[13] Formation of the Solar System, Part 1 (10/12/17)

Upcoming Items

1. Read Ch. 9.1 & 9.2 by next class and do the self-study quizzes.
2. Homework #6 due next class.

APOD 10/12/16

Great Job on the Midterm!

- Class average 118/150=79%
- Class standard deviation 21/150
- This was a tremendous performance! I tried to be fair in writing the exam, but also to challenge you to show your knowledge across quite a breadth of material
  This was ***far*** deeper than previous ASTR 120 exams
  You really came through! I know you have worked hard in this course. I'm very proud of you.

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- What if you didn't do as well as you hoped?
  1. Remember, midterm was only 15% of class total
  2. Consider going to see tutors, not just before HW is due
- Again, though, I'm really impressed by how well you did!

LEARNING GOALS

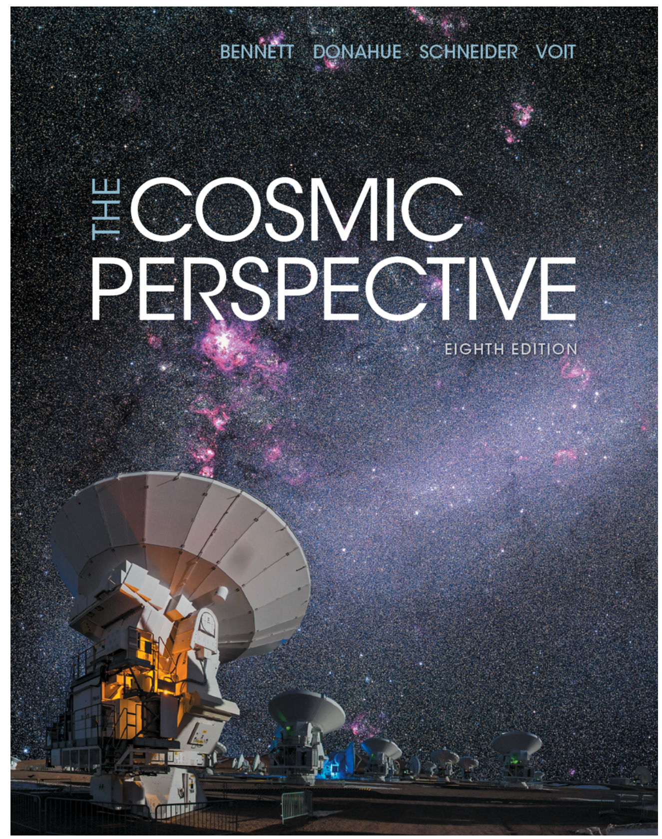
Chapter 8.1–8.2

For this class, you should be able to…

… *use the nebular theory and conservation laws to predict the configurations of planets (orbit directions and alignment) and their dominant compositions (metal, rock, ice, and/or gas as a function of distance from the star) in a solar system.*

… *deduce how the temperature varies as a function of distance from a star based on thermal radiation laws;*

… *demonstrate that the Sun lost most of its angular momentum after it formed.*



Any astro questions?

LIGO Press Conference, 10 AM Mon.

- Viewing in PSC lobby
- At 3 PM on Monday, also in PSC lobby, there will be talks by Prof. Peter Shawhan (UMd Physics), Dr. Julie McEnery and Dr. Brad Cenko (Goddard), and me, about implications of the announcement
- Feel free to come to either or both!

What Trends Should We Explain?

- Planets all orbit in the same direction?
- Two types of planets?
- Planetary orbits are nearly circular?
- Small-integer ratios of many orbital periods?
- Four small planets and four large planets?
- One planet is more massive than the rest put together?
- As astronomers, we have to make choices; if we try to account for *all* the details, we'll go crazy!
- In this case, let's start with the orbits all being the same way
  Very improbable if the orientations were random
- Perhaps if we can explain that, then some of the other trends can also be explained...

Derivations in Classes

- Note: to improve depth of understanding and to make contact with what we've learned so far, we'll do a number of derivations going forward including today
  The book only has qualitative discussion of the Solar System; you're prospective majors, you can do more ☺
- I intend to give you time to discuss derivations in groups
  If I forget, please remind me!
- Important that you follow the derivations and, especially, that you understand the physical content of the arguments, so have your group ask if you're not sure about a detail!

What Does Common Direction Signify?

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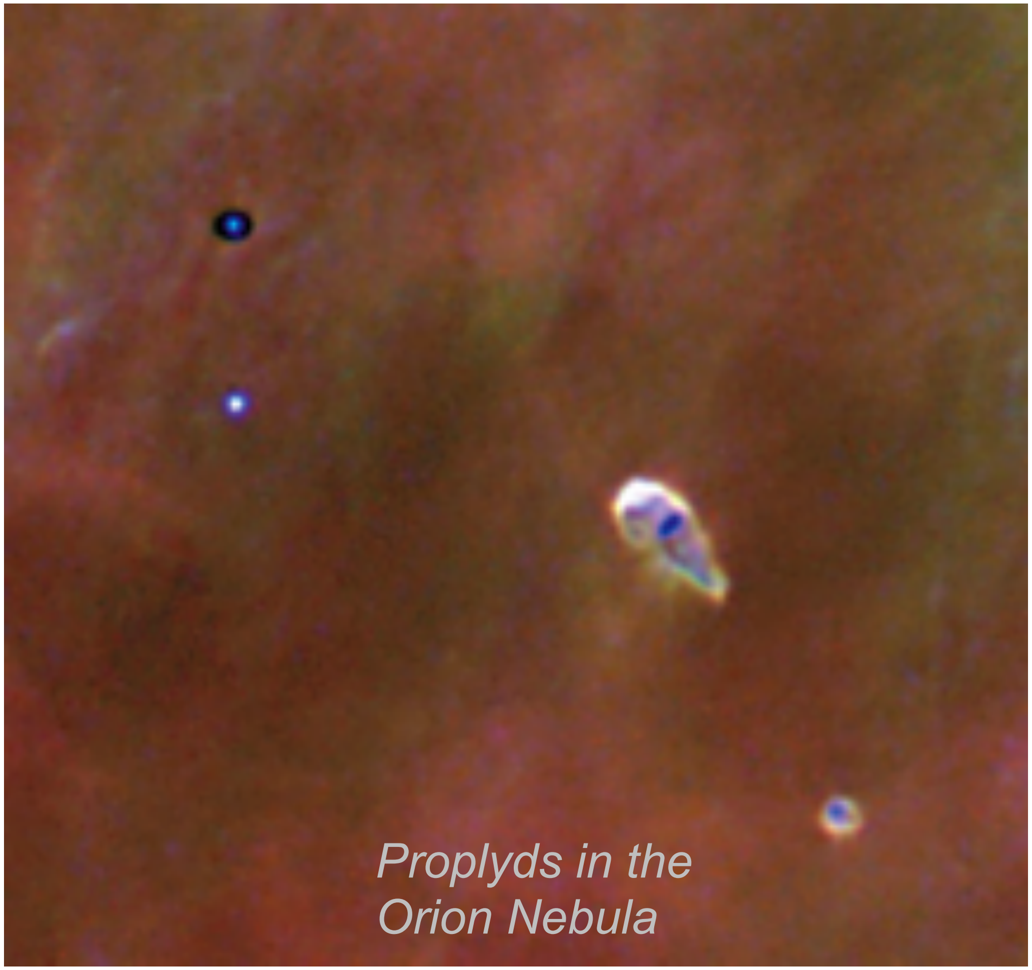
- Large net angular momentum
- Why? If directions were random then the angular momentum would tend to cancel out
  Remember that angular momentum is a vector.
  An orbit going one way, combined with the same orbit but going the opposite way, add to zero total ang. momentum
- Thus we need to have some mechanism that will naturally give us a lot of angular momentum
- But in astronomy, “a lot” has to be with respect to something
- In this case, it means “as much as circular orbits over tens of AU” Why?

The Nebular Theory

- According to the nebular theory, our solar system formed from a giant cloud of interstellar gas.

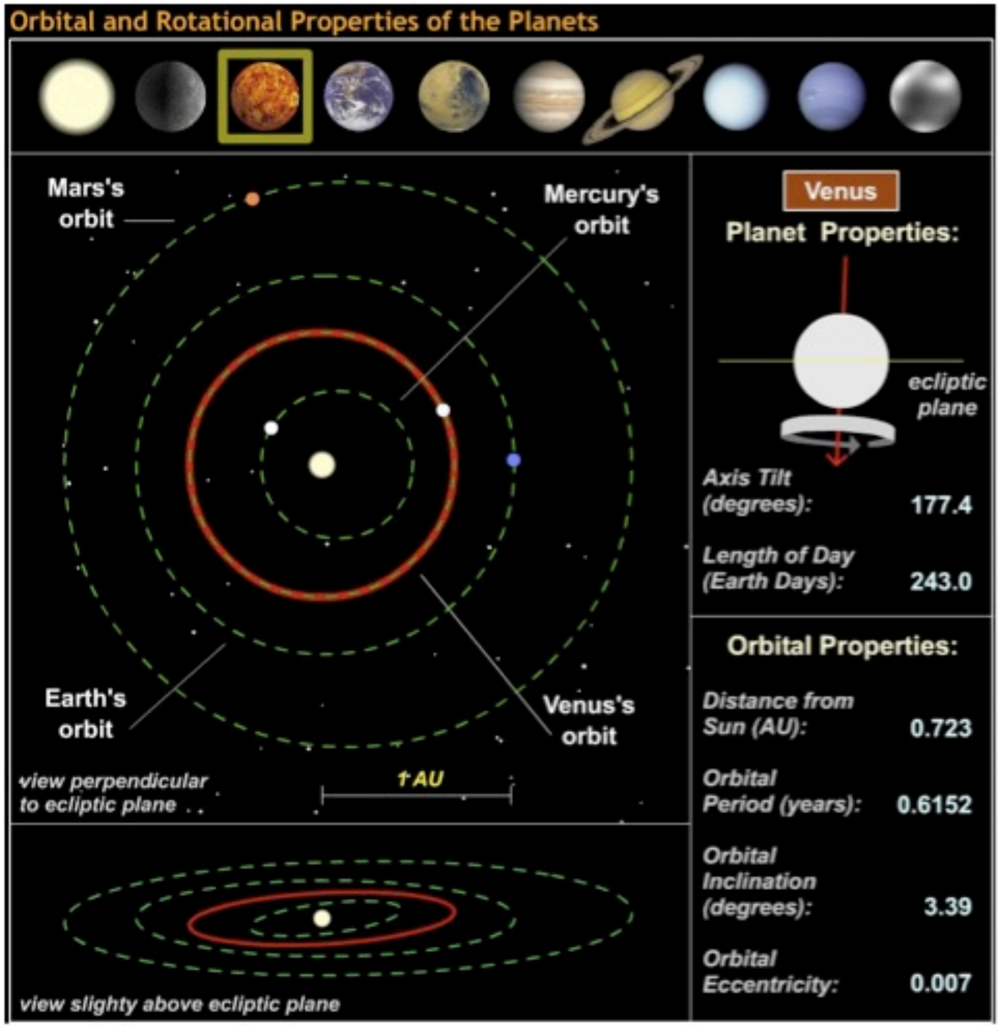
(*nebula* = cloud)

Evidence from Other Gas Clouds



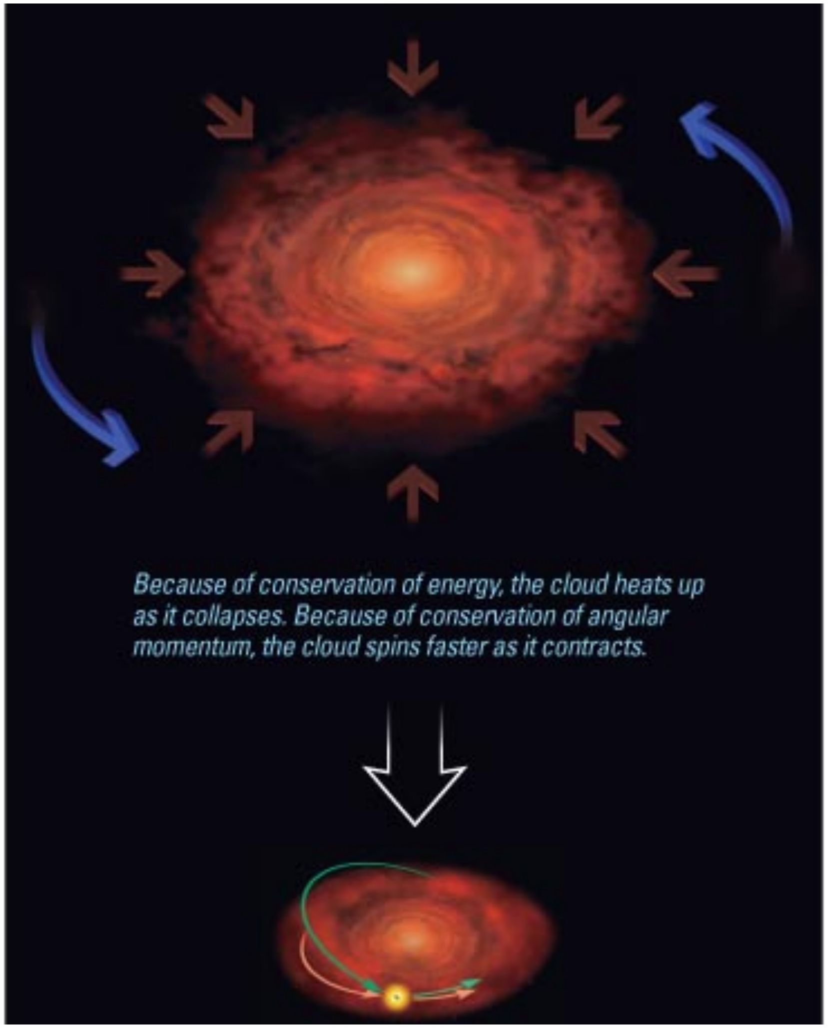
- We can see stars forming in other interstellar clouds, lending support to the nebular theory.

What caused the orderly patterns of motion in our solar system?



Conservation of Angular Momentum

- The rotation speed of the cloud from which our solar system formed increased as the cloud contracted.



Now let's be quantitative...

- Is there enough angular momentum to cause flattening when the nebula contracts to the size of the Solar System?
- Magnitude of angular momentum: mrv_{perp}
  But $v_{perp}=r\Omega$, where Ω is angular velocity
  Thus the magnitude of angular momentum is $mr^2\Omega$
  So at constant m, and constant ang. mom., $\Omega \sim 1/r^2$
- Initial size and angular velocity? Maybe 1 pc (about 200,000 AU) and 10^{-8} radians/year (rotation of MW)
- If the cloud contracts to 5 AU (orbital radius of Jupiter), how fast would it rotate?

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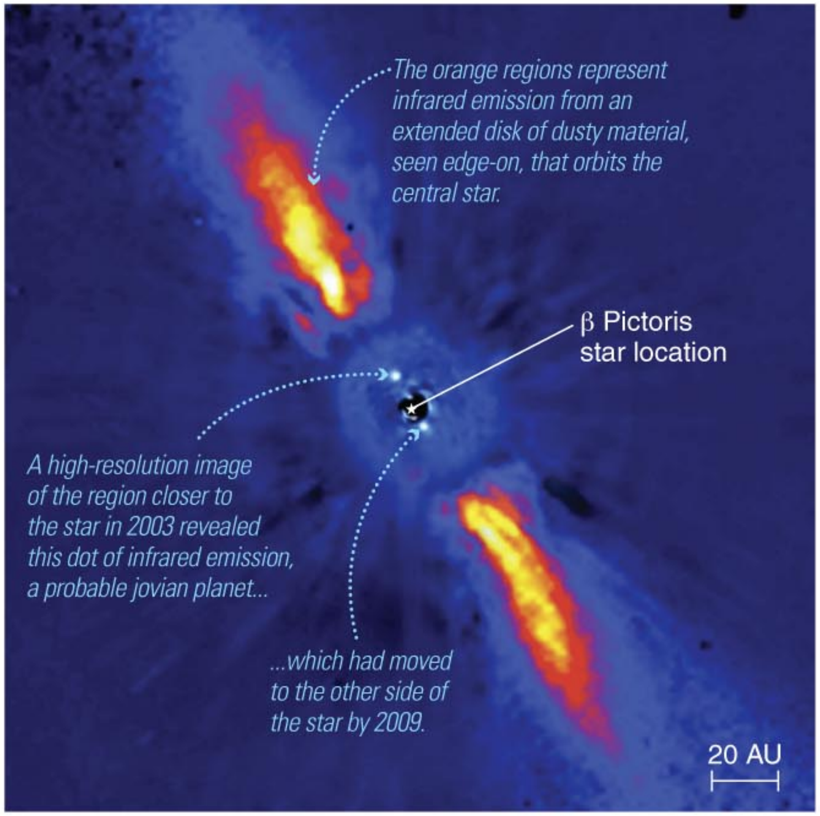
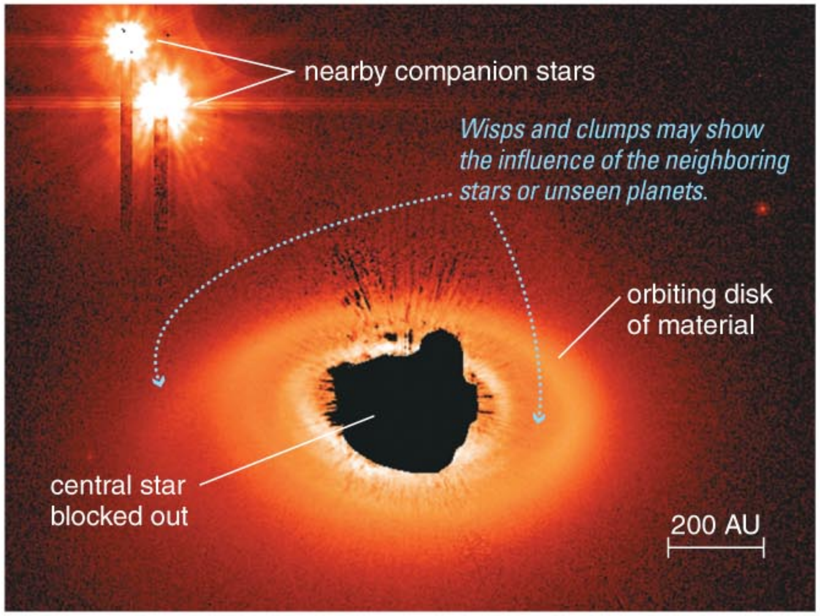
- If the cloud contracts to 5 AU (orbital radius of Jupiter), how fast would it rotate?
  10^{-8} rad/yr x $(2\times10^5/5)^2=16$ rad/yr
- Jupiter: $\sim 2\pi/12$ years, or ~30 x less
- Quantitatively, contraction leads to orbits in same direction!

Disks Around Other Stars

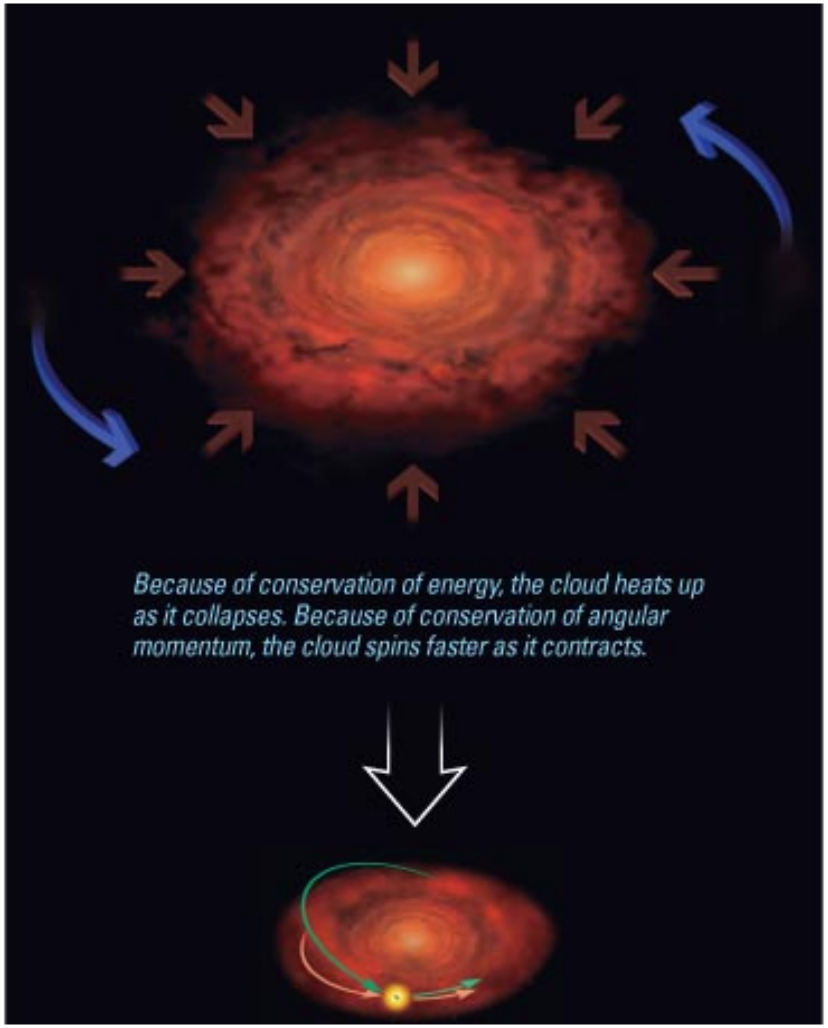




- Observations of disks around other stars support the nebular hypothesis.

Collisions

- Collisions between particles in the cloud caused it to flatten into a disk:
  - Collisions *reduce random motions* by converting orbital energy into heat: particles tend toward *orderly circulation*.
  - Collisions also *reduce up-and-down* motions.
  - The result is the spinning cloud flattens as it shrinks.



Are Circular Orbits Special?

- Yes! At constant angular momentum, circular orbit has the least energy. Let's see why.
- Energy of orbit of semimajor axis a is $E = -GMm/(2a)$
- If orbit has eccentricity e, apocenter distance is $a(1+e)$
  Thus $E=(1/2)mv^2-GMm/[a(1+e)]$
  But still must equal $-GMm/(2a)$. We can cancel "m"
- $(1/2)v^2-GM/[a(1+e)] = -GM/(2a)$
  $v^2=(GM/a)[2/(1+e)-1]=(GM/a)[(2-1-e)/(1+e)]$
  $v^2=(GM/a)[(1-e)/(1+e)]$, so $v=(GM/a)^{1/2}[(1-e)/(1+e)]^{1/2}$
- Angular momentum is mrv at apocenter (why?)
  $L=ma(1+e)(GM/a)^{1/2}[(1-e)/(1+e)]^{1/2}$
  $L=m[GMa(1-e^2)]^{1/2}$
- So why does circ. orbit have least energy at constant L?
  And what does this imply if stuff runs into itself in disk?

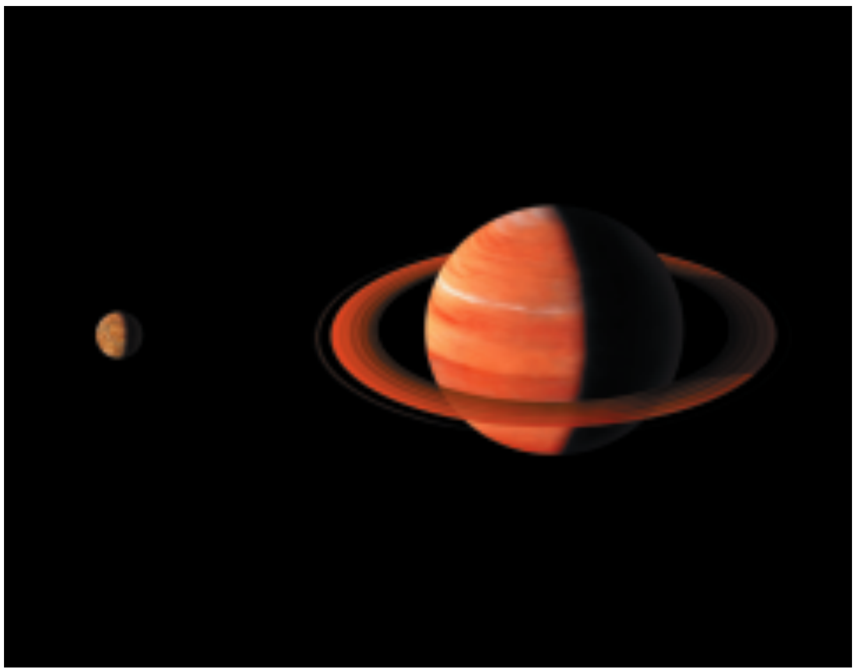
Same principle for other motion

- Example: if gas, or many particles, move in orbits with different orbital planes, collisions will release energy and the orbits will settle into the same plane
  That's why rings can occupy a very thin plane
- When objects orbit around each other, the lowest-energy configuration with a fixed total angular momentum is (1) circular orbit, (2) synchronous orbit (rotation periods equal to orbital periods), and (3) rotation and orbit in the same plane
  Moon presents one face to Earth; most moons are "tidally locked" to planet; Pluto and Charon mutually synchronous
- Can you think of why this might not always be the case?

Why Conserve L, not E?

- Maybe you're starting to wonder:
  Energy and angular momentum are both conserved
  But here we're talking about only L; why not also E?
- Conservation is only for a closed system
- Photons can escape easily from the system
  For photons, $E=pc$, so $p=E/c$
  For particle, $E=(1/2)mv^2=(v/2)mv=(v/2)p$, so $p=(2/v)E$
- Particle speeds are $v<<c$. Thus the energy taken away by photons takes away a tiny amount of linear momentum
  $\mathbf{L}=\mathbf{r}\mathrm{x}\mathbf{p}$, so also a tiny amount of *angular* momentum
- Another factor: photons go in all directions; every photon carries energy, but angular momentum nearly cancels
  Questions or discussion about these points?

Why are there two major types of planets?



	Examples	*Typical Condensation Temperature*	*Relative Abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	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%

Temperature Variation Over Disk

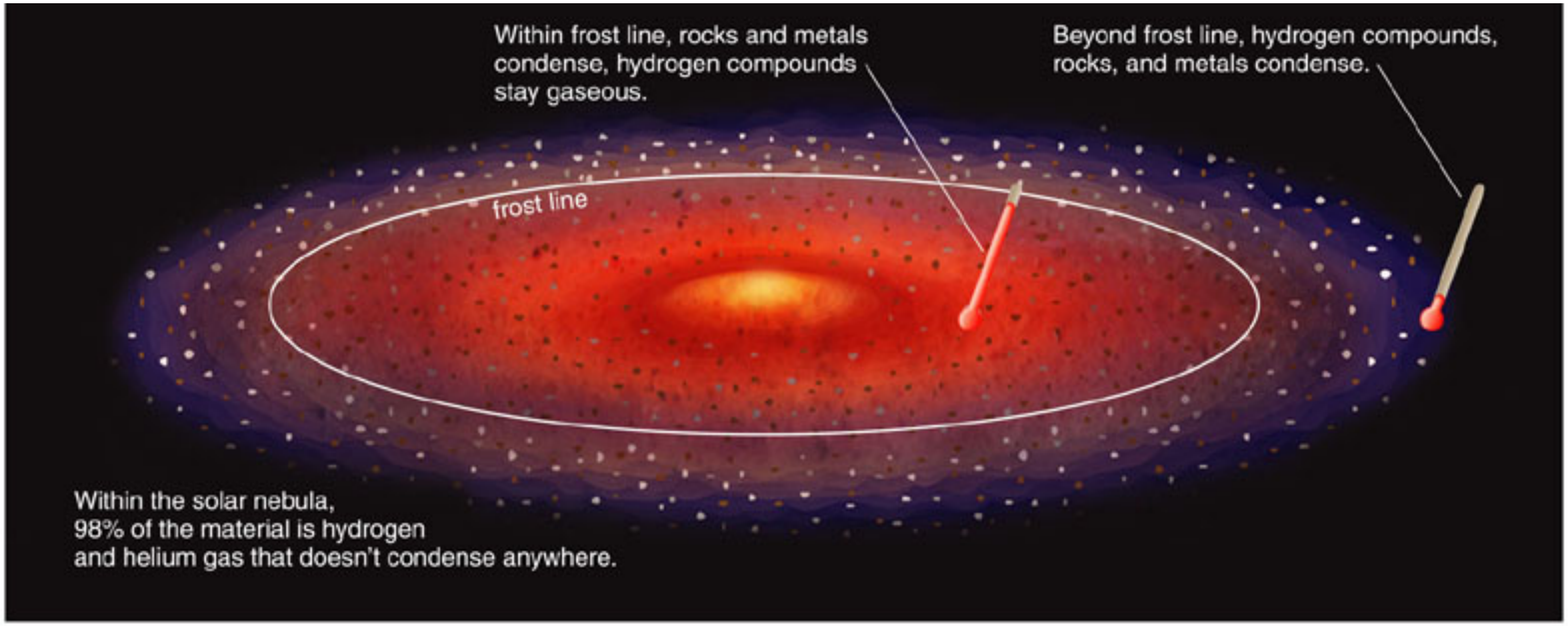
- As gravity causes the cloud to contract, it heats up.
- Inner parts of disk are hotter than outer parts.
- Why? Think about the orbital speed; for a circle, $v_{orb}=(GM/r)^{1/2}$
- Faster motion=>hotter
- Rock can be solid at much higher temperatures than ice. Why does that matter?

What if There is a Star at the Center?

- First, how does the intensity (flux) of light F vary with distance d from a star?
  - Answer: $F \propto 1/d^2$ (inverse-square law, like gravity).
- If you put a sphere at that distance, how does the amount of light (power) it intercepts depend on F and its radius R?
  - Answer: Power absorbed $\propto R^2F$ (cross-section times flux).
- How does the power emitted by the sphere depend on R and its temperature T?
  - Answer: Power emitted $\propto R^2T^4$ (Stefan-Boltzmann law).
- At equilibrium, power absorbed = power emitted, so

$$\frac{R^2}{d^2} \propto R^2 T^4 \text{ or } T \propto \frac{1}{\sqrt{d}}.$$

The Frost Line

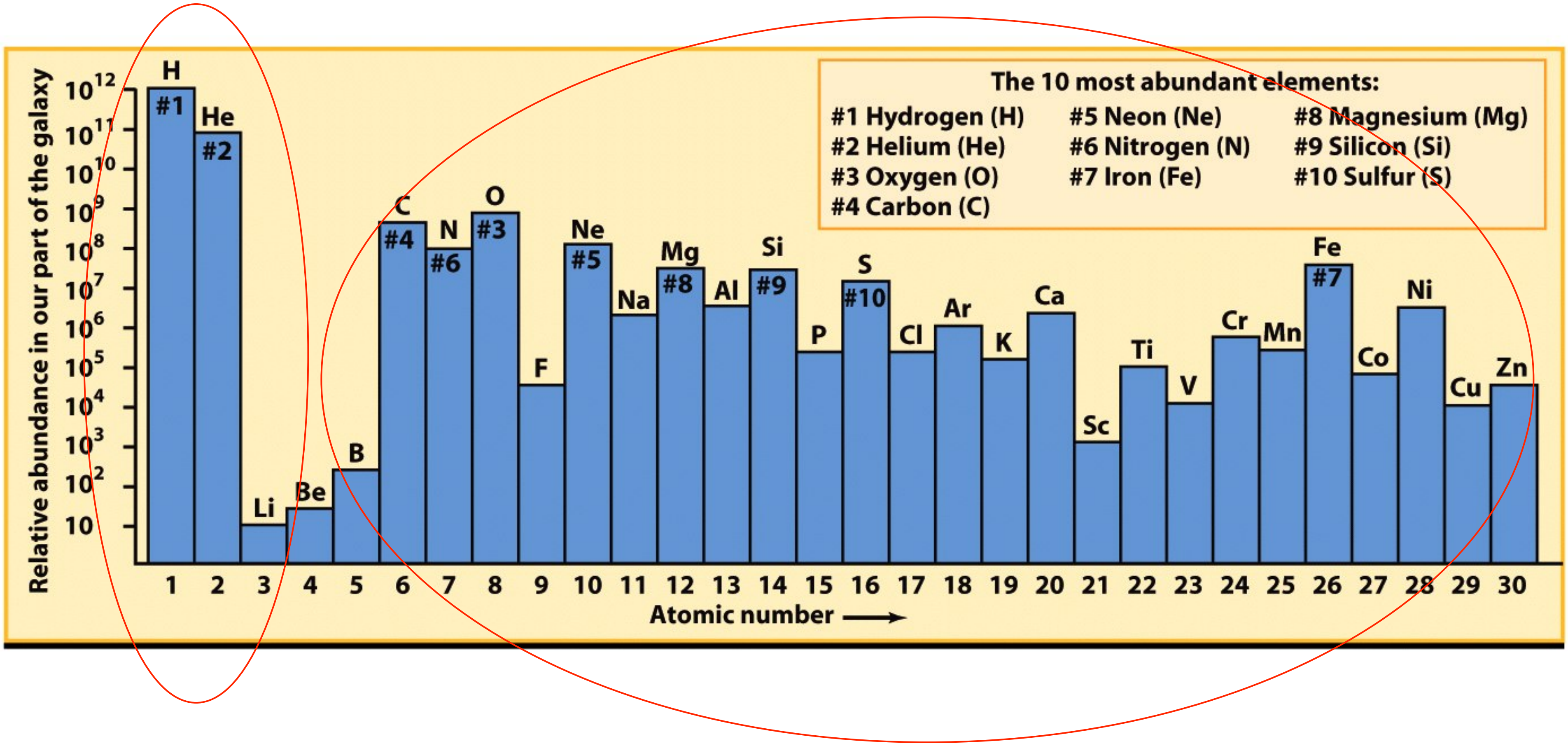


- Inside the ***frost line***: too hot for hydrogen compounds to form ices. Most mass in the nebula is in hydrogen
- Outside the ***frost line***: cold enough for ices to form. Ices can adhere to each other, grow, attract gas

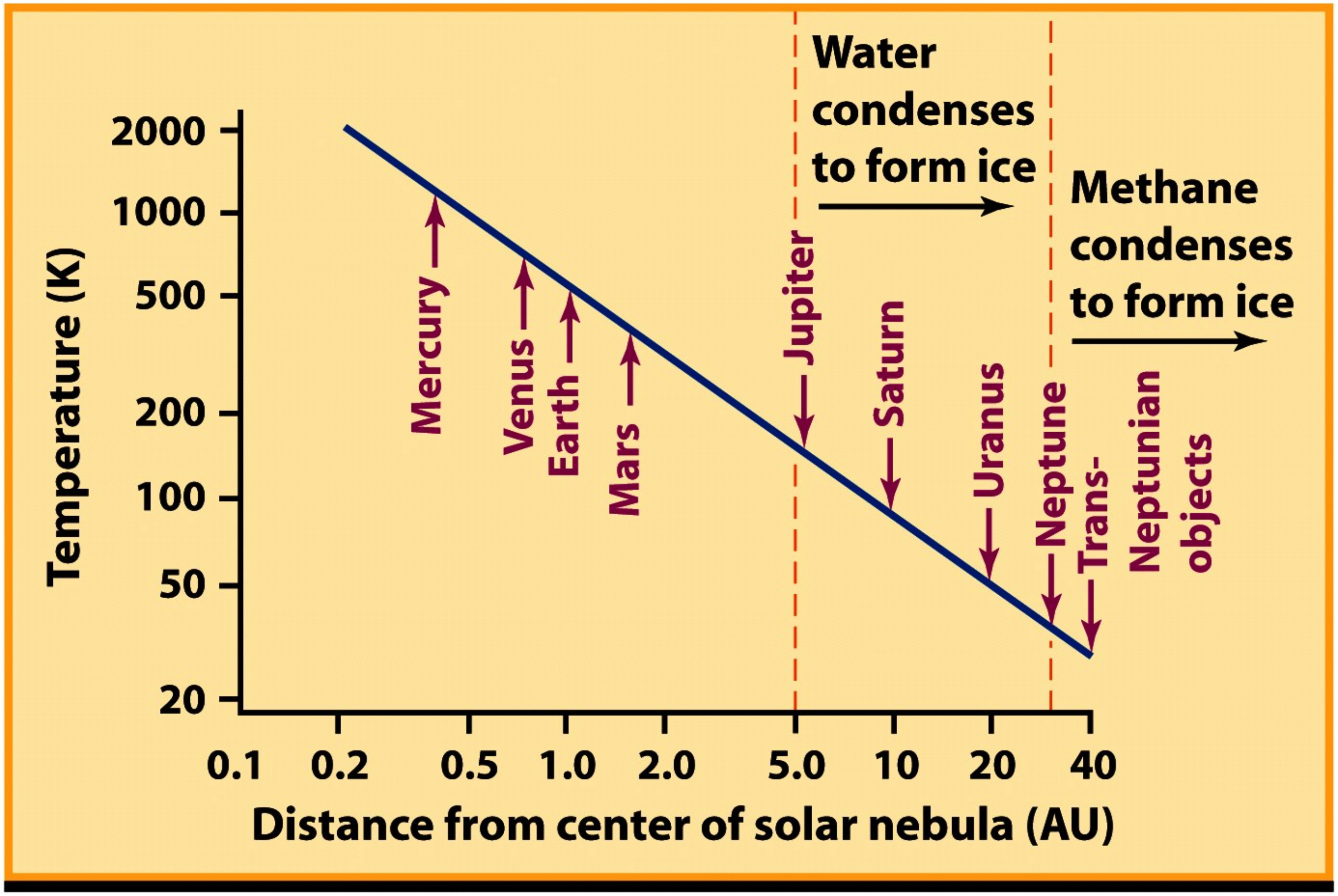

Mount Fuji (Japan)

Big Bang

Made in Stars



Composition of interstellar gas in our part of the galaxy (log scale!).



- Likely temperature distribution in the solar nebula.
- Much warmer then than now—why? And why doesn't ice form closer to the Sun (at temperatures near 273 K)?

Summary: Planet Formation 1

- The raw material comes from a very large, very tenuous nebula of gas
- That matter contracts (because it can radiate energy), and flattens (angular momentum conservation).
  Leads to orbits in the same direction
- Disk is hotter nearer center
  Naturally faster motions
  If star has already formed, hotter because closer to star
- When hot, only rock grains can condense
  Outside the "frost line", ices can condense
  Much more mass in ices (which contain hydrogen) than in rock (which does not)...