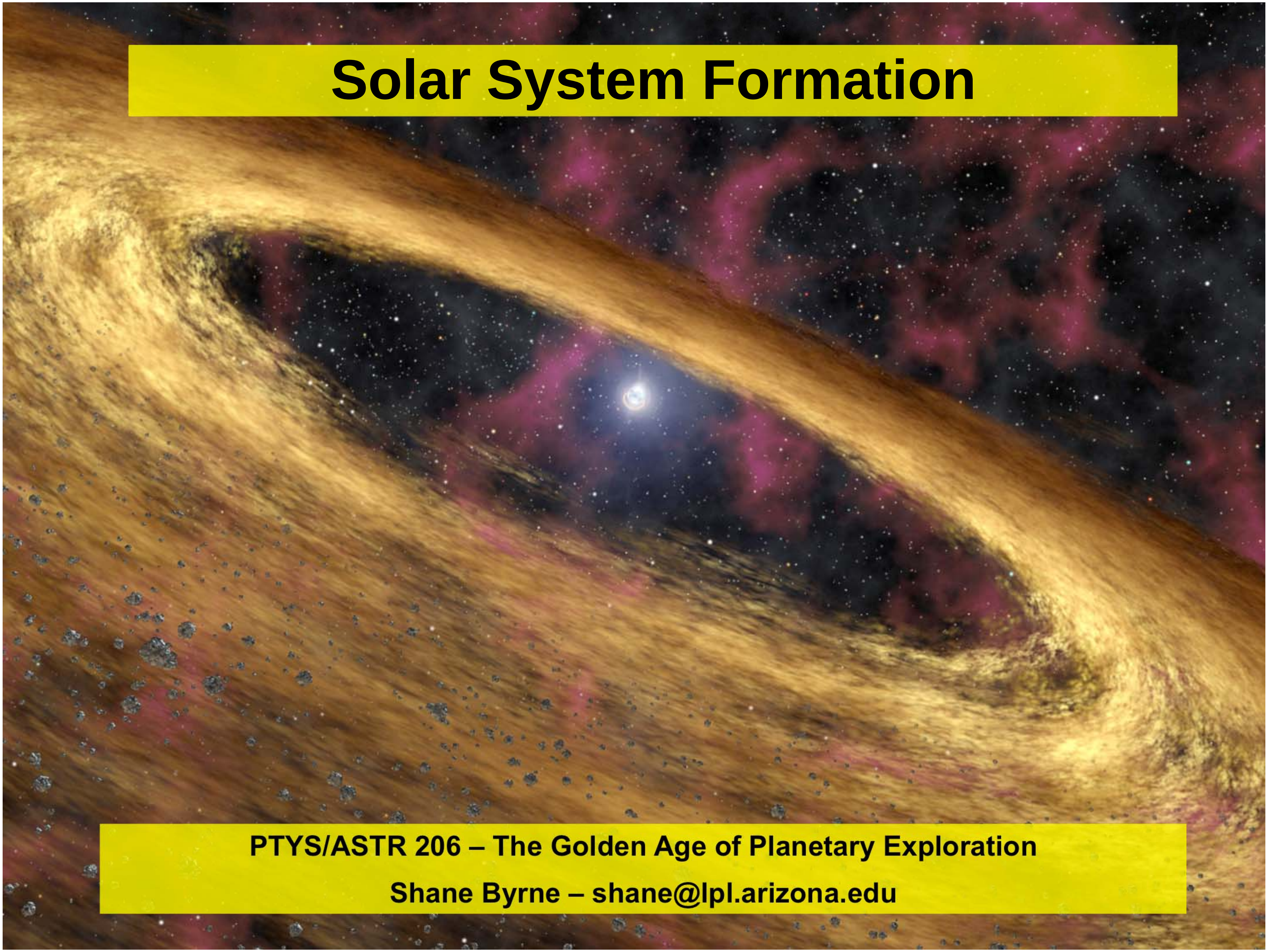
Announcements

- **HW6 due on Thursday**
  - Use Kevin as the TA for this one
  - Office hours are today 2-4pm

- **HW6 typo**
  - Question 4 said Neptune's orbital period was ~165 days!
  - Should have read ~165 years

- **TA award nominations**
  - Optional – if you think one of the TAs should get special recognition
  - Don't just check the boxes, you need to write a few words about what the TA did that you liked.
  - Forms and submission box are on the table outside



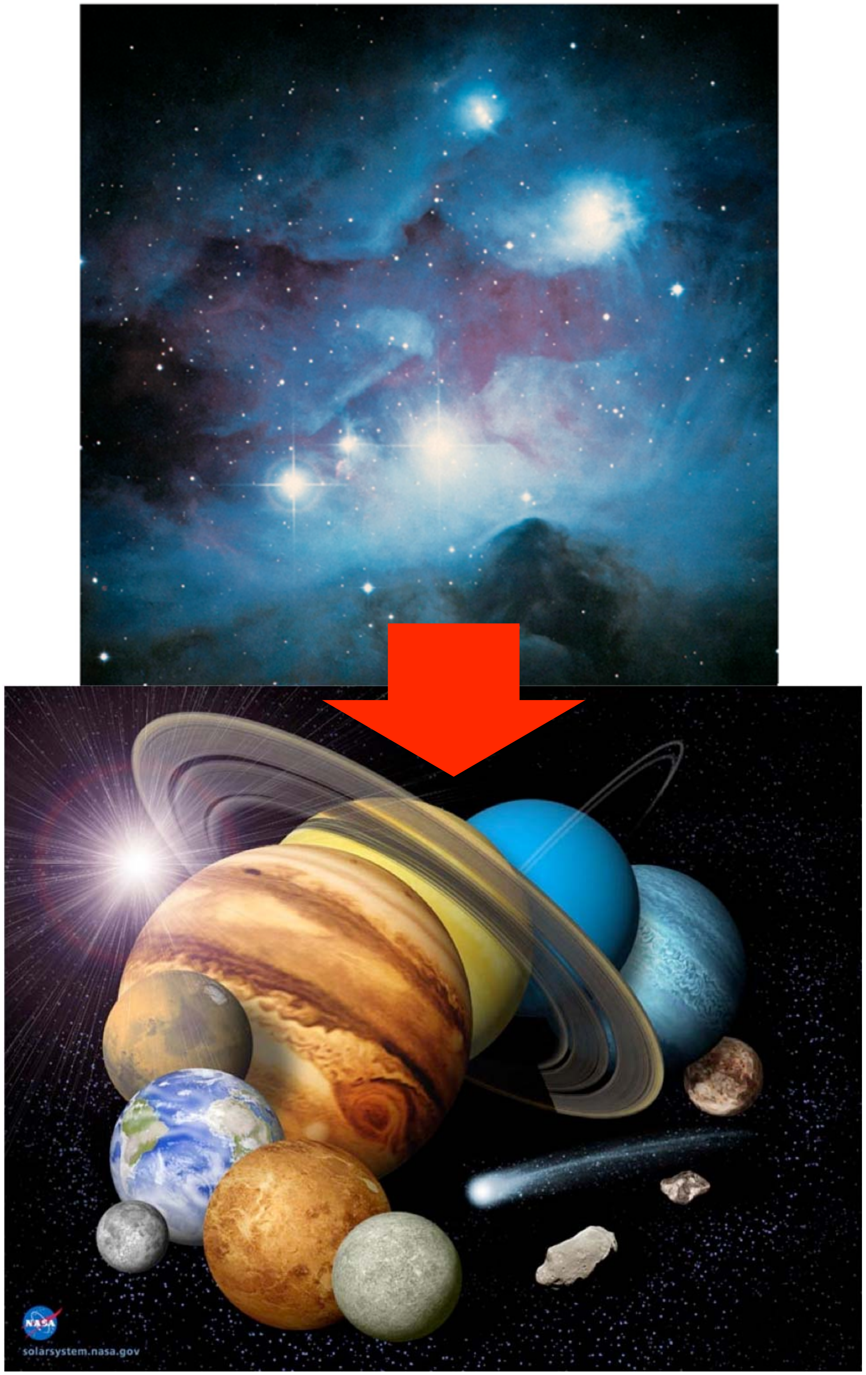
Solar System Formation

PTYS/ASTR 206 – The Golden Age of Planetary Exploration

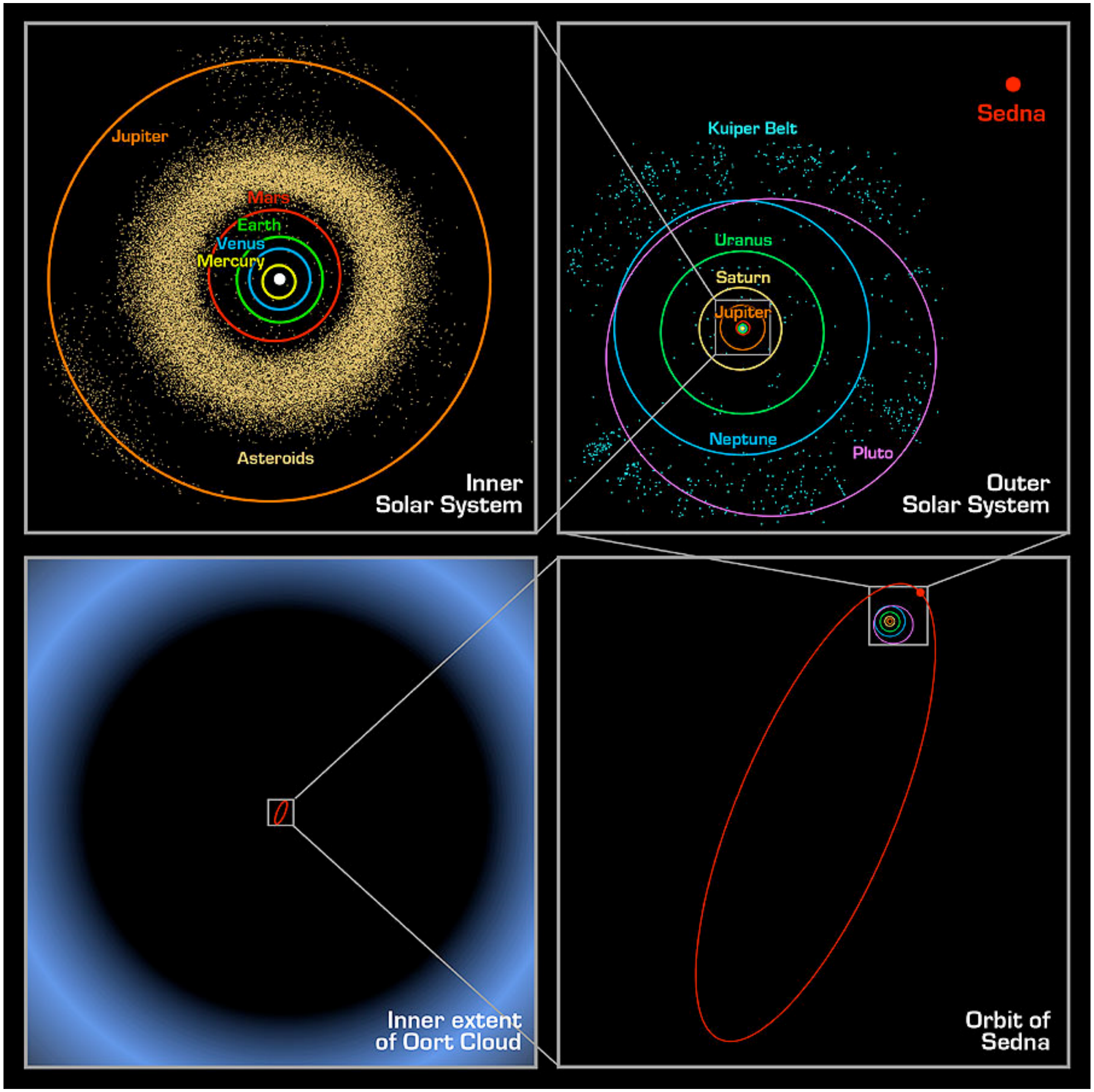
Shane Byrne – shane@lpl.arizona.edu

In this lecture…

- Review of the solar system
  - Structure
  - Composition
  - Dynamics
- Giant Molecular Clouds
  - The raw material
- Formation steps
  - Stars and Disks
  - Planetesimals
  - Terrestrial Planets
  - Giants Planets
- Small Bodies and Planet Migration
- Cleaning up the Mess



- Overall solar system structure
  - Inner rocky planets
    - Mercury 0.39 AU
    - Venus 0.72 AU
    - Earth 1.00 AU
    - Mars 1.52 AU
  - Asteroid belt (2-4 AU)
    - Hundreds of members
    - Several groups
    - Sizes from dust to ~950 km (Ceres)
  - Giant planets
    - Jupiter 5.2 AU
    - Saturn 9.6AU
    - Uranus 19.2 AU
    - Neptune 30.1 AU
  - Kuiper Belt (30-50 AU)
    - Contains Pluto
    - Several groups
    - Sizes from dust to >2400 km (Eris)
  - Oort cloud
    - Long period comet reservoir
    - Affected by passing stars



- **Solar composition**
  - **Bulk composition of the solar system**
  - **Jupiter still has roughly solar abundances**
  - **Saturn is helium deficient at its surface**
  - **Other planets are highly enriched in heavier elements**

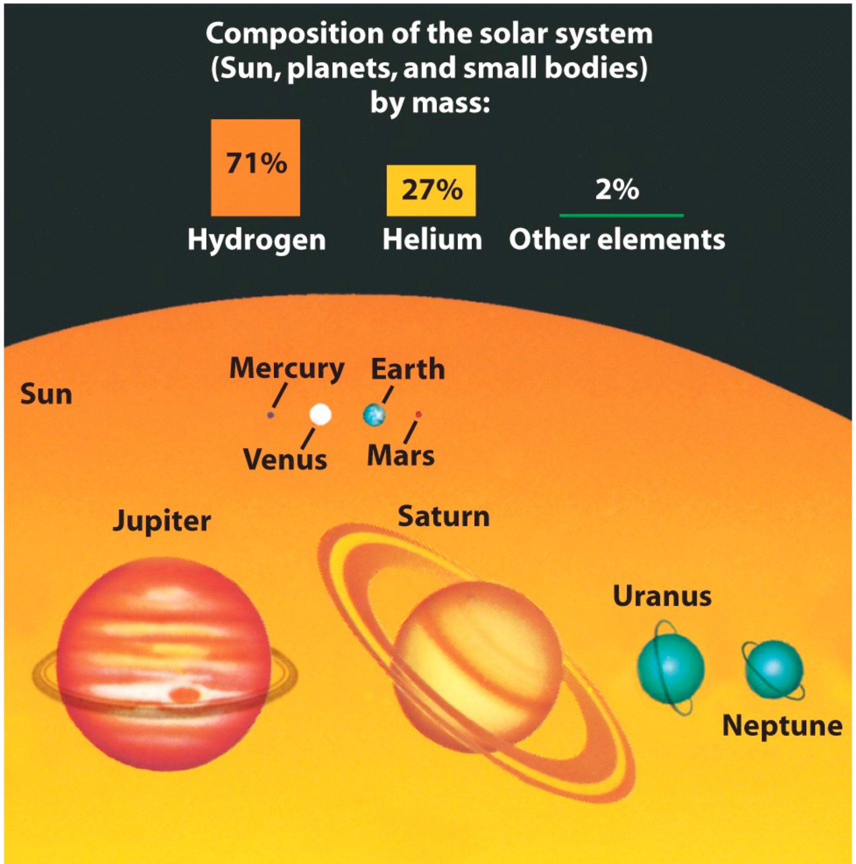
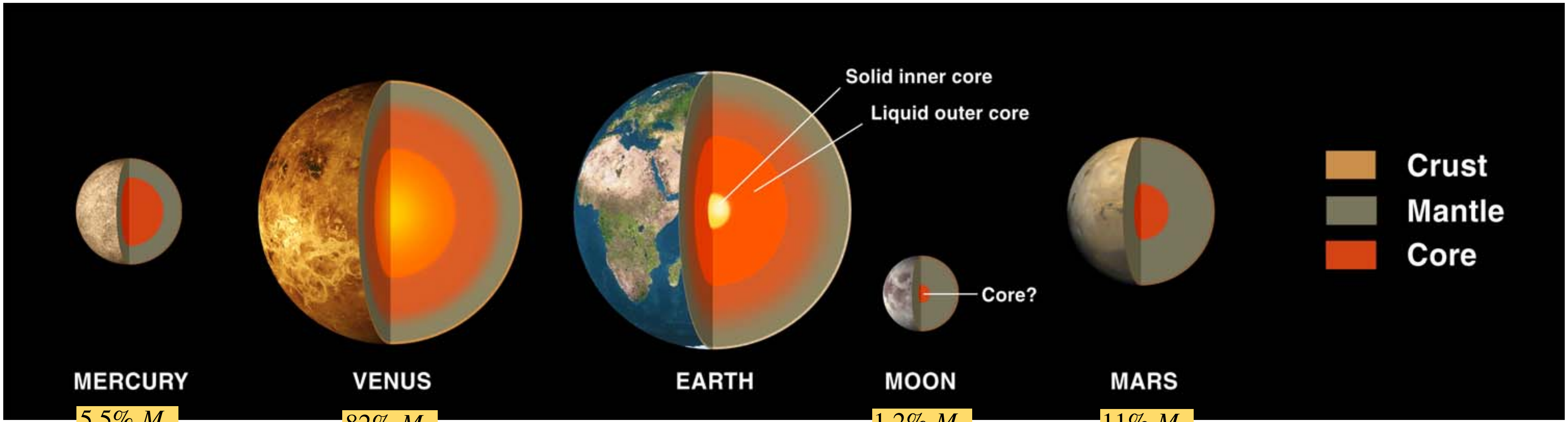


Figure 8-1
Universe, Eighth Edition

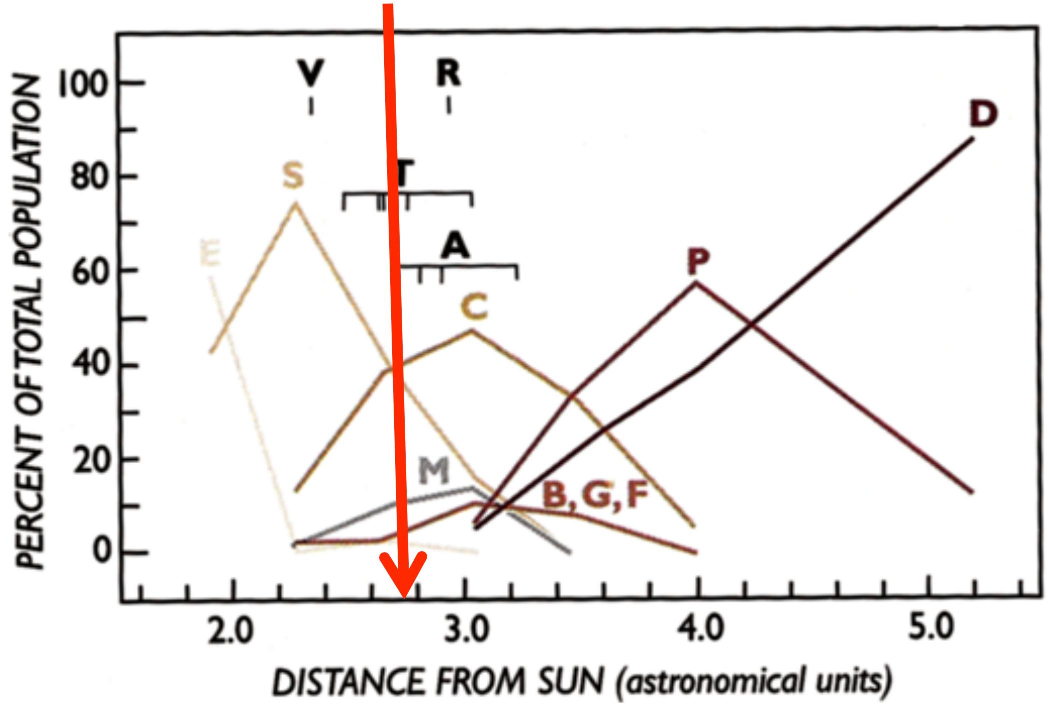
- Inner planets are composed of rock and iron
  - Heated by radioactive decay

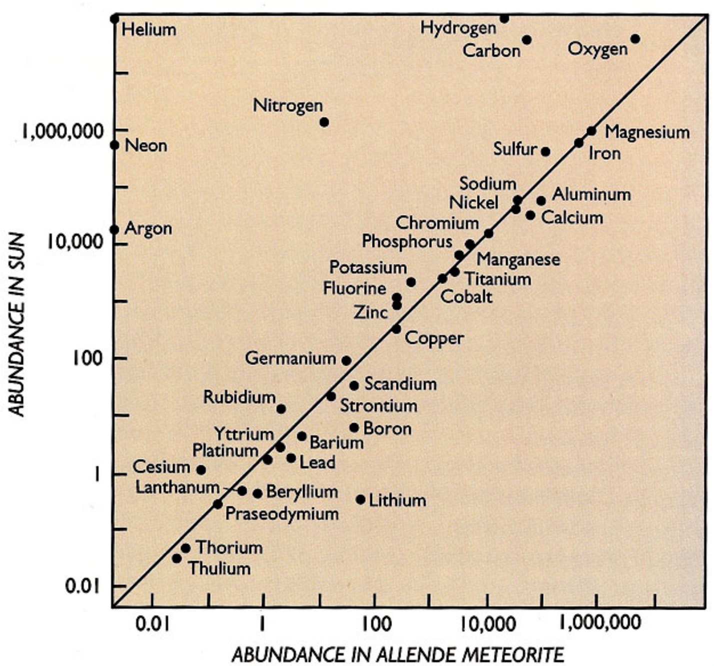


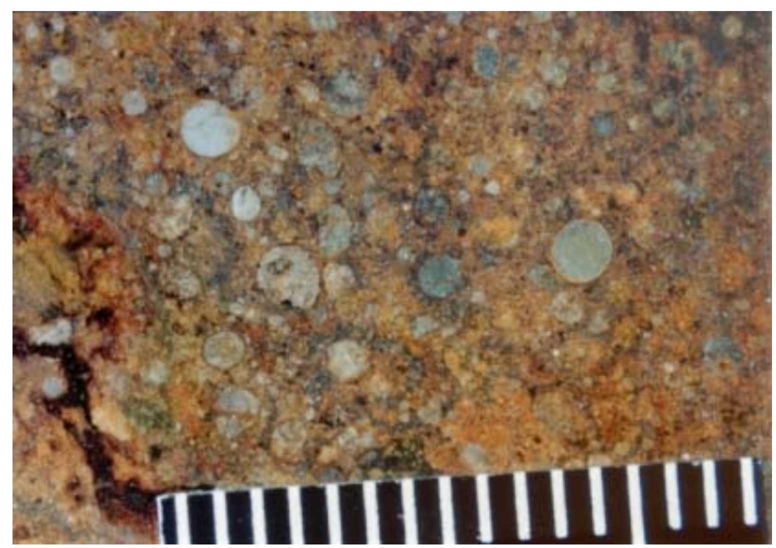
$5.5\% \, M_\oplus$ $82\% \, M_\oplus$ $1.2\% \, M_\oplus$ $11\% \, M_\oplus$

- **Asteroid belt is compositionally zoned**
  - **Ice-free asteroids close to the sun**
  - **Icier asteroids further out**
- **Meteorites**
  - **Chondrites mostly reflect solar composition**
  - **Provide the timing constraints**

Ceres ~25% water ice



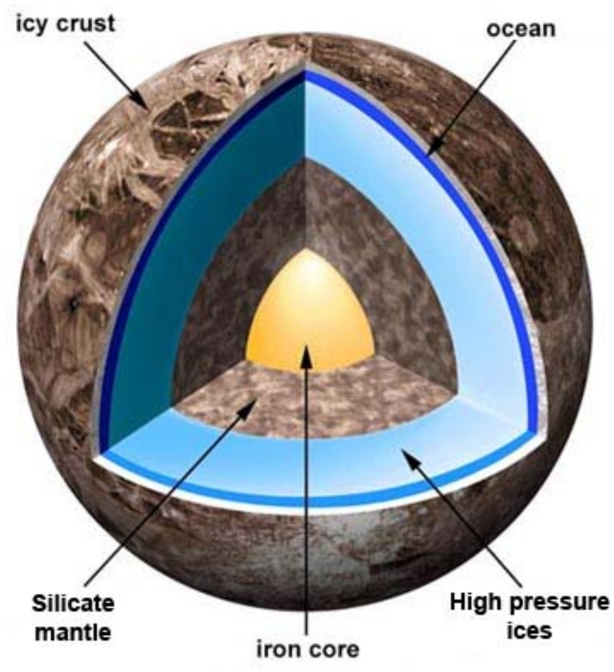




- **Giant planet satellites get icier with increasing distance from the Sun**
  - **Saturn's satellites are very ice rich**

    But…
  - **This trend is reverses at Uranus**
    - **Preference of oxygen for carbon monoxide vs. water ice**

	Warmer Jupiter ~ 5AU Saturn ~10 AU	Cooler Uranus ~19 AU Neptune ~30 AU
C	CH_4	CO
O	H_2O	CO
N	NH_3	N_2

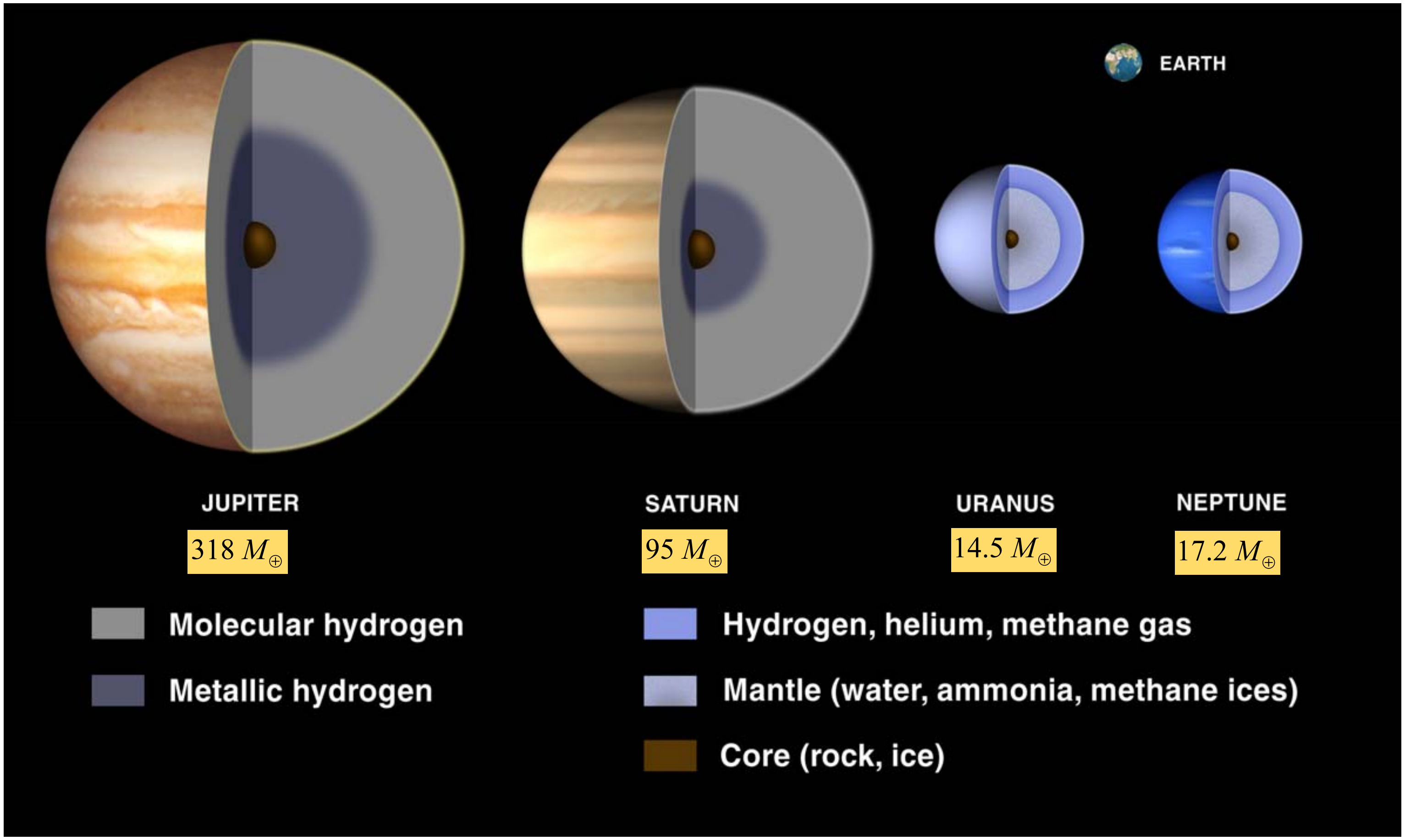


Ganymede 1940 kg m^{-3} (Jupiter)

Iapetus 1030 kg m^{-3} (Saturn)

Titania 1700 kg m^{-3} (Uranus)

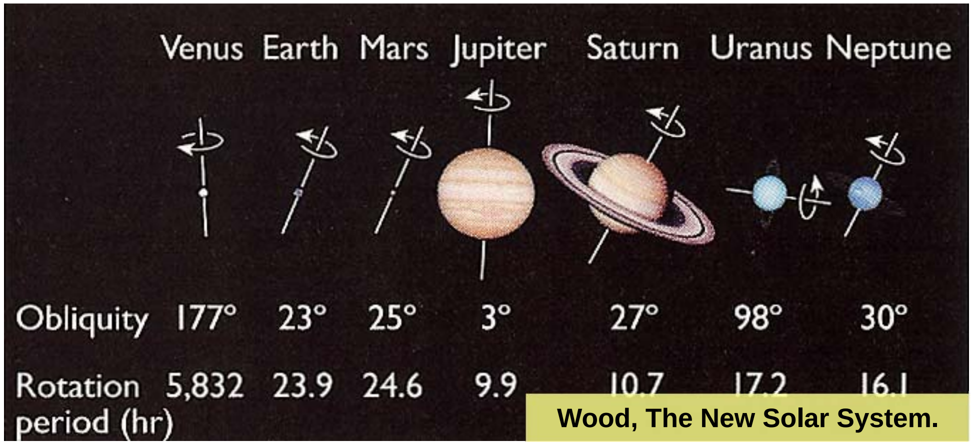
- Gas giant planets: Jupiter and Saturn
  - Similar rock/ice cores of about 10 earth masses
  - Large hydrogen envelopes – molecular and metallic
- Ice Giant Planets: Uranus and Neptune
  - Rocky cores
  - Water and Ammonia interiors
  - Large hydrogen molecular envelopes



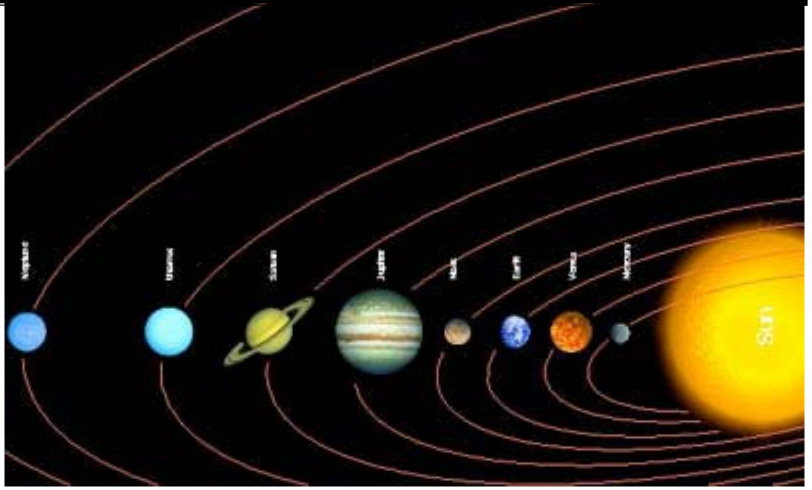
- Dynamical state of the solar system
  - Low inclinations and eccentricities – very disk like

	Planetary Inclinations and Eccentricities							
	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
i	7°	3.4°	0°	1.85°	1.3°	2.49°	0.77°	1.77°
e	0.2	0.0068	0.0167	0.0934	0.0485	0.0532	0.0429	0.01

  - Sun and most planetary bodies orbiting and (mostly) spinning in the same direction



Wood, The New Solar System.



  - Theories of solar system formation involving a disk of material…
    - Starting with Kant in 1755!

A <u>lot</u> of active research involving astrophysics, geochemistry, computer modeling etc

Here's what happened (or at least here's our current best guess)…

The raw material

- Solar systems form from large clouds of gas and dust
  - Giant Molecular clouds

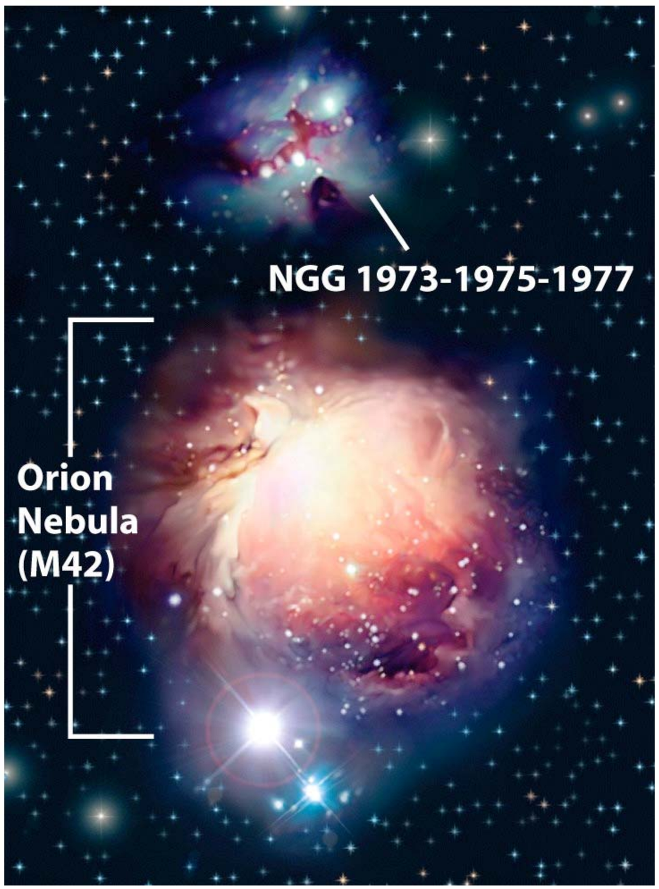


Figure 8-8a
Universe, Eighth Edition

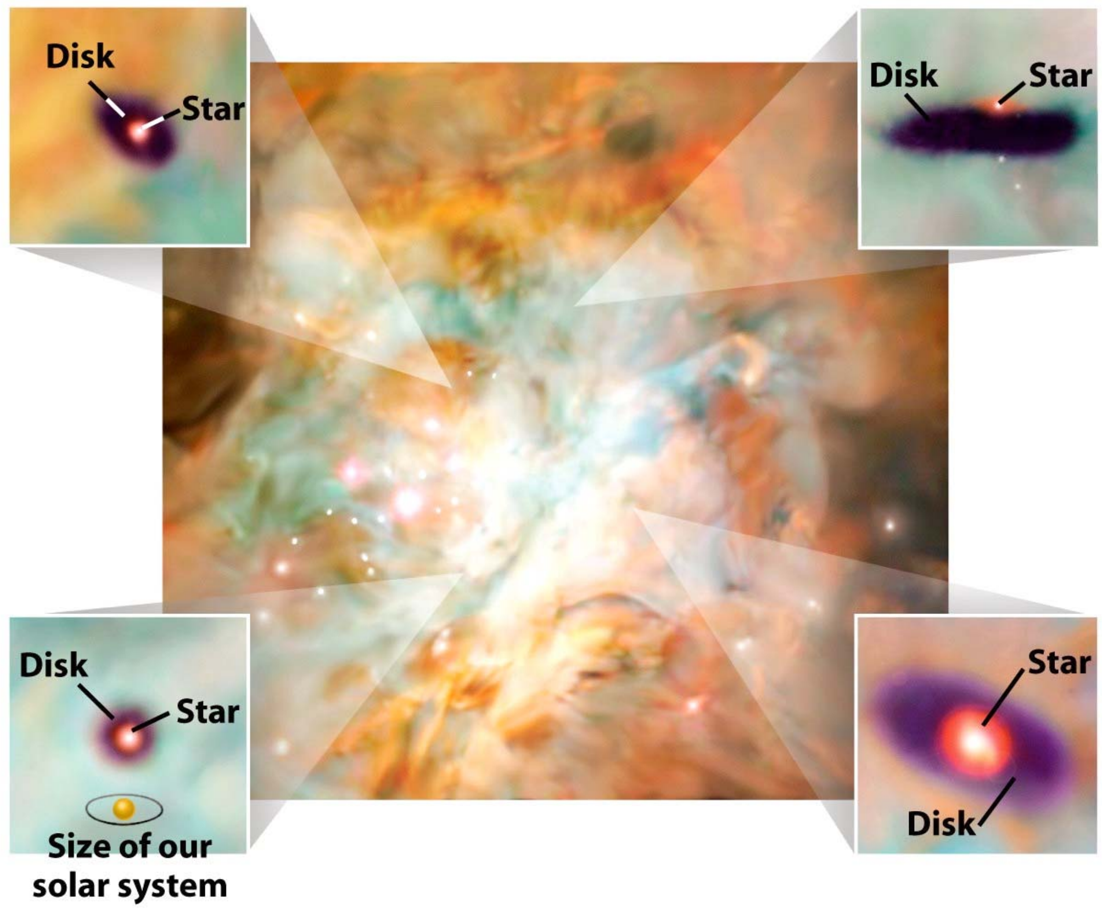
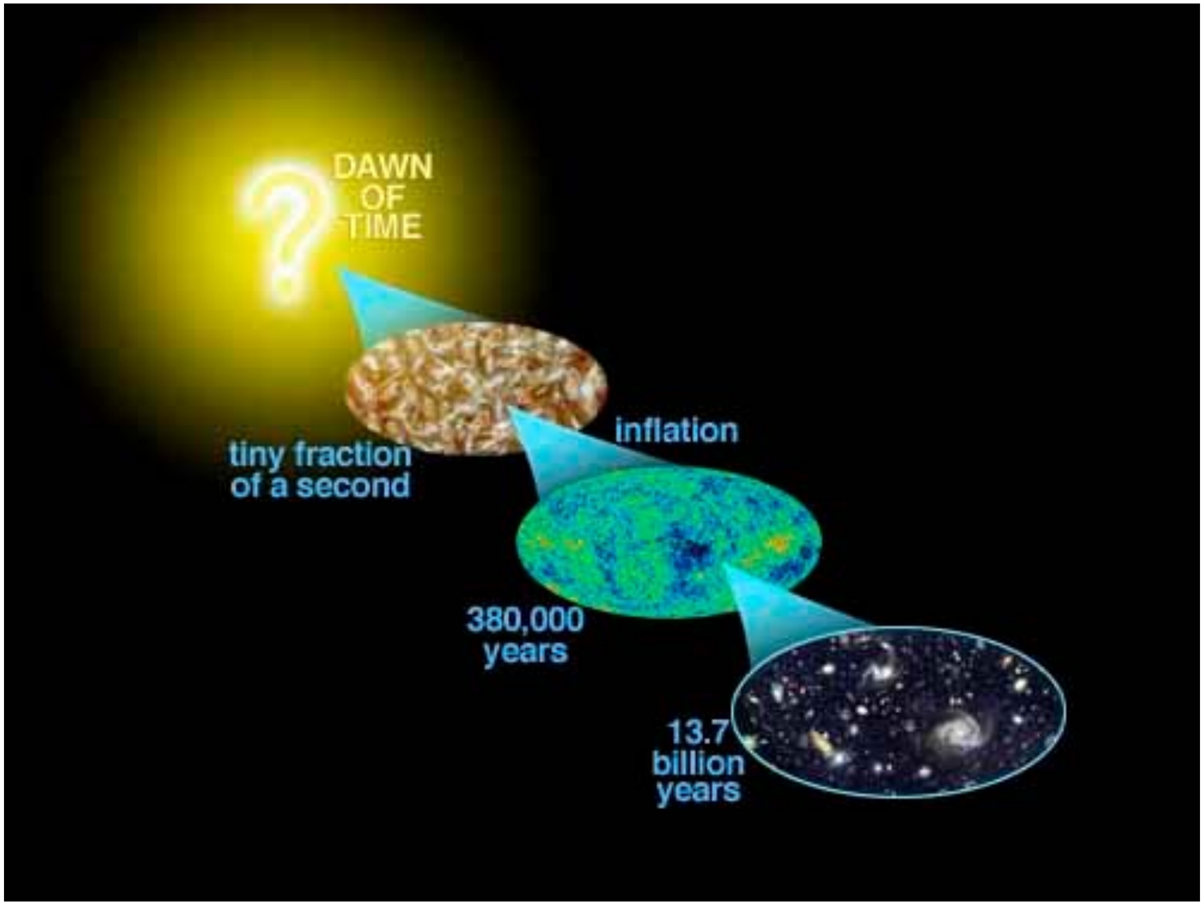
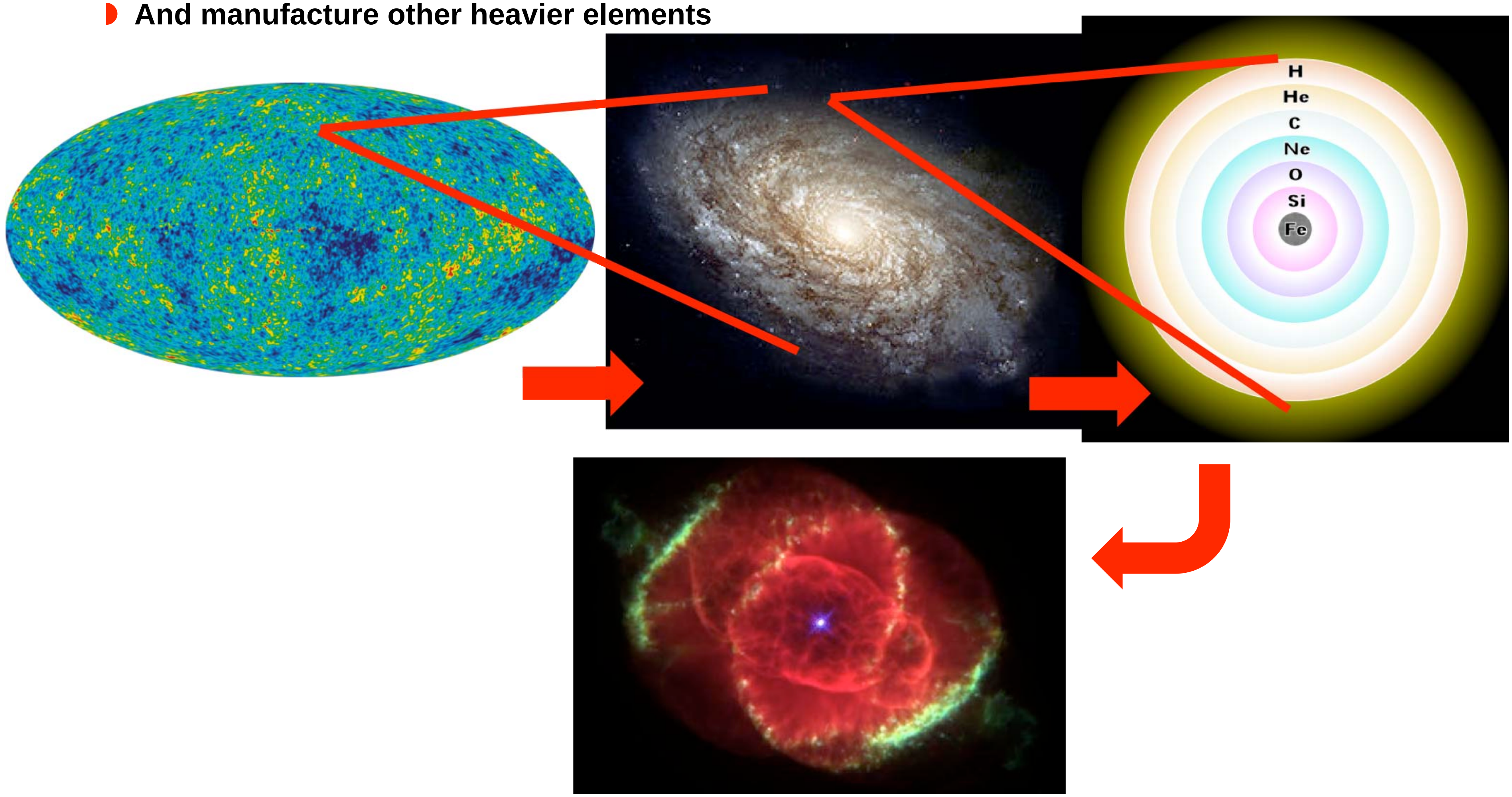


Figure 8-8b
Universe, Eighth Edition

- So where did these clouds come from?
- Universe formed 10-15 billion years ago
  - Process generated all of today's hydrogen and most of the helium
  - Small amounts of other elements produced



- Early universe almost featureless
  - Primordial material breaks up to form galaxies
  - Clouds in galaxies collapse to form the first stars – starts nuclear fusion
  - These stars manufacture heavy elements up to iron
  - Supernovae spread these elements through the galaxy
    - And manufacture other heavier elements



- **Material in giant molecular clouds**
  - **Cycled through stars already**
  - **Still dominated by Hydrogen and Helium**

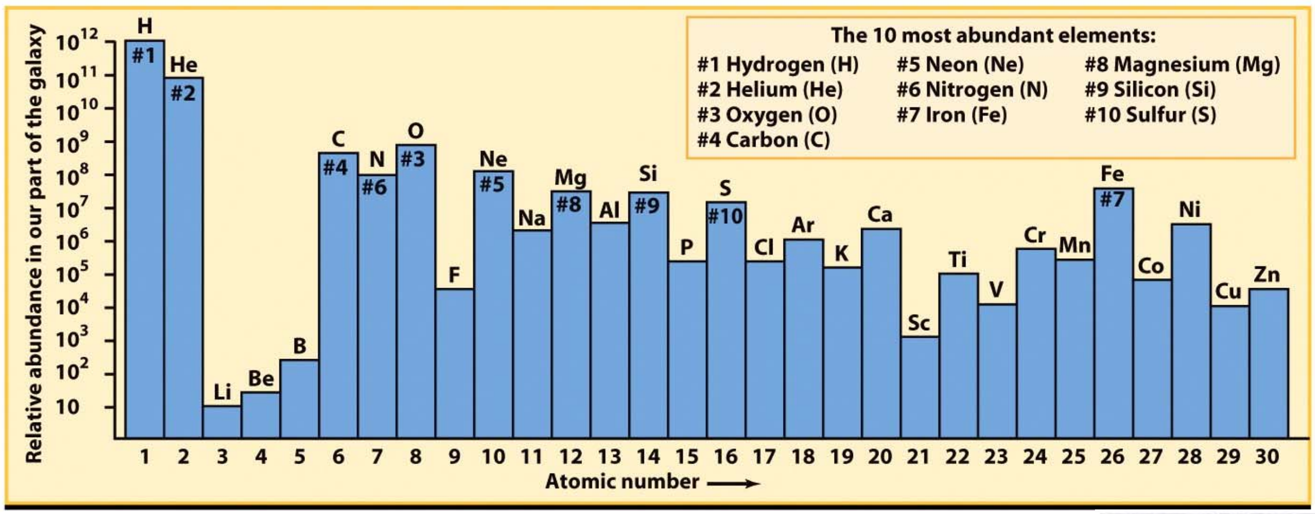
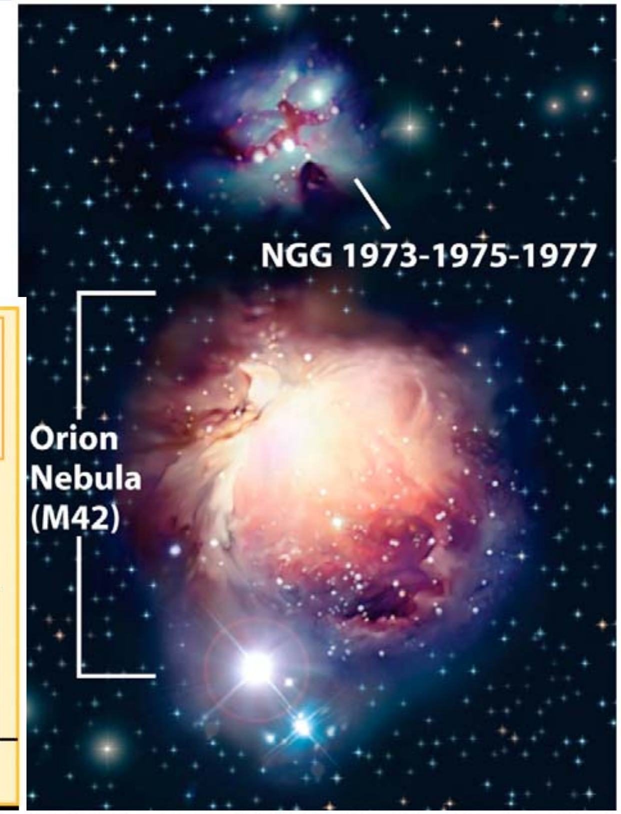


Figure 8-4
Universe, Eighth Edition



  - **Contains solid material in small grains**
  - **Densities of a few 1000 molecules cm^{-3}**
    - **Room air has ~2.4x10^{19} molecules cm^{-3}**
  - **Temperatures of 10-30 K**

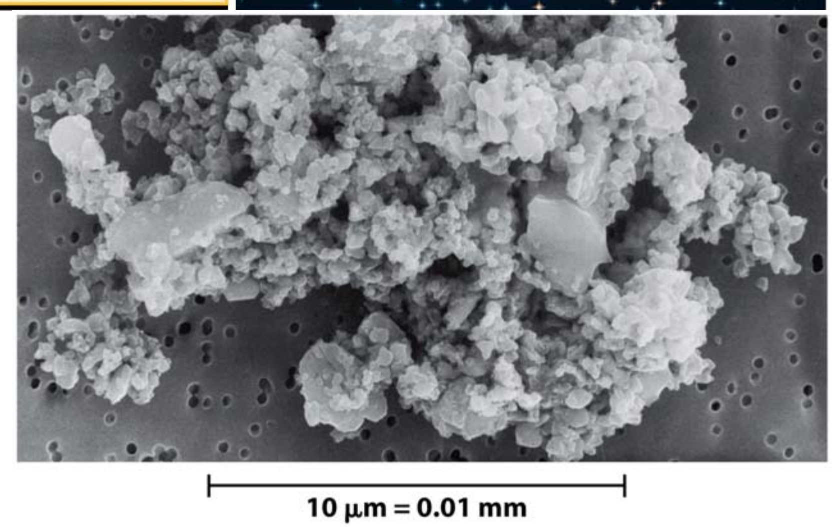
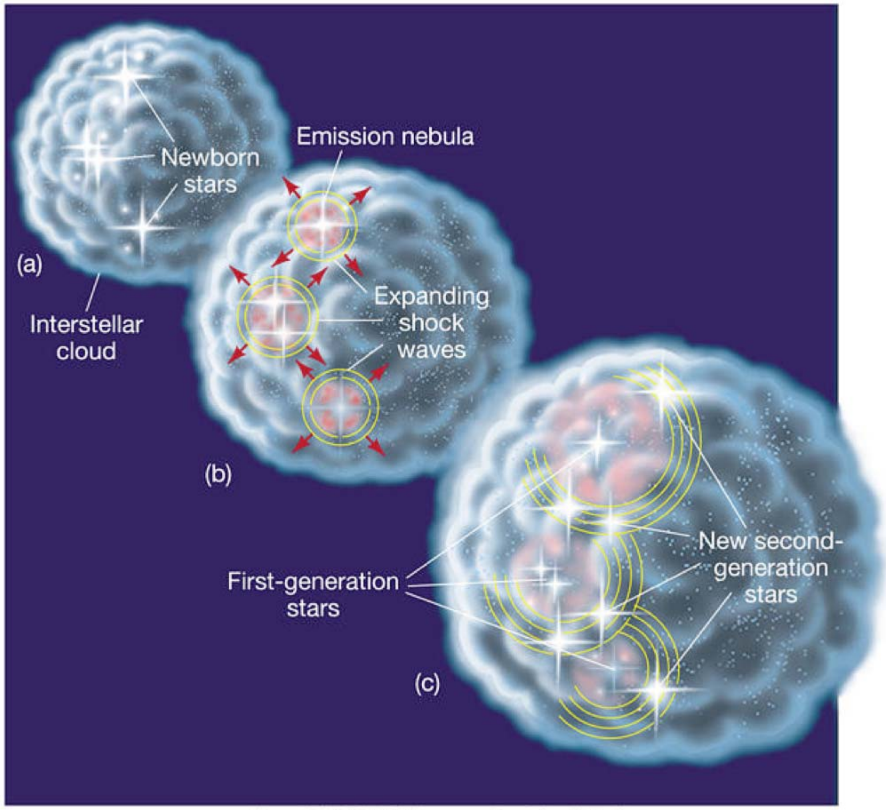


Figure 8-9
Universe, Eighth Edition

Forming the Sun

- The giant molecular clouds are barely stable
  - Supported by pressure, magnetic fields and slow rotation
  - In competition with self-gravity
- Give the system a little shove…
  - Collapse starts – gas heats up
  - Collapse continues? – yes, if the cloud is big enough
  - The ‘shove’ can come from
    - A nearby supernova
    - Passing through a galactic spiral arm
  - Clouds collapse from the inside out
  - Cloud fragments into many small protostars
    - Sun probably formed in a cluster of stars



- **Angular momentum is conserved**
  - **Size of the cloud is reduced so its rotation rate goes up**

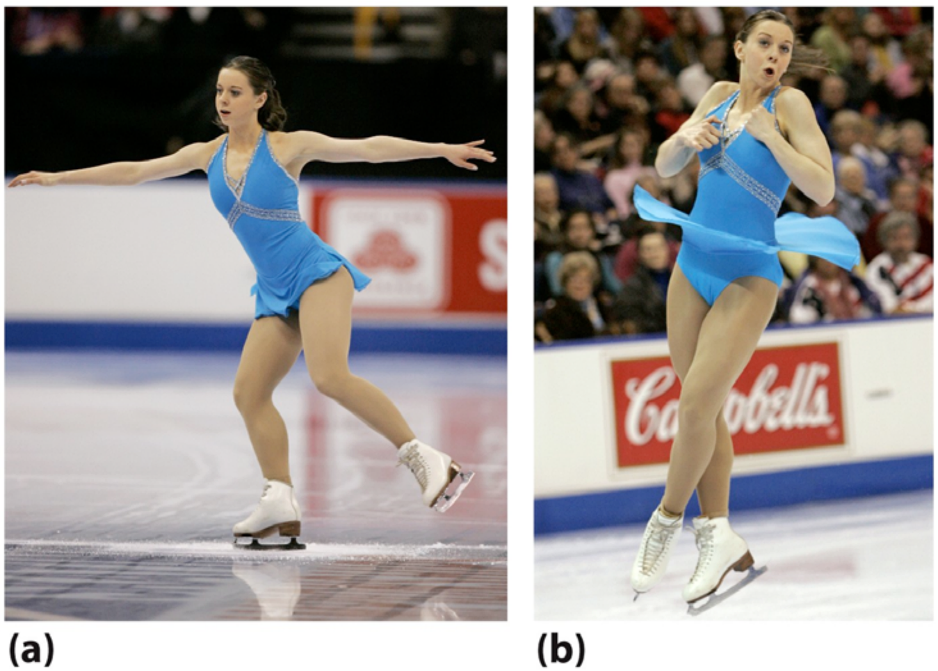


Figure 8-7
Universe, Eighth Edition

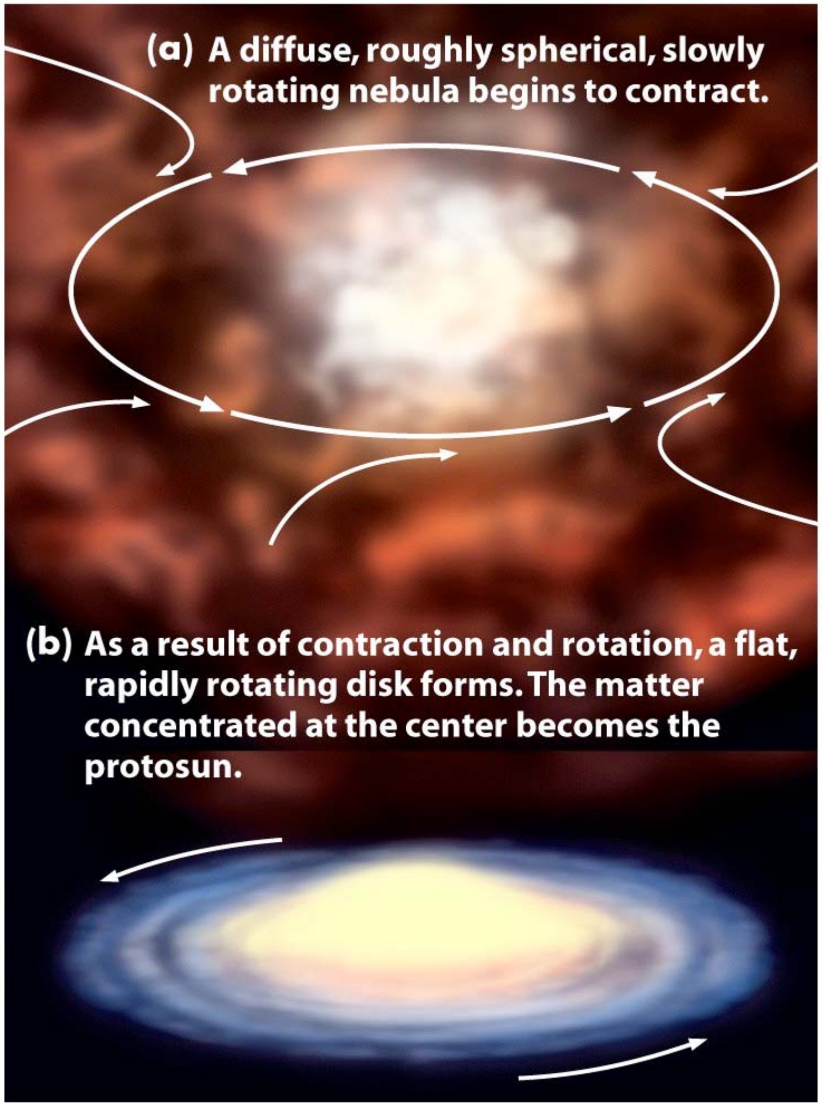
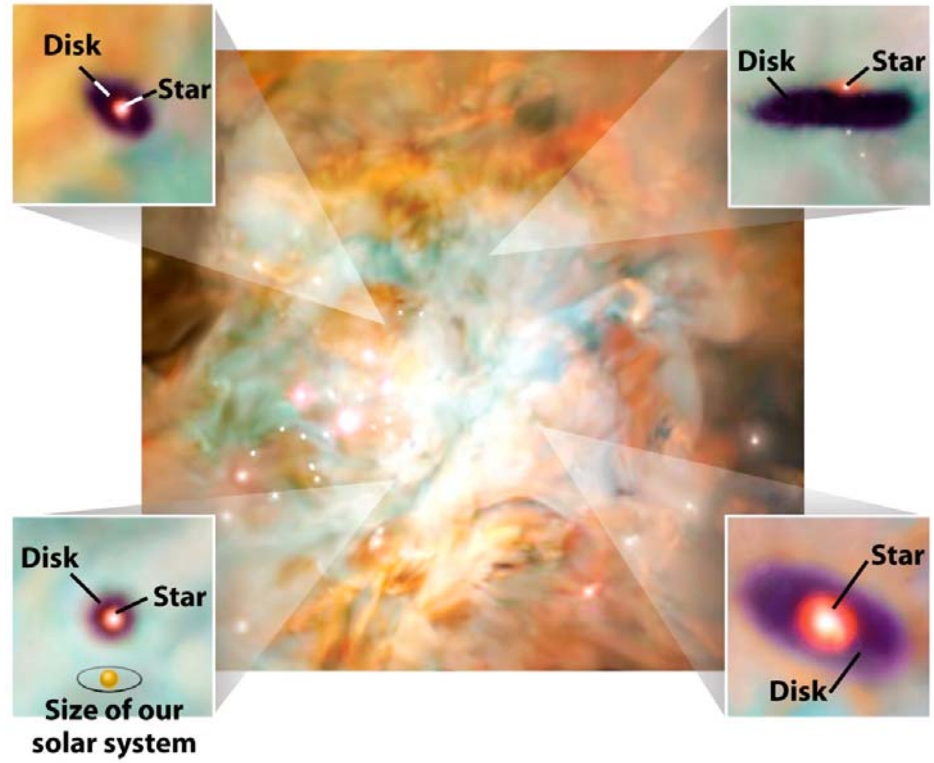


Figure 8-6
Universe, Eighth Edition

- **These disks are a common occurrence**
  - **Disk material is much hotter and denser than the giant molecular cloud**
- **Proto-star at center**
  - **Contraction generates heat**
  - **Heat and pressure allow nuclear fusion**
  - **Star switches on and generates its own energy**



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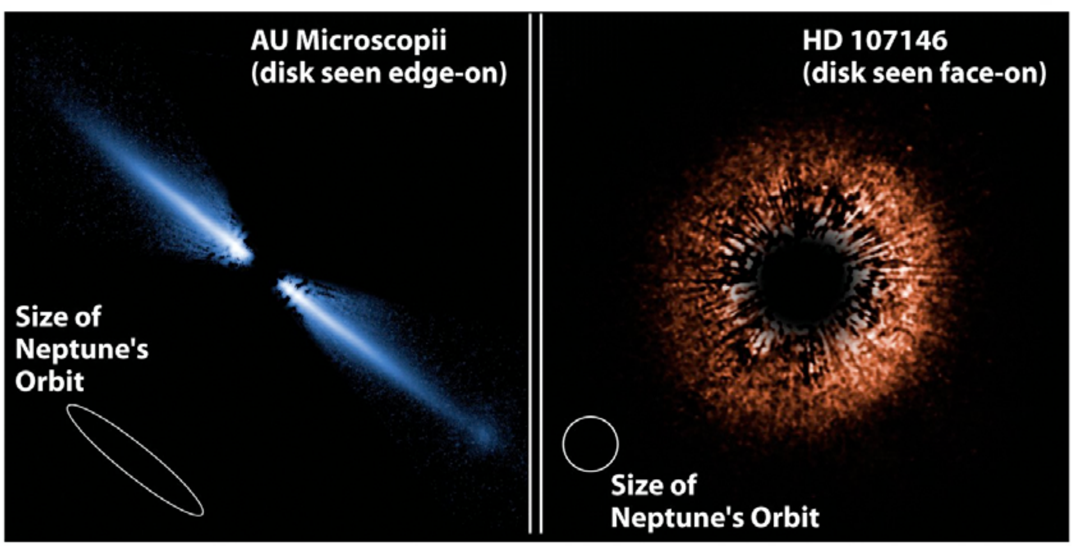
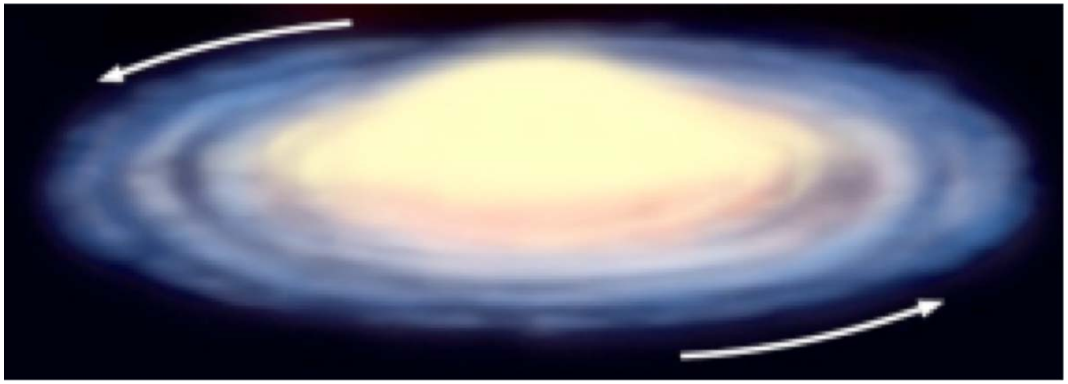
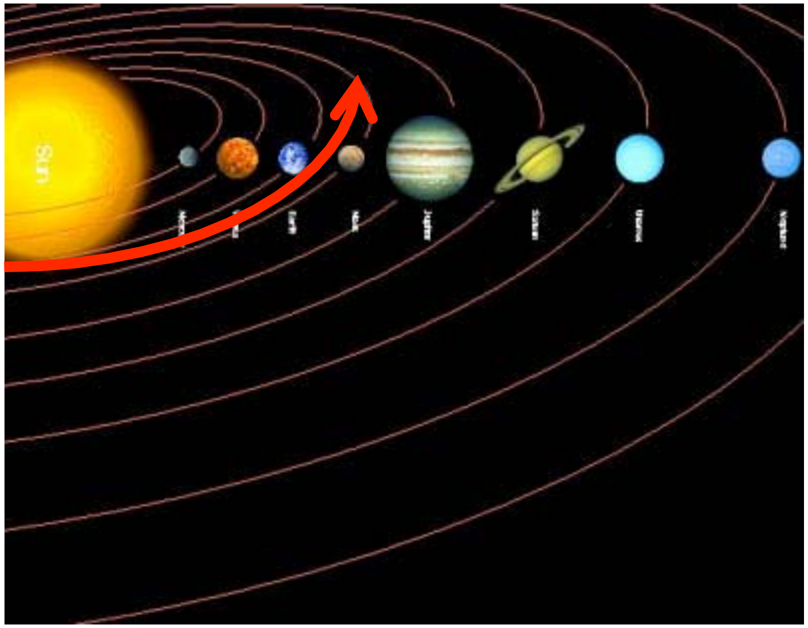


Chapter 8 Opener
Universe, Eighth Edition

- **Rotation direction of our disk is stamped on every solar system object**
  - **All planets orbit the sun in the same direction**
  - **Almost all planets rotate in the same direction**





- Disk gets colder with increasing distance from the sun
  - Inner disk is hot from extra contraction
  - Young sun very luminous and heating the inner disk
    - Astronomy majors: look out for this in your star formation courses - T Tauri stage
- The water ice stability line has a profound effect on the way things will turn out

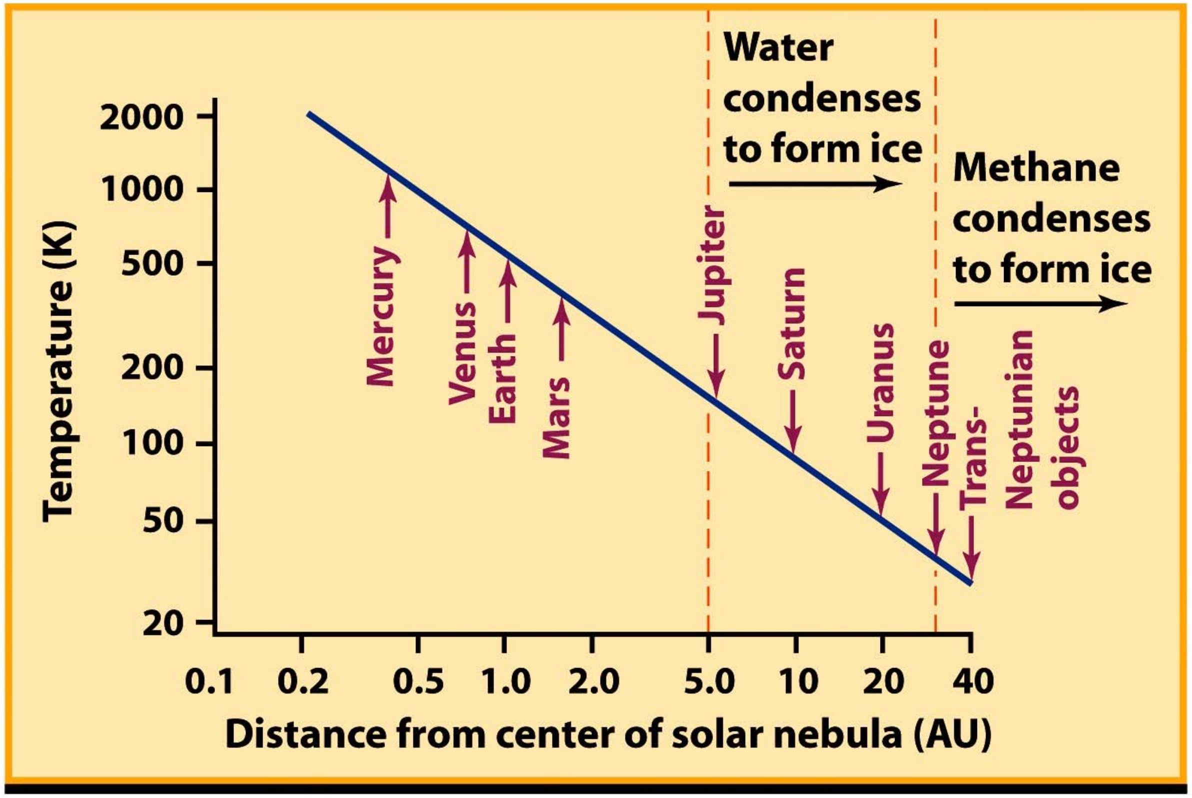
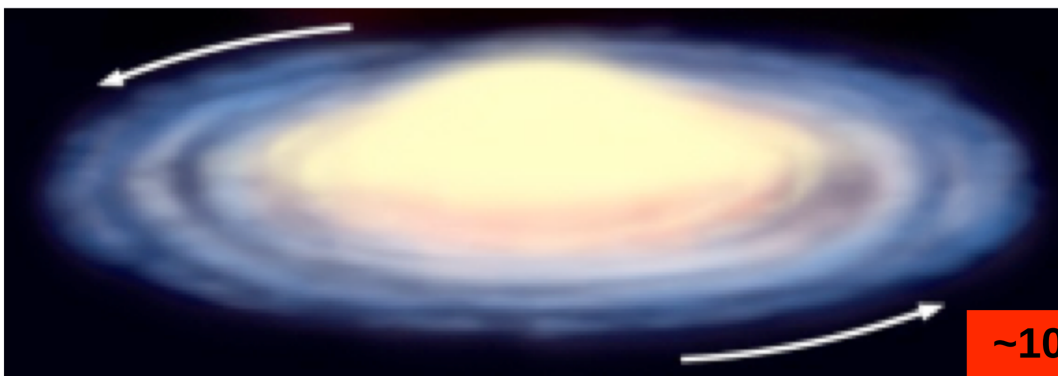


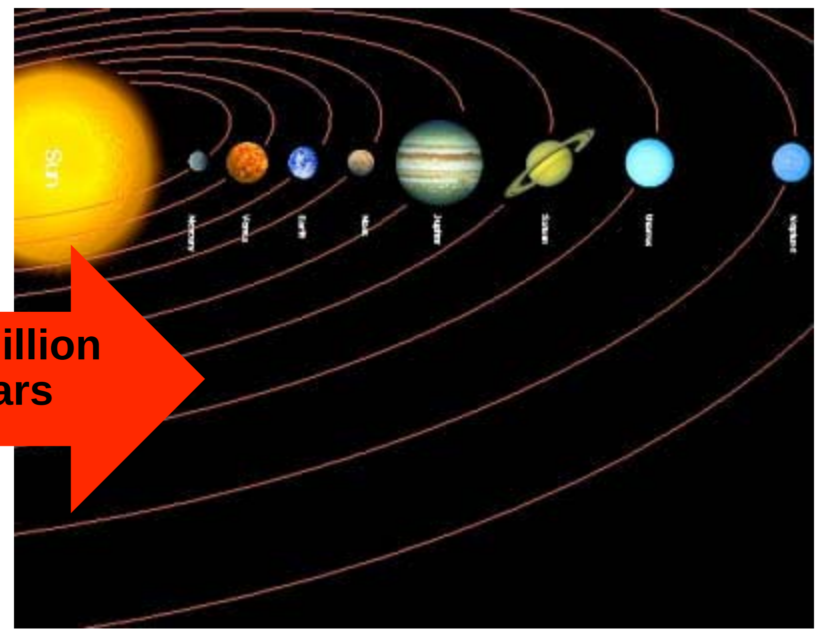
Figure 8-10
Universe, Eighth Edition

The clock is ticking…
The disk will only last ~10 Myr
(~ 0.2 % of solar system history)

- **Building a solar system from a disk in three parts**
  - **Forming planetesimals**
    - **Gets particles up to asteroid sized bodies**
    - **Too slow to build big planets**
  - **Forming solid planets and giant-planet cores**
    - **Uses gravity to speed things up**
  - **Forming giant planets**
    - **Captures gas from the disk**



~10 Million years



Forming Planetesimals

- In this stage we go from dust grains to objects 1km in size
  - The hardest stage to explain in the whole process

- Within a few AU of the proto-sun
  - Silicates and metals condense out of the gaseous disk
  - Other material stays as a gas

- A few AU from the sun
  - It's cold enough for water ice to condense
  - More solid material

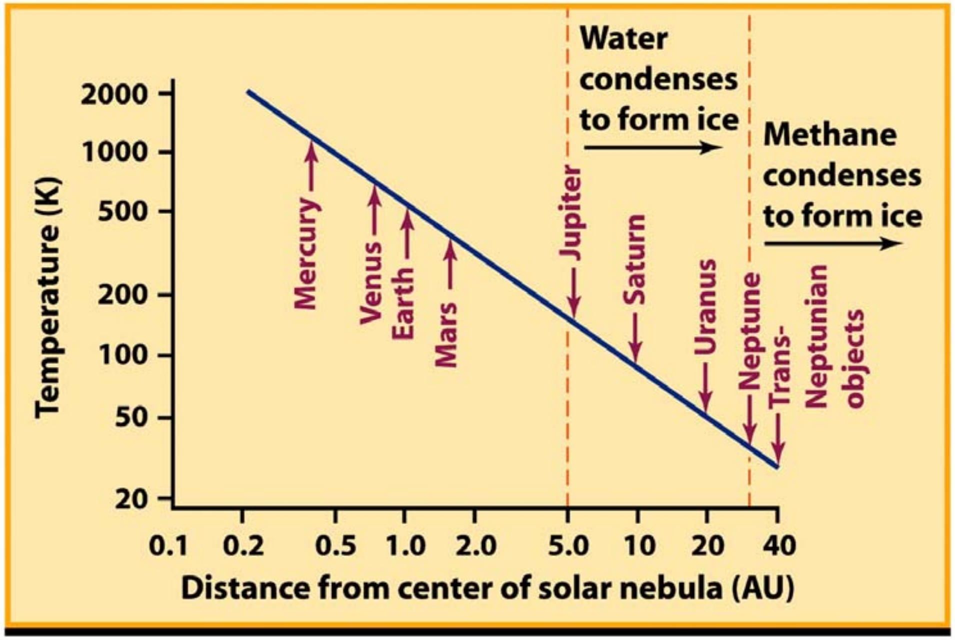


Figure 8-10
Universe, Eighth Edition

- Particles suspended in gas
  - Collide and join together to form clumps
  - Grow to 1cm in size

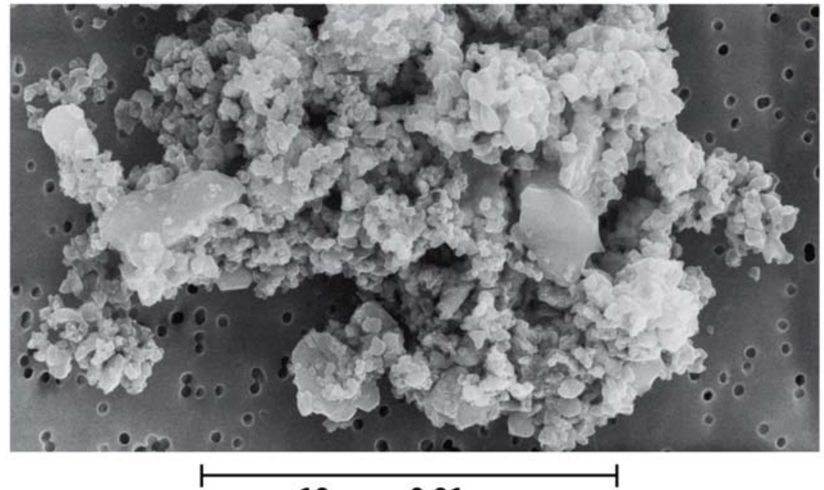
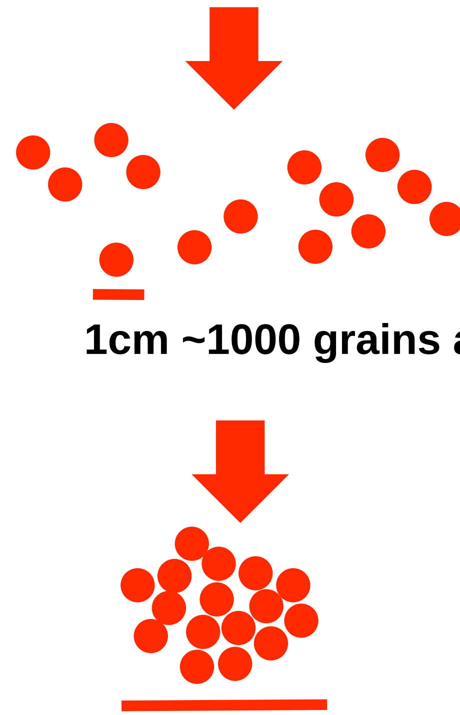


Figure 8-9
Universe, Eighth Edition

- Particles >1cm in size grow by collisions
  - Decoupled from the gas motions
  - Suffer gas drag
  - Start spiraling into the sun

The weak link in the story goes here.

Getting to kilometer-size before falling into the sun is still an unsolved problem…



1cm ~1000 grains across

1km
~100,000 particles across

- Particles eventually grow to 1km
  - Gas drag becomes irrelevant

- These 1km planetesimals go on to form planets
  - Within but unaffected by the gas disk
  - Close to sun material is iron and rock
    - Makes terrestrial planets
  - Far from the sun the material is ice and rock
    - Makes giant planet cores
    - Makes moons of giant planets
    - Kuiper belt objects, comets etc…

- Some meteorites are basically samples of this material
  - Chondrules are the oldest solar system solids
  - Material that was flash-heated and quenched
  - Can be dated from remaining radioactive elements
  - Solar system is <u>4.56 billion years</u> old!

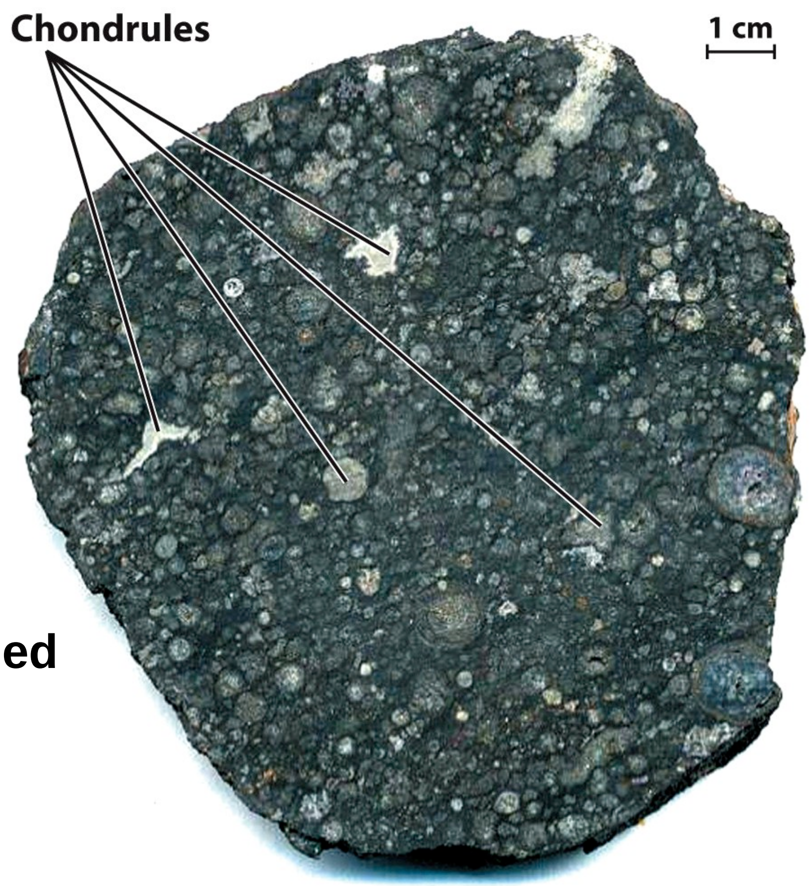
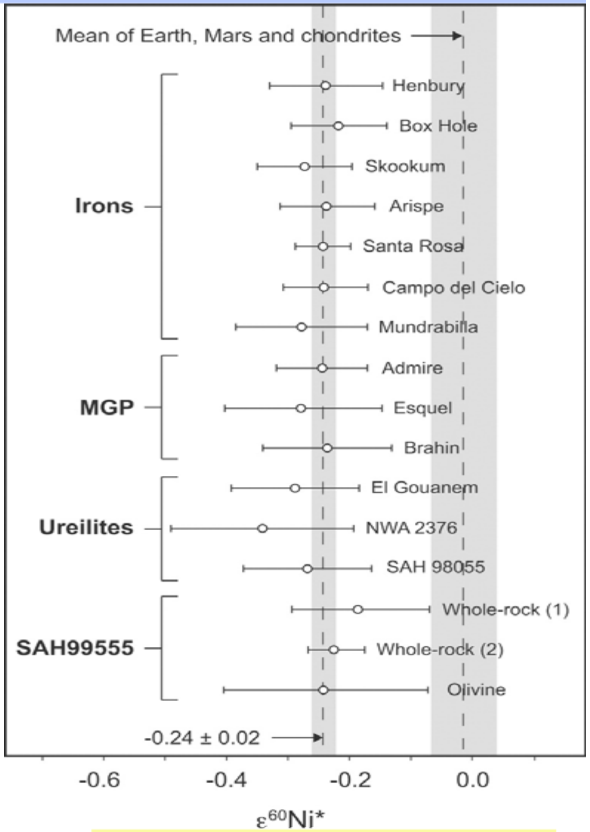


Figure 8-11
Universe, Eighth Edition

- New results – the early sun's rough neighborhood…
  - ^{60}Fe decays to ^{60}Ni – T_{half} ~ 1.5 Myr
  - Excess ^{60}Ni is due to this process
  - Major planets formed later and have more ^{60}Ni



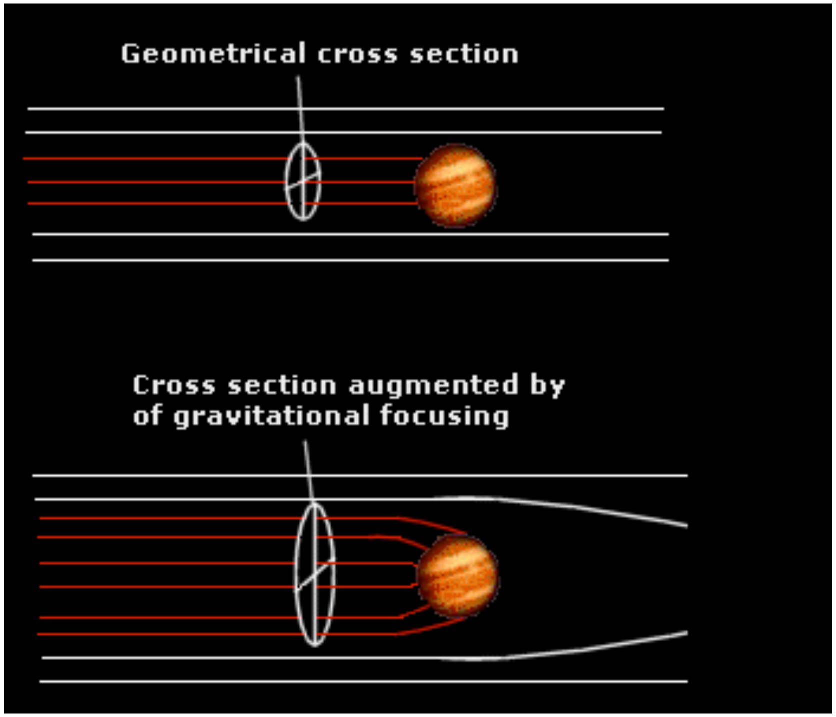
Bizzarro et al., Science 2007.

- So…
  - Solar system had an injection of ^{60}Fe, ~1 million years after first bodies formed.

The main suspect…

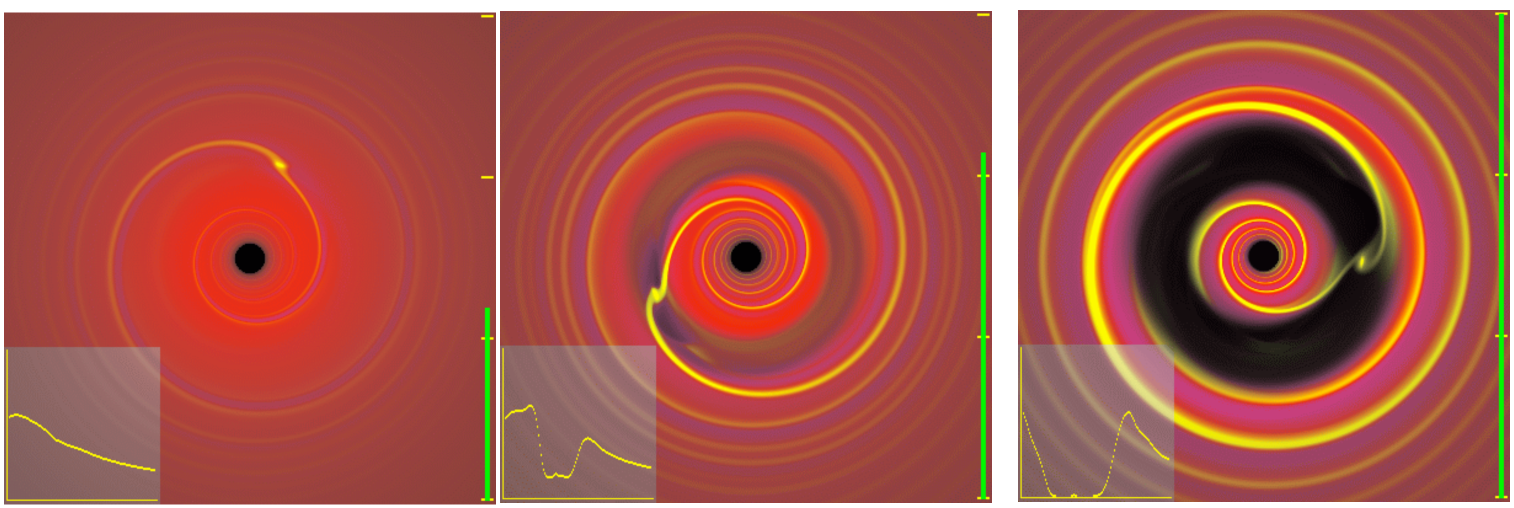
- Wolf-Rayet Stars
  - Extremely massive
  - Lifespans of 1-2 Myr
  - Ends in a supernova
    - Supernova can supply large amounts of ^{60}Fe

- **1km sized planetesimals are a long way from planets**
- **Objects bigger than 1km start to have appreciable gravity**
  - **Gravitational focusing speeds up accumulation of material**
  - **Planetesimals start to grow very fast**
- **The biggest objects grow the fastest**
  - **Oligarchic growth where the big guys absorb the small guys**
  - **Planets develop ‘feeding zones’ within the disk**
  - **Eventually they exhaust the ‘food’ supply**
- **At this point a few million years have passed**

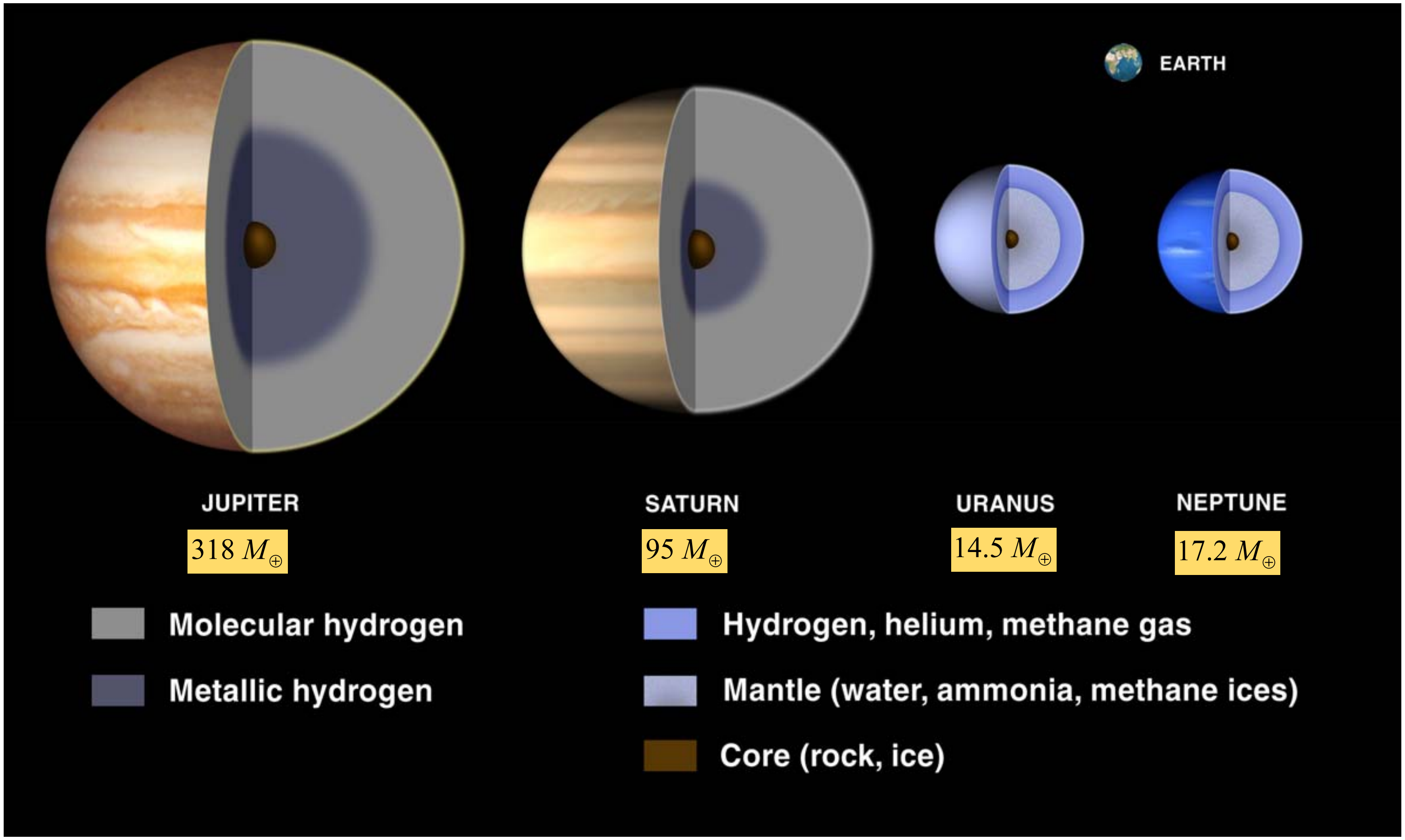


Giant planet Atmospheres

- In the outer solar system
  - Availability of water ice leads to much faster growth of solid bodies
  - Ice/rock cores can grow to 10 Earth Masses
- Gravity of these objects becomes high enough to capture hydrogen and helium directly from the disk
  - These planets can clear a gap in the gas disk
  - Gravitational interactions with the disk can cause them to drift inwards



- **Time's up!**
  - **The gas disk dissipates in about 10 million years**
  - **Jupiter and Saturn successfully grabbed a large Hydrogen and Helium atmosphere**
  - **Neptune and Uranus grew too slowly and didn't accumulate as much gas**



- **What's left?**
  - **A debris disk flooded with many small objects**
  - **Where did all these smaller objects end up**
  - **What about?**
    - **The asteroid belt**
    - **The Kuiper belt**
    - **The Oort cloud**

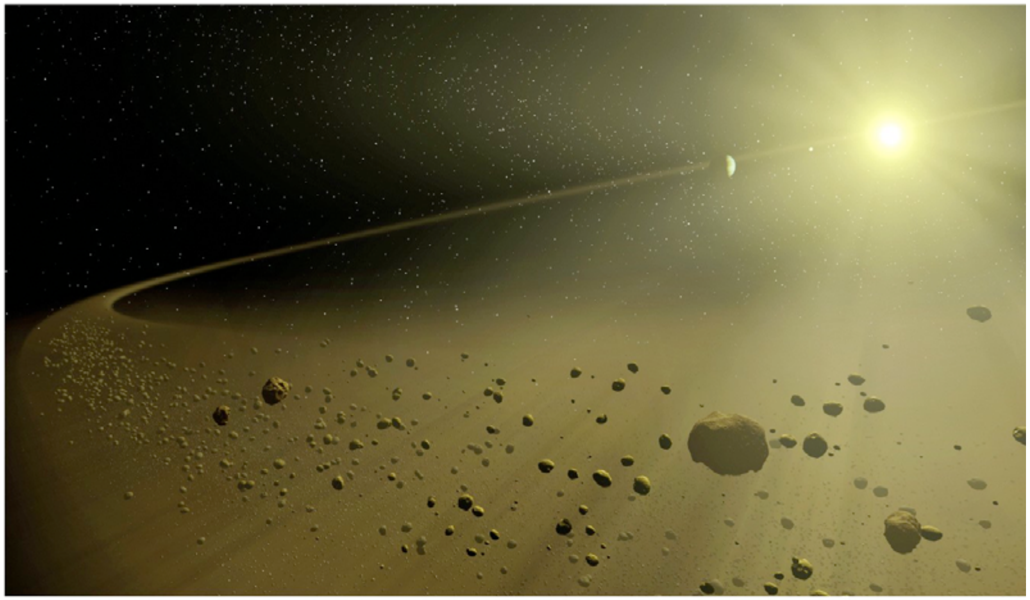
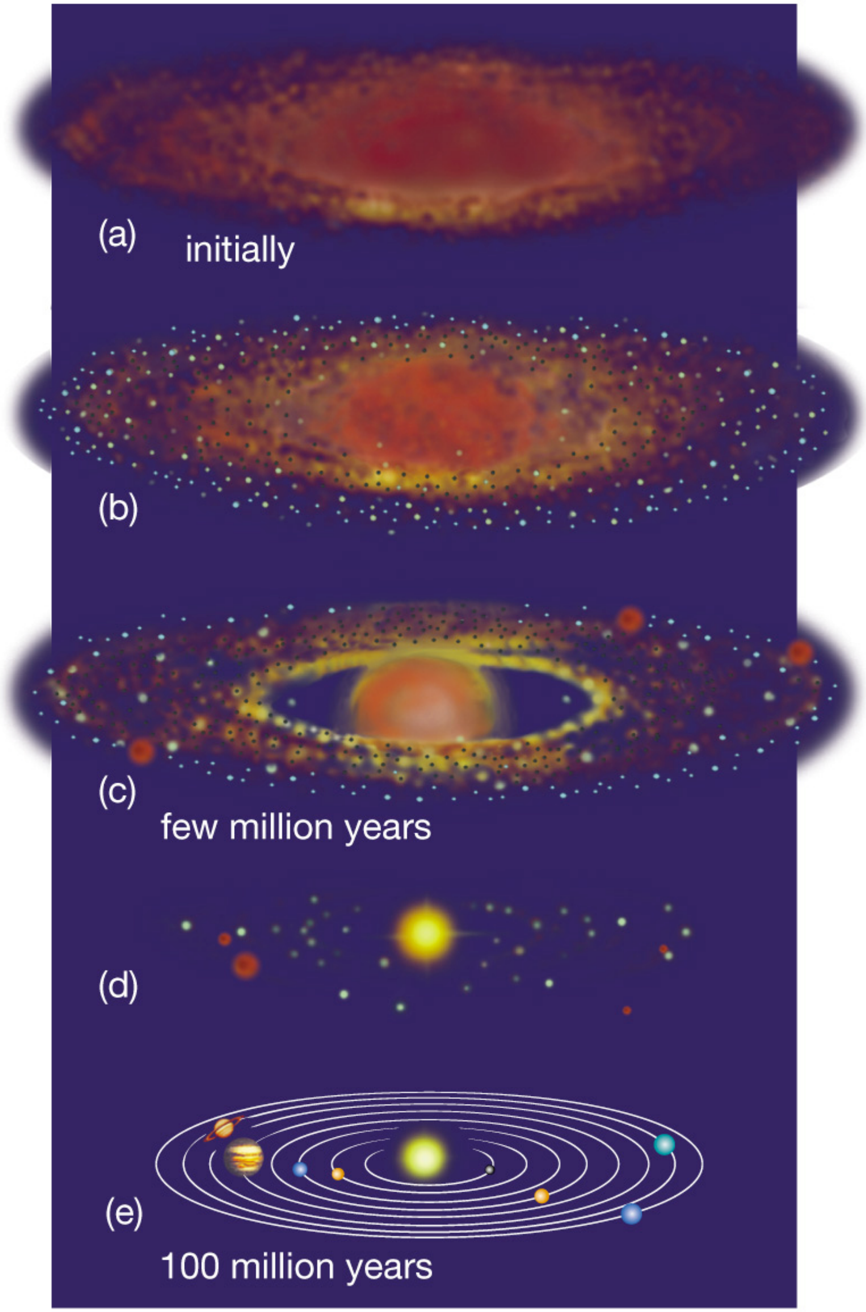
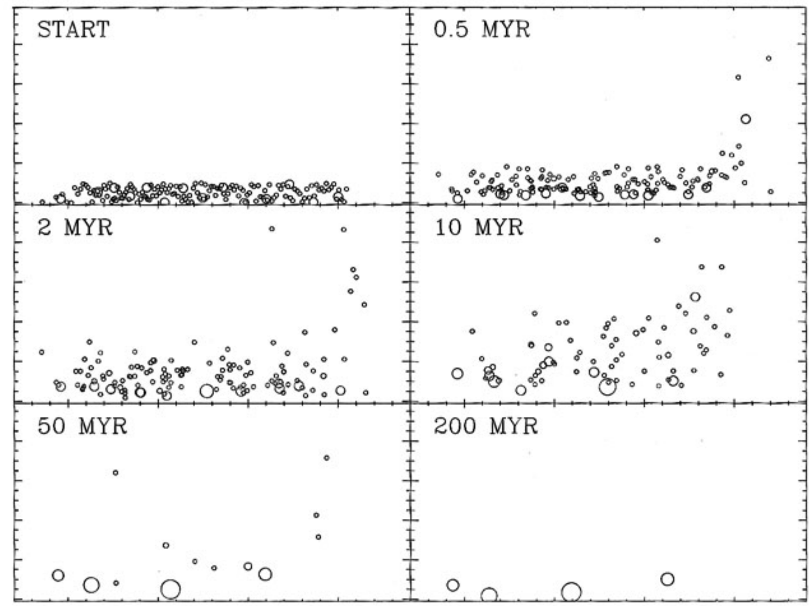


Figure 8-14
Universe, Eighth Edition



Cleaning up the mess

- This stage takes 100s of millions of years
- Many proto-planets left in the terrestrial planet zone
  - These impact the big four
    - Mercury, Venus, Earth & Mars
  - Gradually get removed
- The last few impacts are the biggest ones
  - Formation of Earth's Moon
  - Mercury's oversized core?
  - Mars' hemispheric dichotomy??



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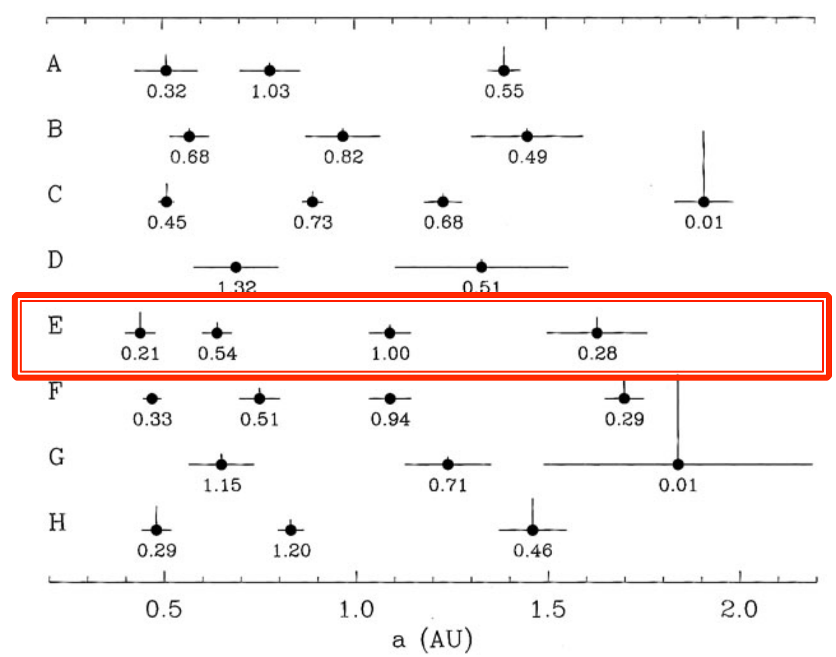


- **In the outer solar system the giant planets are surrounded by a sea of small icy bodies**
  - **Some collide with the gas giants**
  - **Some perform a gravitational slingshot and are thrown out to great distances**
  - **Some are thrown out of the solar system completely**

- **Giant planets are also affected by this**
  - **Giant planet also moved (in the opposite direction to small object)**
  - **..but by a tiny amount each time**
  - **This is the reverse of the case where Jupiter 'captures' a new comet into the inner solar system**

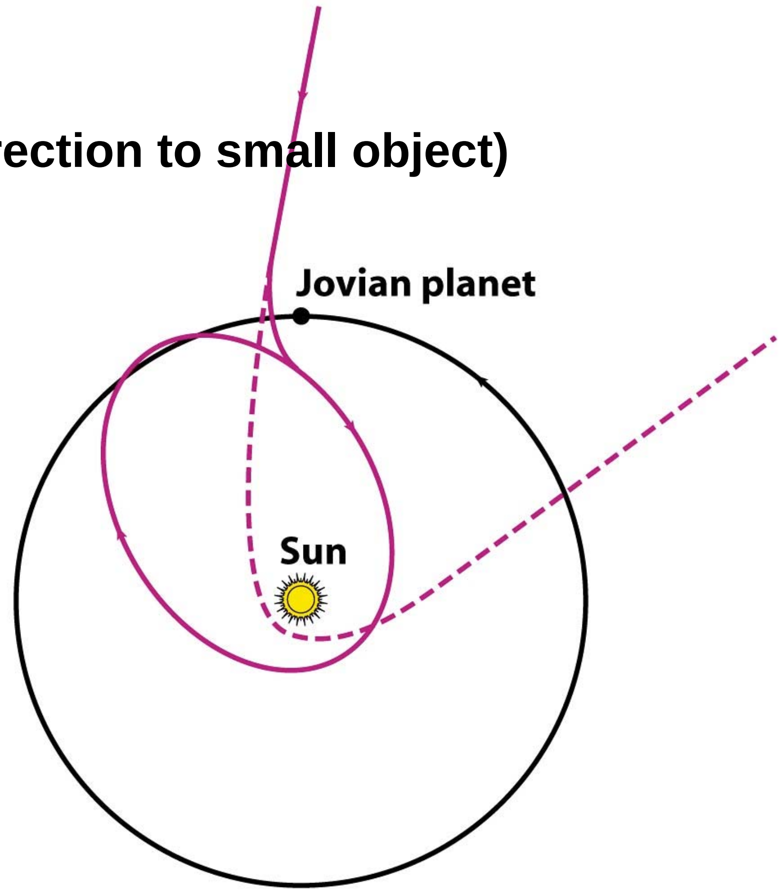
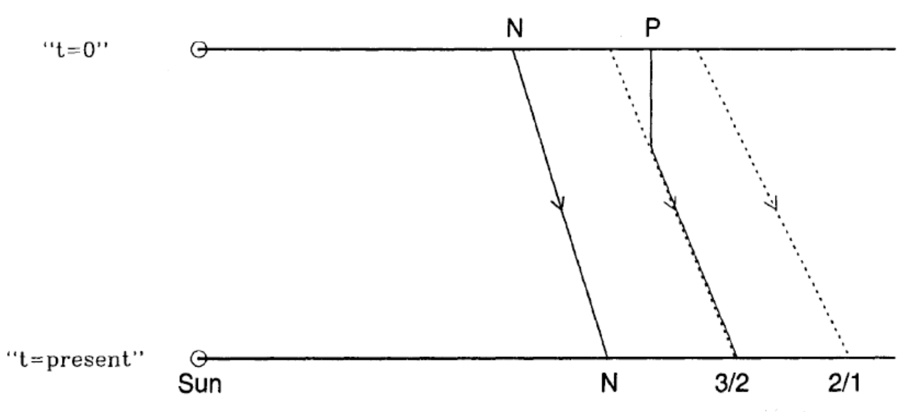
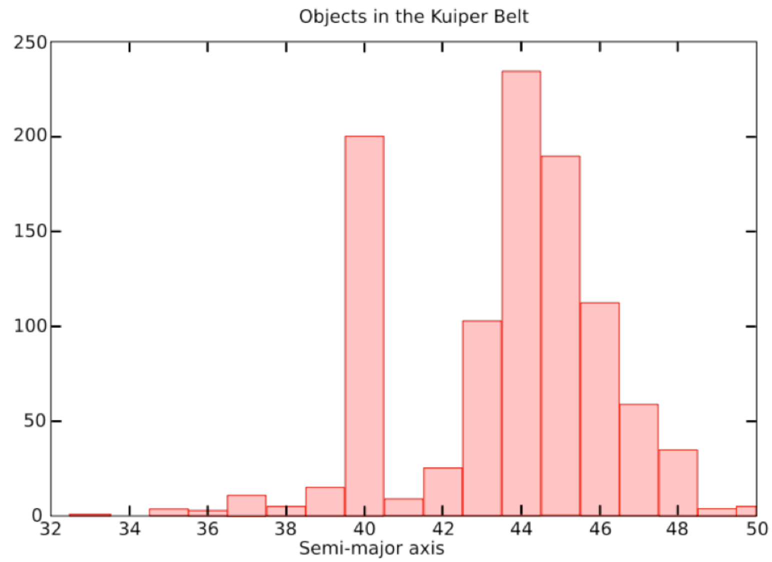


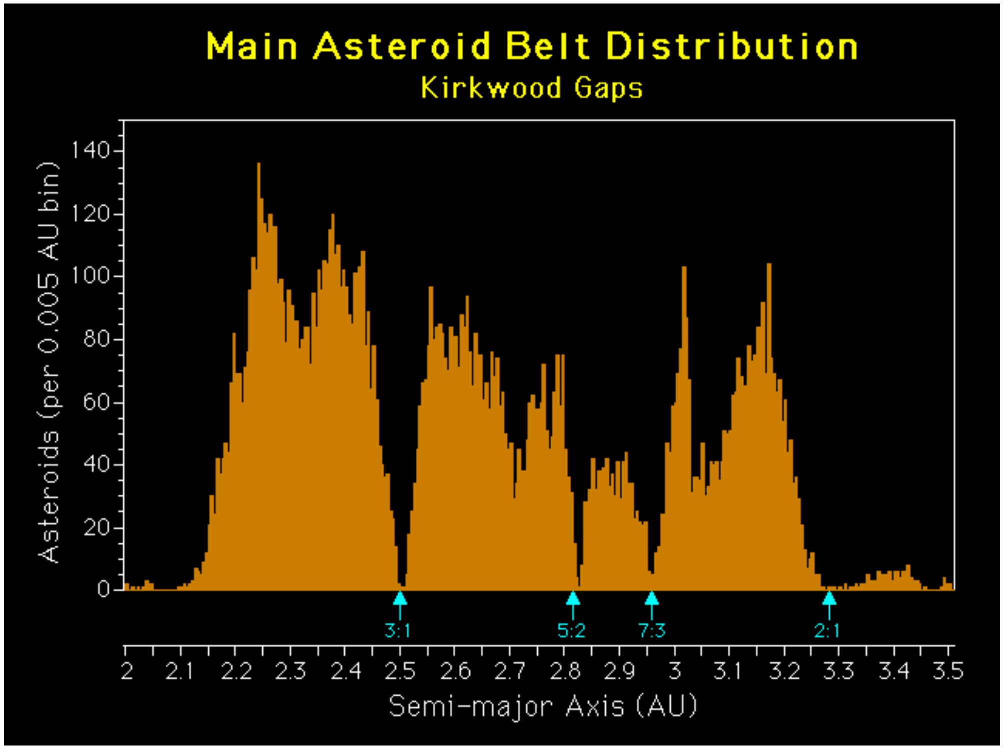
Figure 15-28
Universe, Eighth Edition

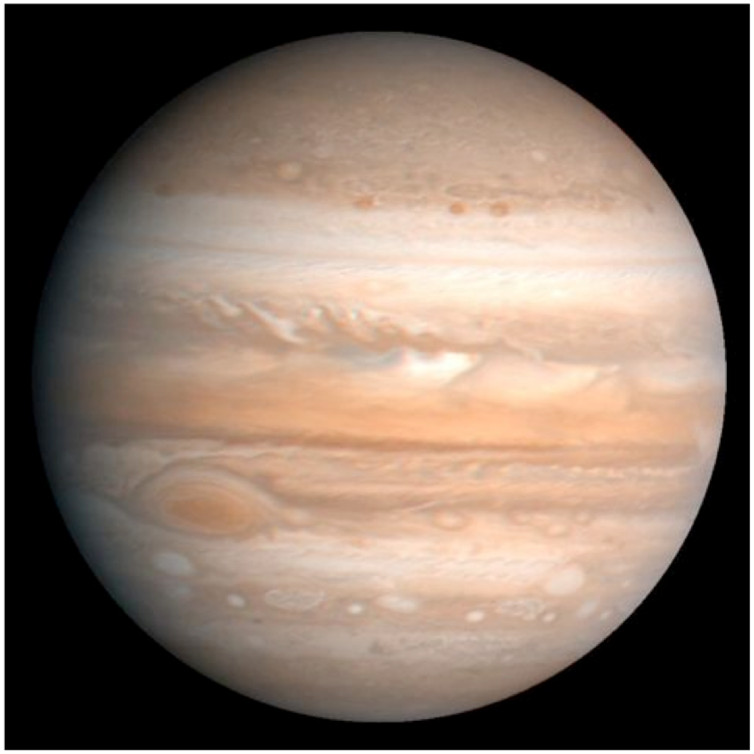
- **The Kuiper belt**
  - **Neptune migrates outwards by as much as 7 AU**
  - **Captures some Kuiper Belt Objects in the 3:2 resonance (like Pluto)**
  - **Captures one as a moon (Triton)**
  - **Gives the Kuiper belt a sharp outer edge at 50 AU**
  - **Ejects the other into the inner solar system**
    - **Where Jupiter tosses them into interstellar space (or the Oort cloud)**
    - **Allows Jupiter to migrate inwards**



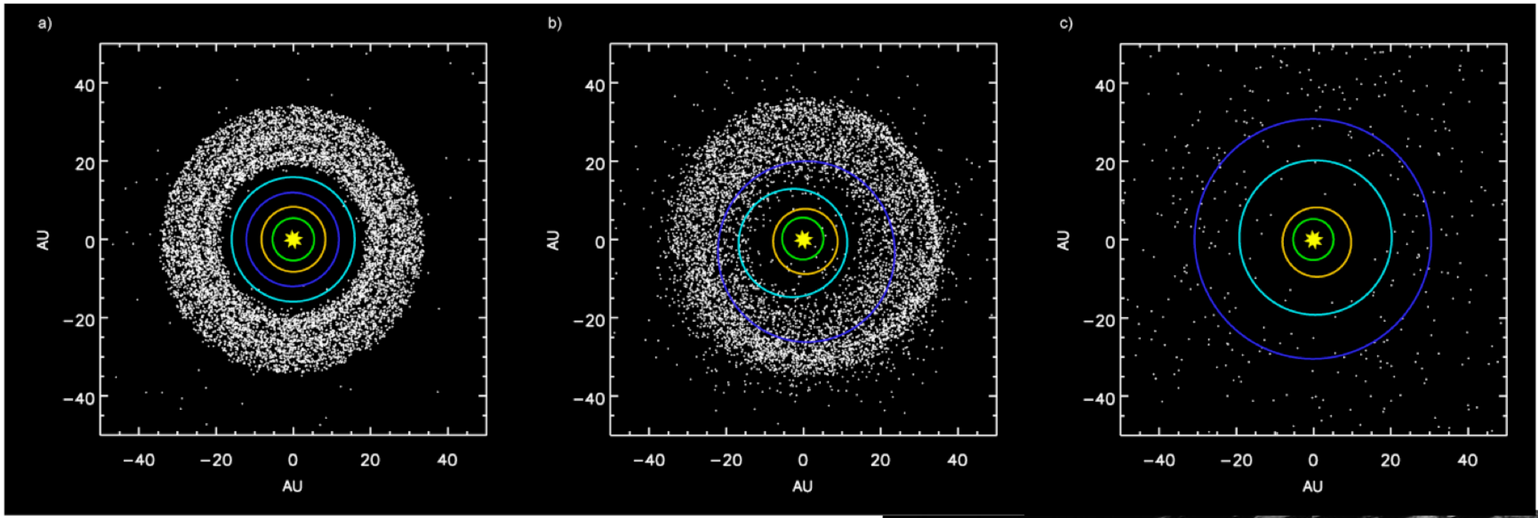


- **The asteroid belt**
  - **Jupiter migrates towards the sun (so it threw more small bodies outwards)**
  - **Truncates the outer edge of the asteroid belt**
  - **Speeds up asteroid collisions – stops a fifth terrestrial planet forming**
  - **Creates the Kirkwood gaps**

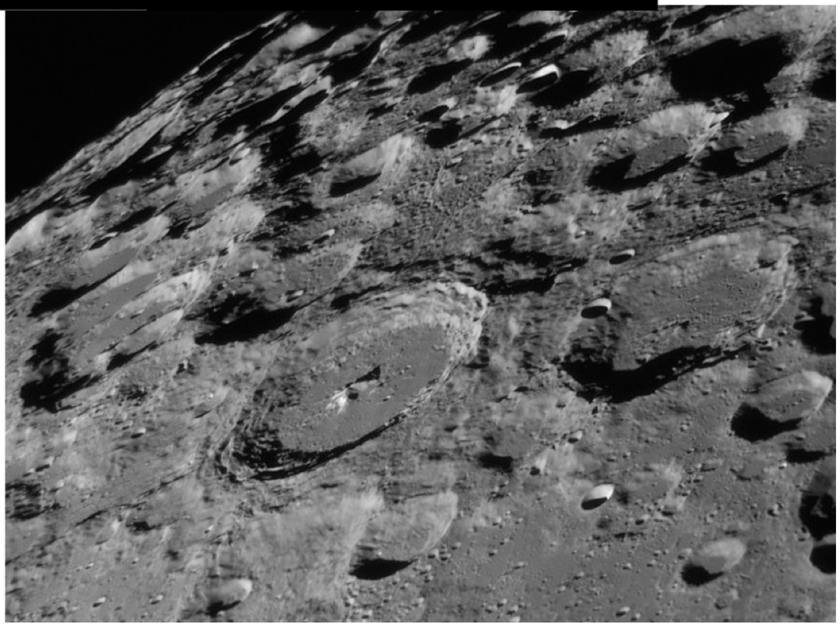




- Planets drift slowly at first
  - Until Jupiter and Saturn get into a resonance
  - Dramatic changes occur that spread the planets apart



- Jupiter migrated inwards
- This thinned out the asteroid belt and sent a rain of impacting bodies into the inner solar system
  - The late heavy bombardment



- **The Oort cloud**
  - **Icy bodies form closer to the giant planets**
  - **Gravitational encounters with Jupiter**
    - **Fling them into very distant orbits**
  - **Passing stars randomize the orbital inclinations**
    - **Less so for objects closer to the sun**
  - **Only a small fraction of the original objects survive**

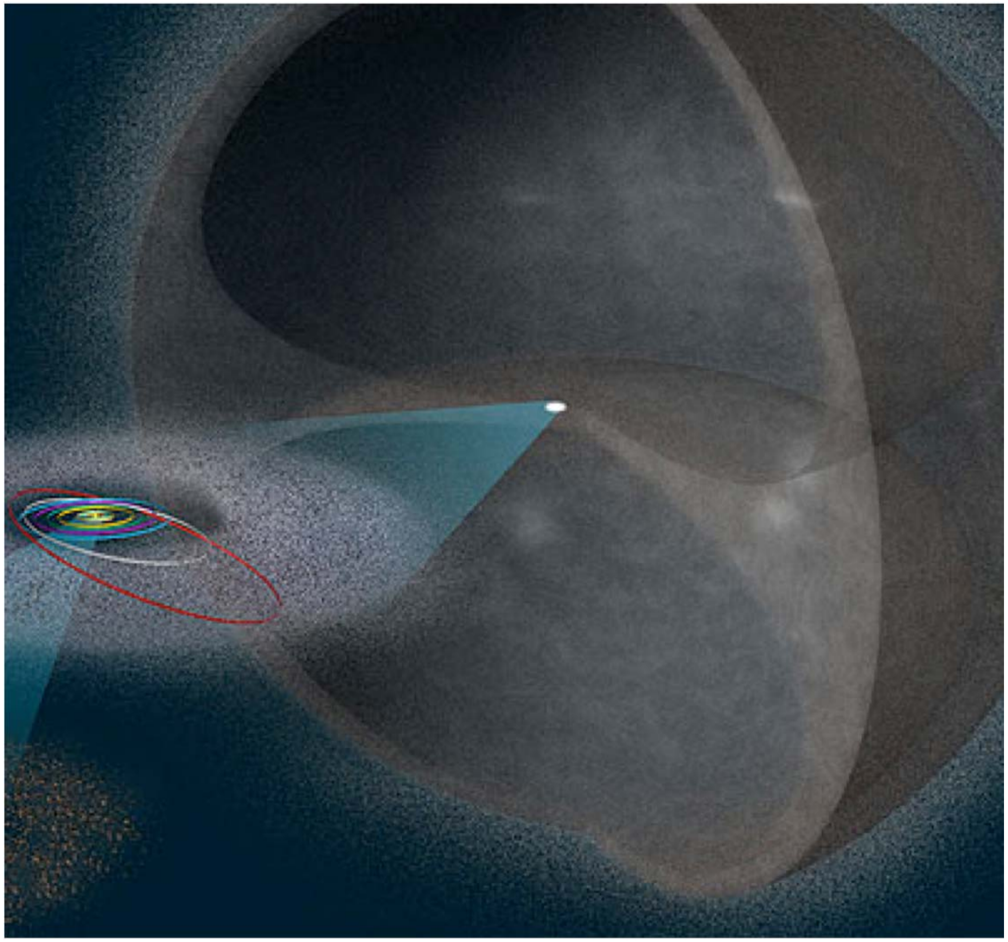


Figure 8-3
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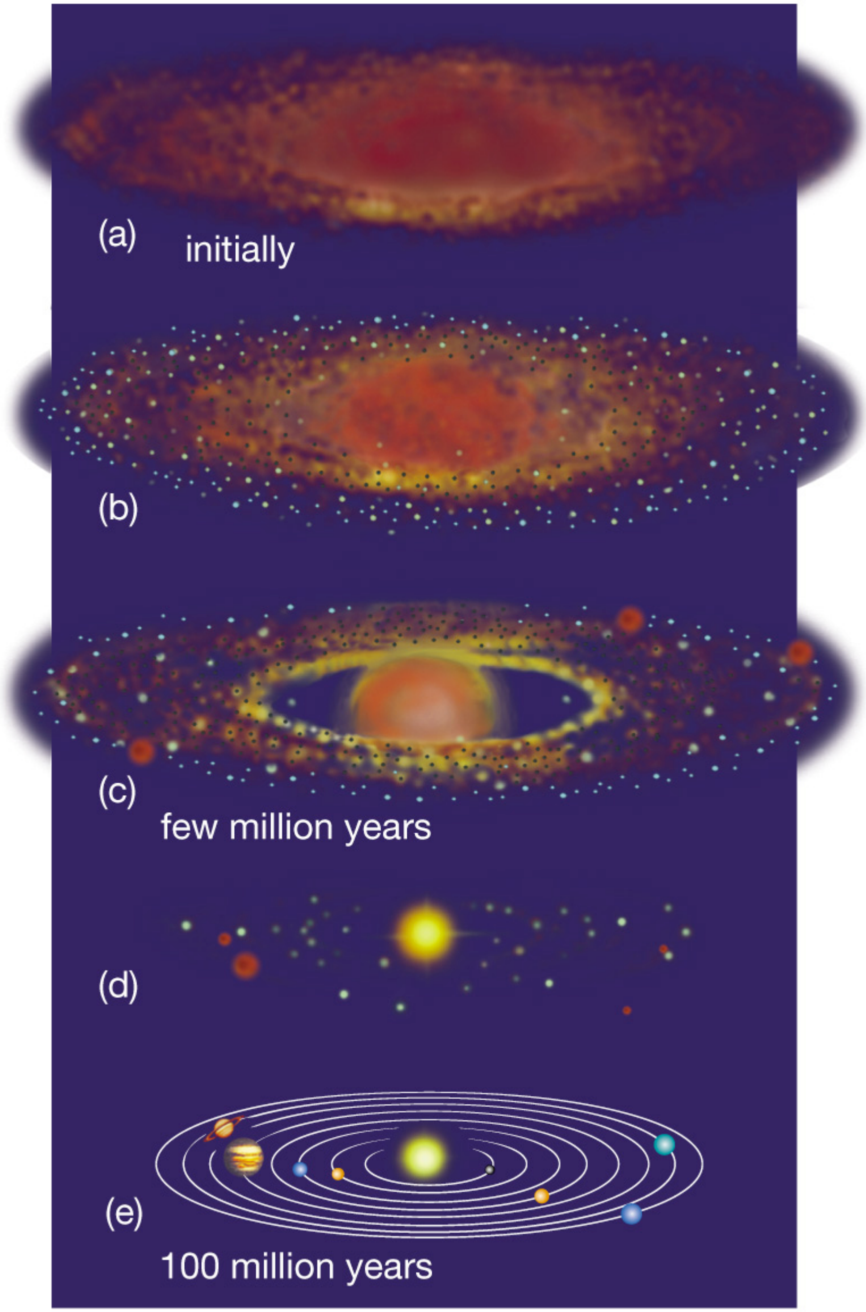
- **Giant molecular clouds collapse**
  - **Forms a quickly spinning disk with the Sun at the center**
  - **Temperature decreases with distance from the Sun**
    - **Water ice stable a few AU from the center**
- **Interstellar dust grains form 1km planetesimals**
- **Planetesimals grow quickly through gravitational attraction**
  - **Proto-planets are bigger where water ice is stable**
- **Giant planet cores capture gas from the disk**
- **Remaining protoplanets coalesce through collisions**
- **Scattering of small bodies allows gas giants to migrate**
  - **Sets asteroid and Kuiper belt structure**
  - **Forms the Oort cloud**
  - **Results in late heavy bombardment**



In this lecture…

- Giant molecular clouds collapse
  - Forms a quickly spinning disk with the Sun at the center
  - Temperature decreases with distance from the Sun
    - Water ice stable a few AU from the center
- Interstellar dust grains form 1km planetesimals
- Planetesimals grow quickly through gravitational attraction
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- Scattering of small bodies allows gas giants to migrate
  - Sets asteroid and Kuiper belt structure
  - Forms the Oort cloud
  - Results in late heavy bombardment

Next: Extrasolar Planets

- Reading
  - Chapter 8 to revise this lecture
  - Chapter 8-7 for next lecture