[14] Formation of the Solar System, Part 2 (10/17/17)

Upcoming Items

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

APOD 10/12/16

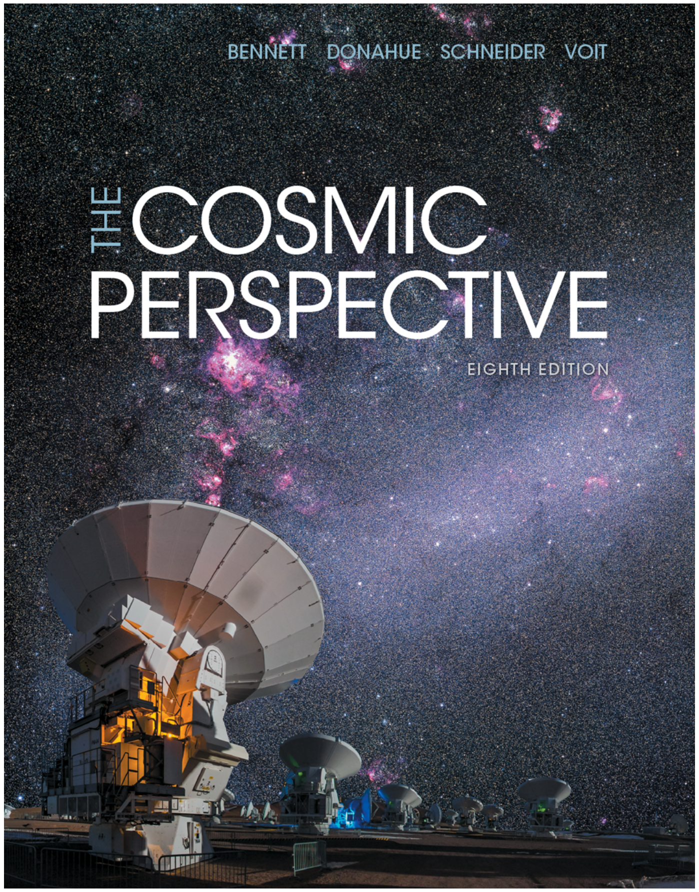
LEARNING GOALS

Chapter 8.1–8.2

For this class, you should be able to…

… *understand gradual accretion as a way of building up planets*

… *understand the role of resonances*



Any astro questions?

Subjects for this class

- Dust to planetesimals to protoplanets to planets
- Gravitational instability; collisions, formation of Earth's Moon, how we get eccentric extrasolar planets
- Tides and resonances

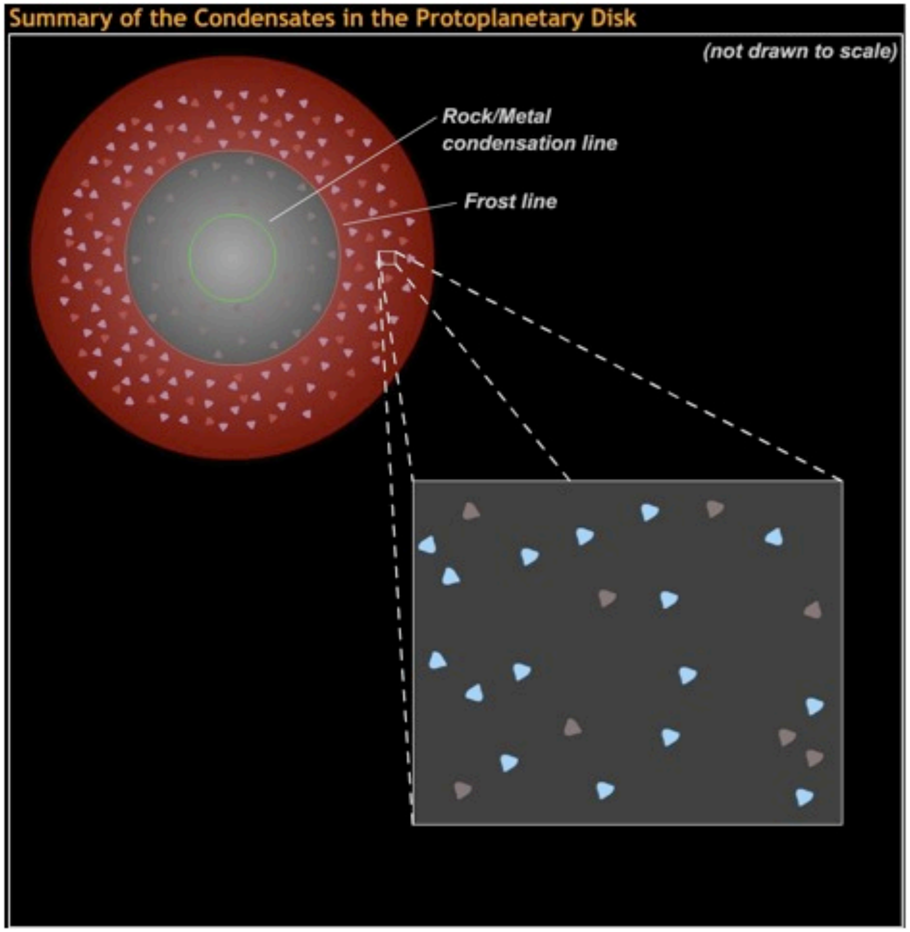
  Europa and the prospects for life outside habitable zone

Formation of Terrestrial Planets

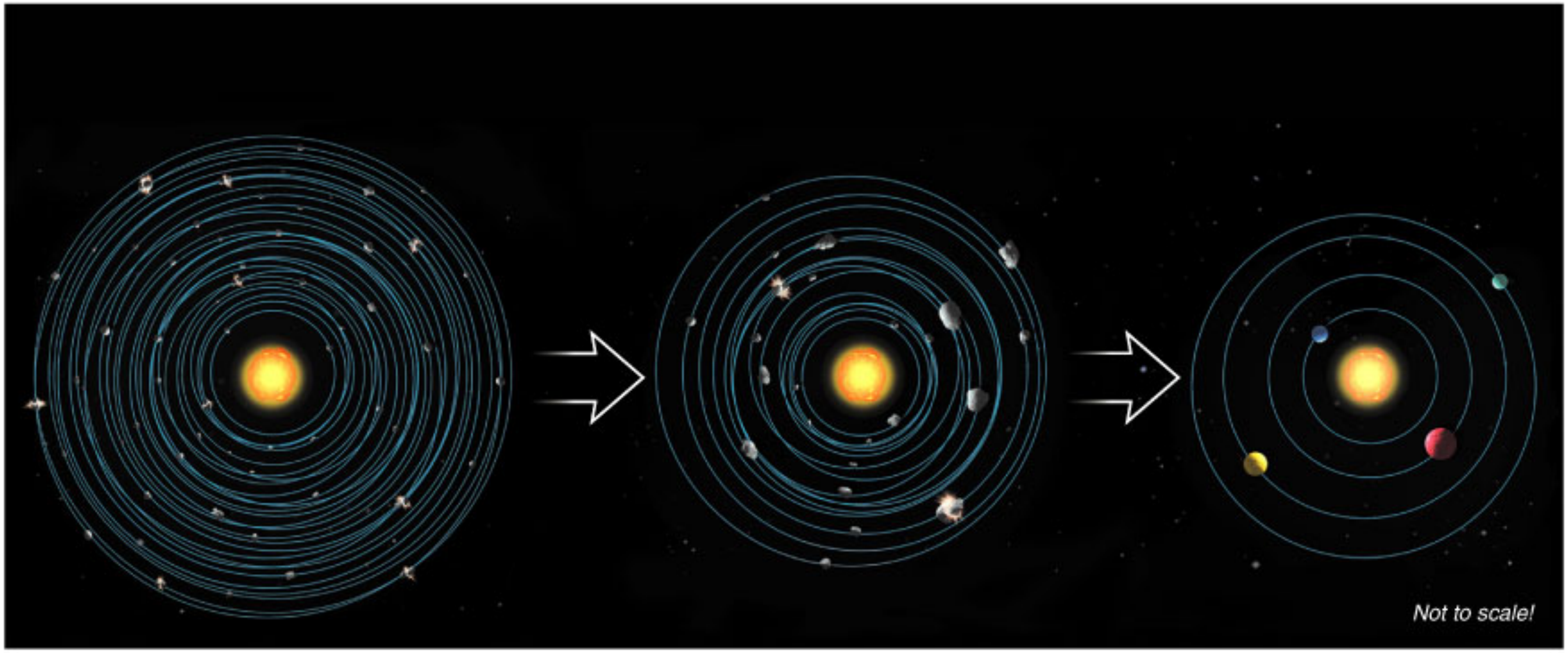
- Small particles of rock and metal were present inside the frost line.
- When sufficiently small, these particles are attracted by *electrical* forces
  Why only when small?
- ***Planetesimals*** of rock and metal built up as these particles collided.
- Gravity eventually assembled these planetesimals into terrestrial planets.

Formation of Terrestrial Planets

- Tiny solid particles stick to form planetesimals.
- Gravity draws planetesimals together to form planets.
- This process of assembly is called *accretion*.



Accretion of Planetesimals



- Many smaller objects collected into just a few large ones.

Can This Produce Eccentricity?

- Remember that many exoplanet systems do have significant eccentricities.
- If there are a very large number of particles, and/or lots of gas, we argued that the lowest energy state involves circular orbits
  So we expect gas disks to be basically circular
- What about when we’re down to the last few big protoplanets?

Can This Produce Eccentricity?

- Remember that many exoplanet systems do have significant eccentricities.
- If there are a very large number of particles, and/or lots of gas, we argued that the lowest energy state involves circular orbits
  So we expect gas disks to be basically circular
- What about when we're down to the last few big protoplanets?
  Yes! If those protoplanets get close enough to each other, their mutual gravity can sling them into eccentric orbits. With little gas or dust around for collisions, the protoplanets don't have to circularize.

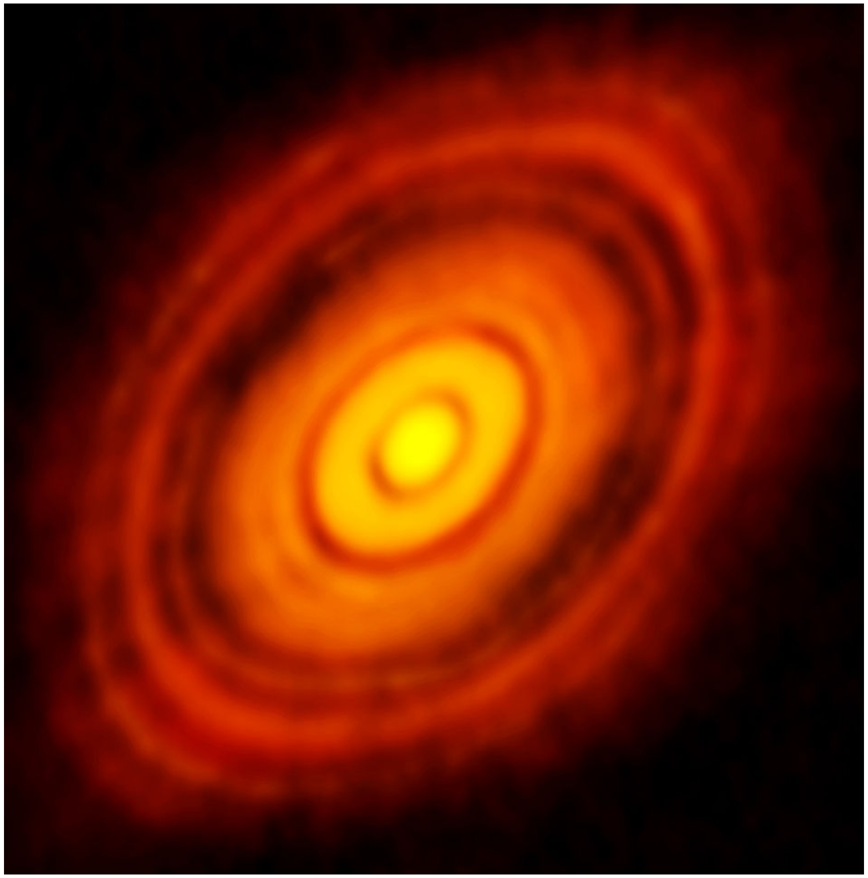
Group Q: Scaling Laws and Collisions

- Scaling laws: a powerful tool
- Problem 2 from Fri discussion:
  Self-grav energy $E_{self} \sim GM_p^2/R_p$
  Orbital energy $E_{orb} \sim GM_sM_p/r_{orb}$
- If the density is constant, how does R_p depend on M_p?
- Given that, how does E_{self} depend on M_p? How about E_{orb}?
- Should small or large things be more easily destroyed if their collisions release $\sim E_{orb}$ of heat?
- What does this imply about the gradual growth of planetesimals?

http://www.highlightpress.com/wp-content/uploads/2015/04/0410-Moon-Collide.jpg

Formation of Jovian Planets

- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- Gravity of larger planets was able to draw in surrounding H and He gases.
  Much higher fraction of H, He
  Clears gaps; resonances?
- Tiny particles follow gas; big planets aren't moved in. But at ~1 meter, dragged in <1000 yr!
- "Meter size barrier"

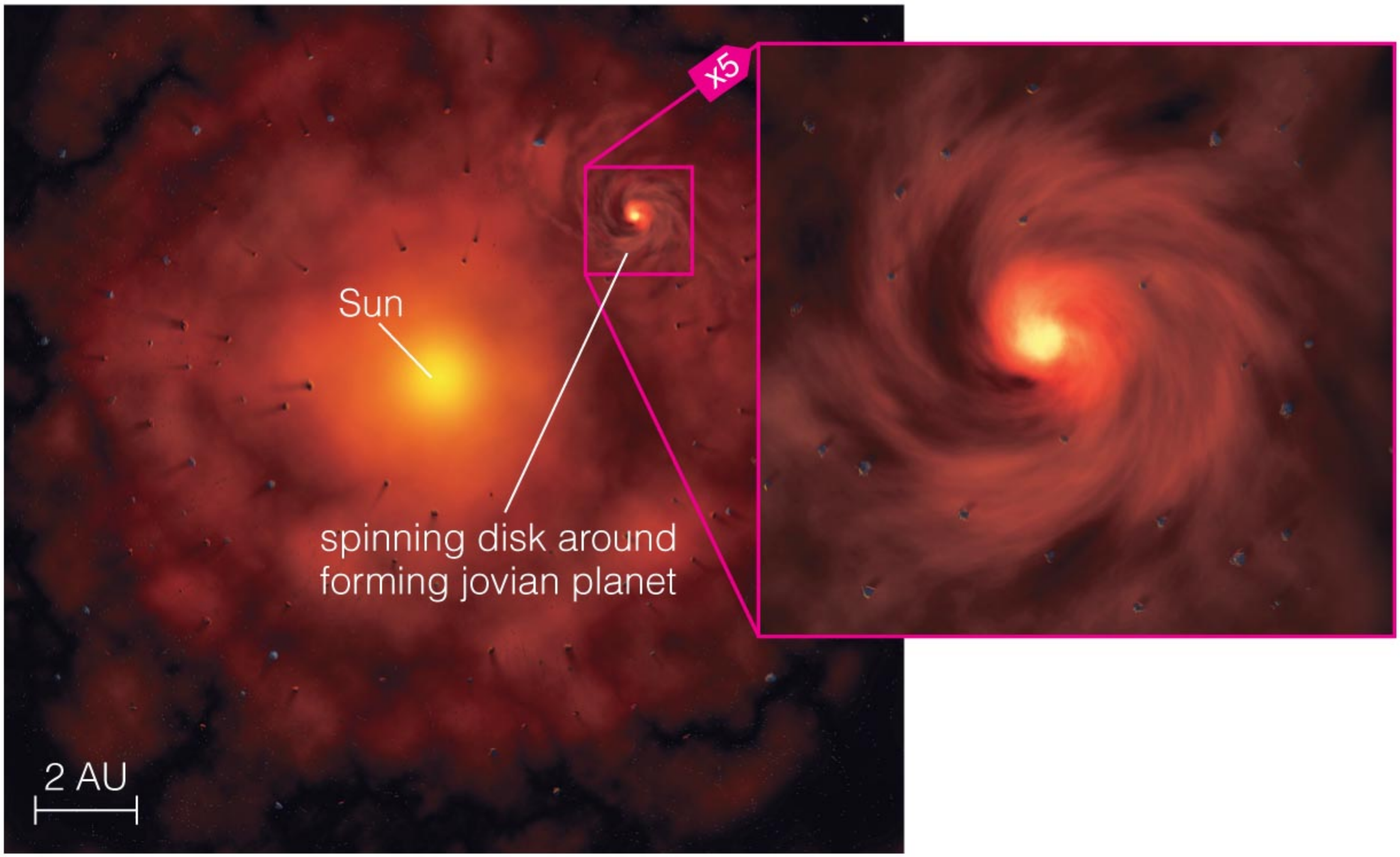


HL Tau, as seen by the Atacama Large Millimeter Array

Rotation of Jovian Planets

- Jupiter, Saturn, Uranus, Neptune all have rotation periods shorter than those of Mercury, Venus, Earth, Mars; why?
- Think of it in terms of angular momentum
  Remember: angular momentum ~$(GMr)^{1/2}$ for circular
- The gravity of the protoplanet extends outward and inward from the center of the orbit
- Outward, the angular momentum is larger; thus when that gas comes into the planet, it is moving faster, in the direction of the orbit, than the planet.
  Why? L=mvr; same r, higher L, means higher v
  Thus this contributes to spin in direction of orbit
- Similarly, gas inward of planet lags behind, also contributing to same spin direction Can you see why?

Formation of Jovian Moons



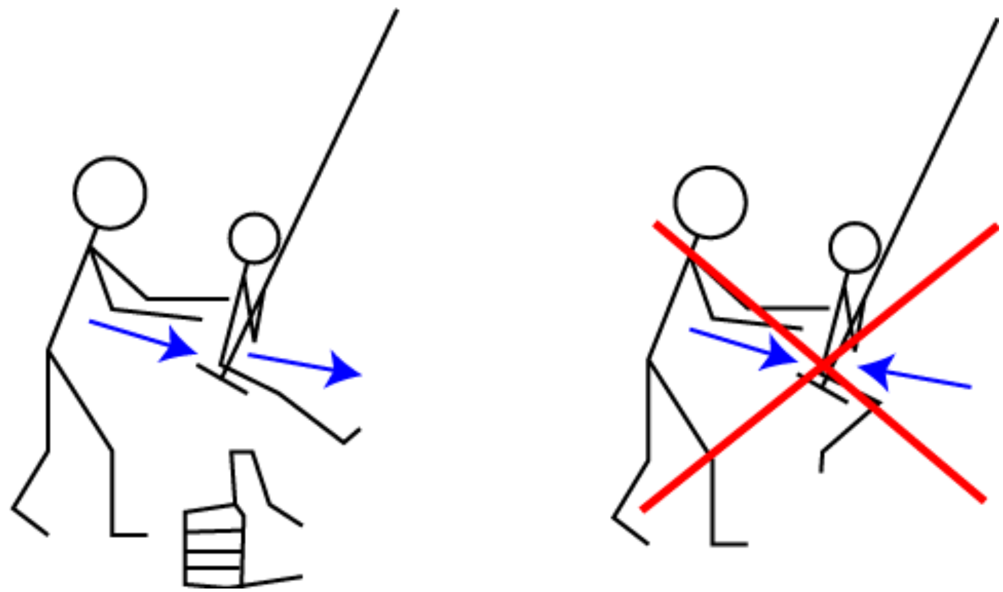
- (Regular) moons of jovian planets form in miniature disks.

Resonances

- The disks (which form moons) arise for the same reason that the planets spin fast
- But remember the strange ratios of orbital periods we saw a couple of classes ago?
- These are examples of resonances, and they are common enough that we need to discuss them further.

Resonances

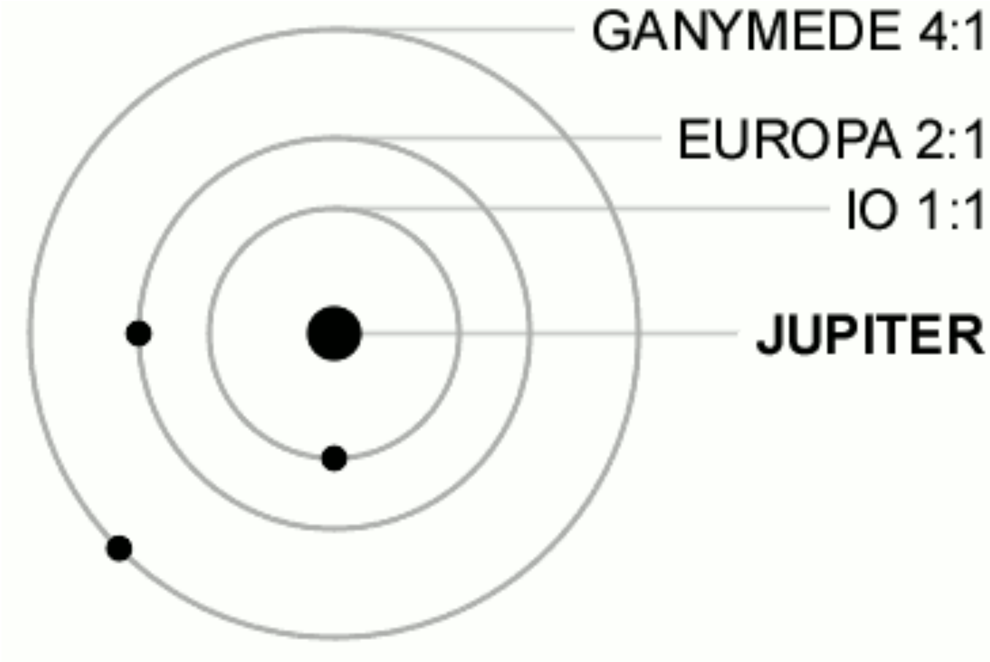
- Happen when a force is in synch with a period
  Classic example: pushing on a swing!
- If one thing in orbit has a period that is in a small integer ratio with another, they push on each other.
  Why "small integer"?
  Strong pushes need to be common
  So, e.g., 2:1 or 3:2 is strong
  109/73 is not!



https://i.stack.imgur.com/Sqd4B.png

Sometimes resonances can trap...

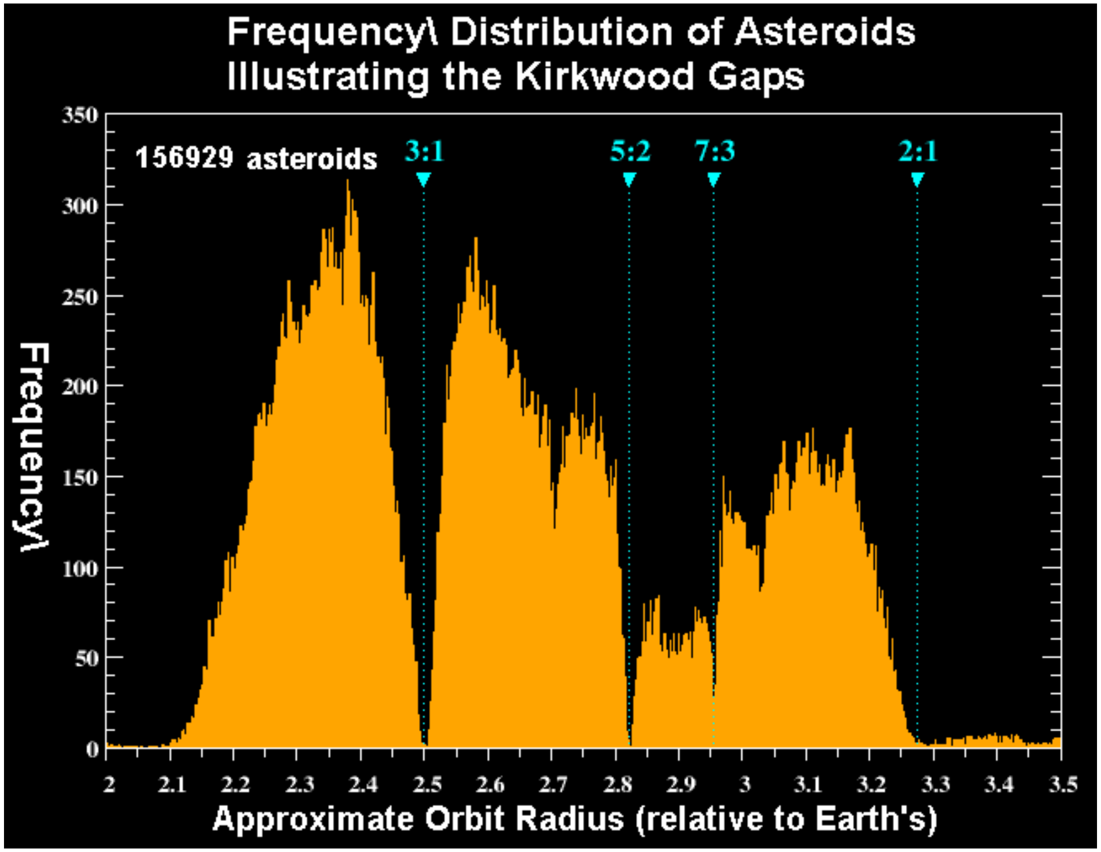
- In case of Io, Europa, Ganymede...
- All orbit more slowly than Jupiter rotates
  Like Moon and Earth
- Thus, Io, Europa, Ganymede are all pushed out by tides
  Io fastest; it's closest
- Io catches up with Europa; when at 2:1, both move together
  Then same with Ganymede



https://upload.wikimedia.org/wikipedia/commons/e/e5/Galilean_moon_Laplace_resonance_animation_2.gif

...and sometimes they don't

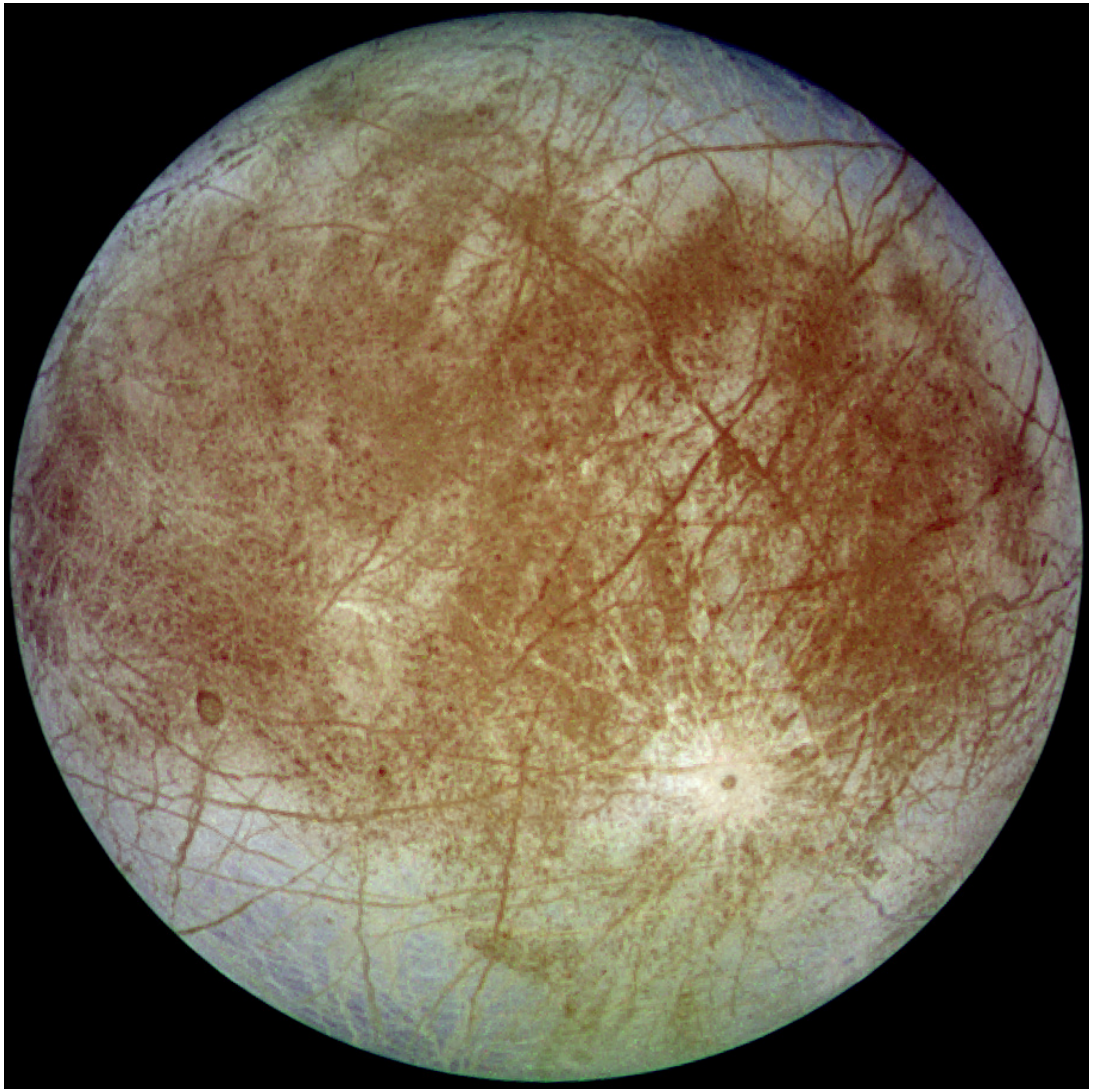
- "Kirkwood gaps" Regions of the main asteroid belt with few asteroids
- Why? Because at those locations, the orbital period is related, in small integer ratios, to Jupiter's orbital period
- So Jupiter gives them frequent kicks
- When trapping vs not? Learn that in ASTR 450!



http://www.sjsu.edu/faculty/watkins/kirkwood01.gif

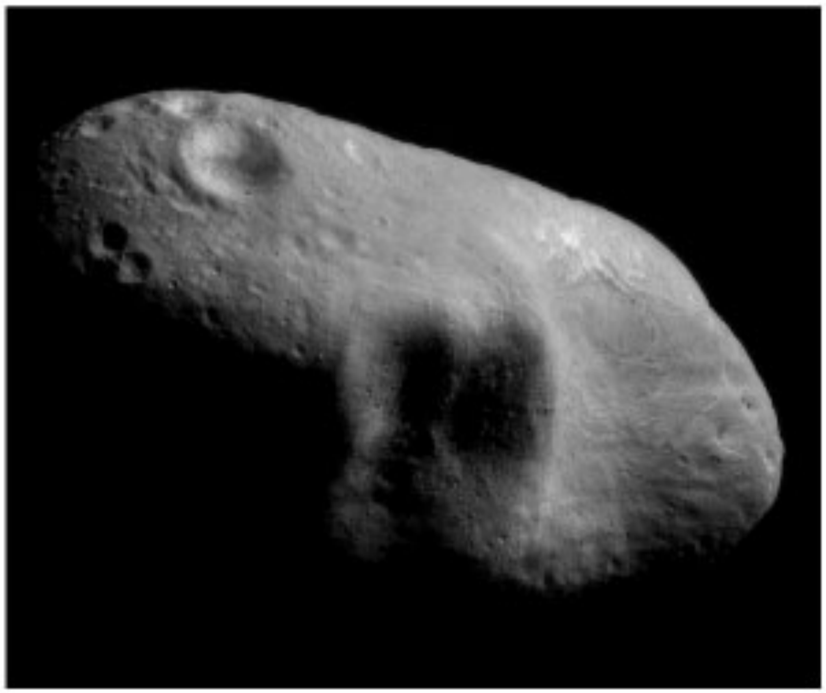
Resonances and Life

- Another reason to care!
- Jupiter and its moons are way too far from Sun to be in the "habitable zone"
  Where liquid water can exist on surface
  But: the resonances give enough eccentricity that tides from Jupiter knead the moons
  Much warmer!
  Europa: sub-ice ocean
  Maybe Ganymede too
- Life?

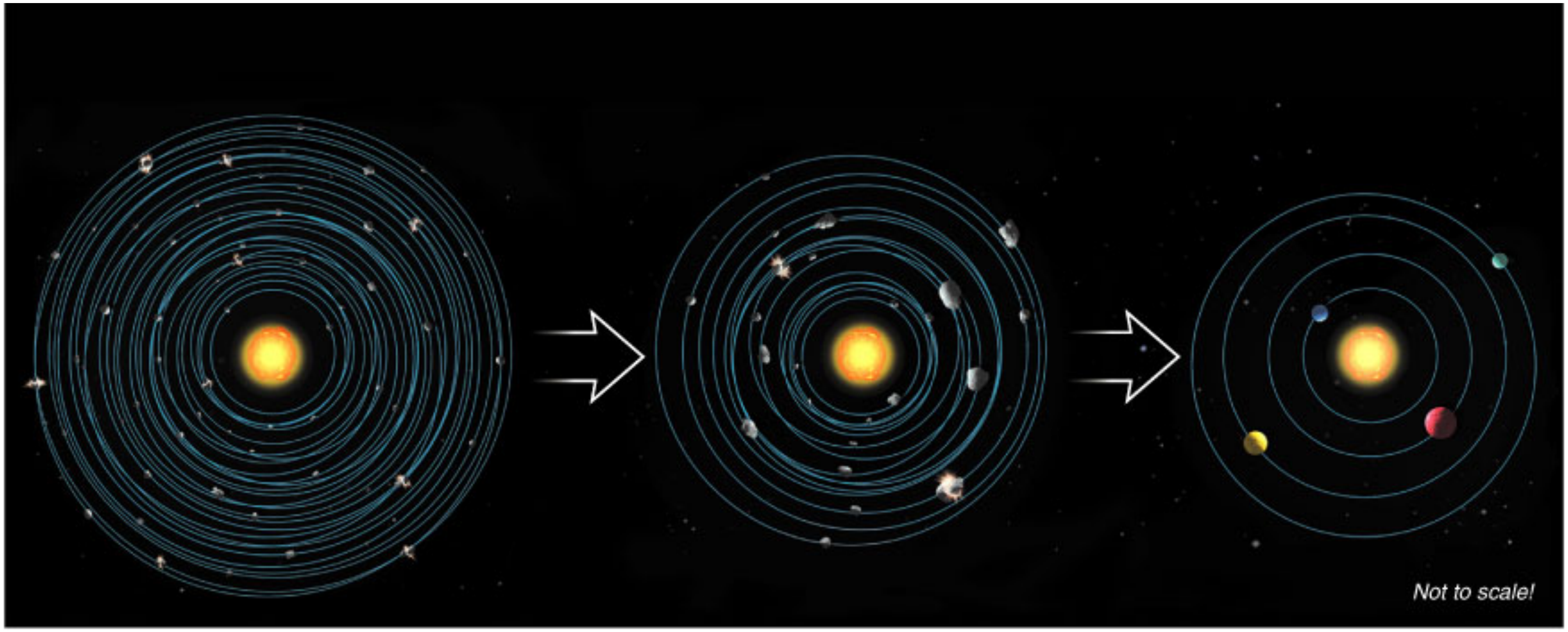


https://upload.wikimedia.org/wikipedia/commons/5/54/Europa-moon.jpg

Where did asteroids and comets come from?



Asteroids and Comets



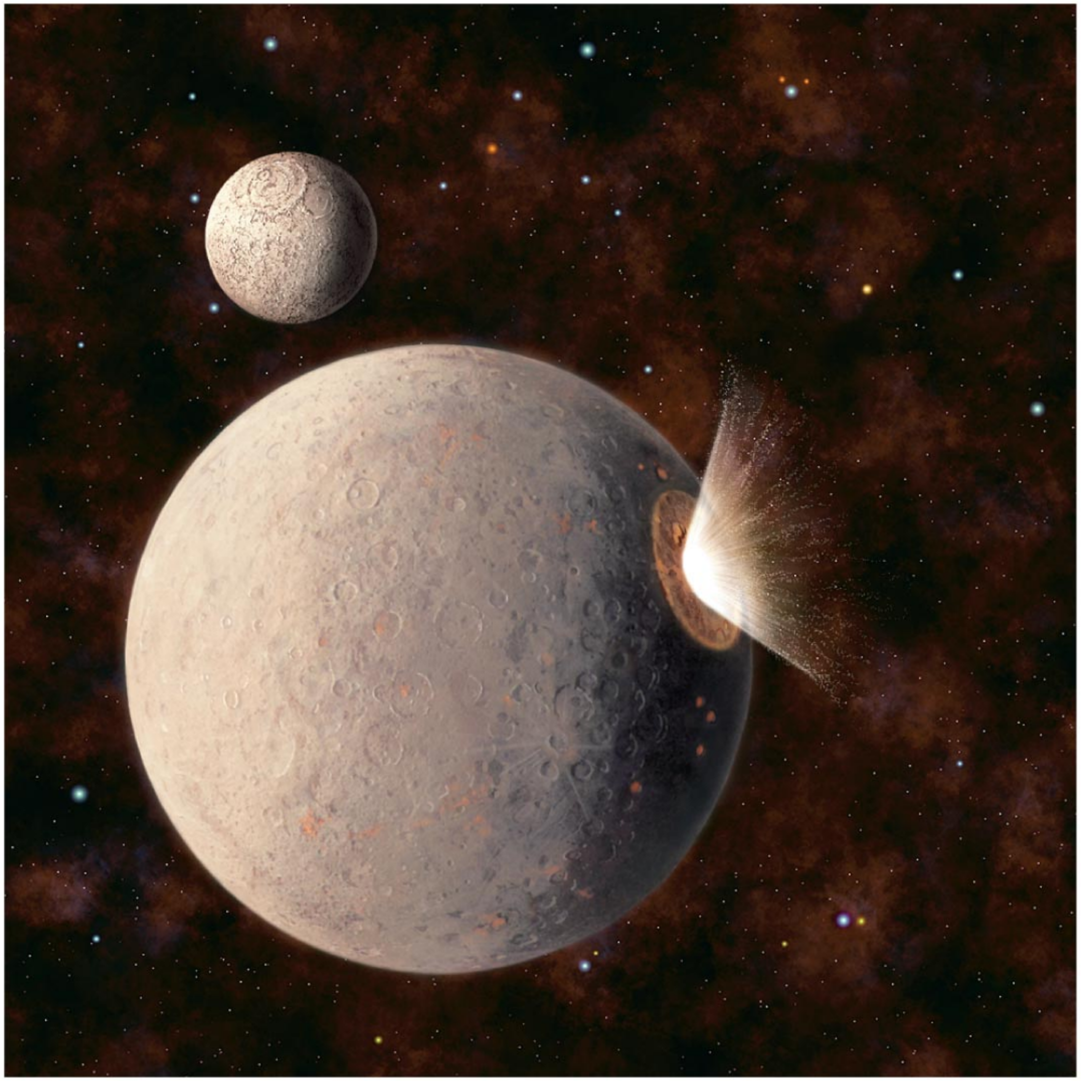
- Leftovers from the accretion process.
- Rocky asteroids inside frost line.
- Icy comets outside frost line.

Kicks from Jupiter!

- Jupiter was in a “sweet spot”; outside the frost line (so ices could form), but close enough that the orbital time was comparatively short (so it could pick up gas rapidly)
- Maybe a planet would have formed at the location of the asteroid belt, but Jupiter’s gravity kicked out 99% of the mass
- Farther out, the “Oort Cloud” of comets is thought to consist of icy chunks that were kicked out by Jupiter Jupiter is capable of throwing things completely out of the Solar System!
- Could be in any direction, which is why comets can come from any direction

Heavy Bombardment

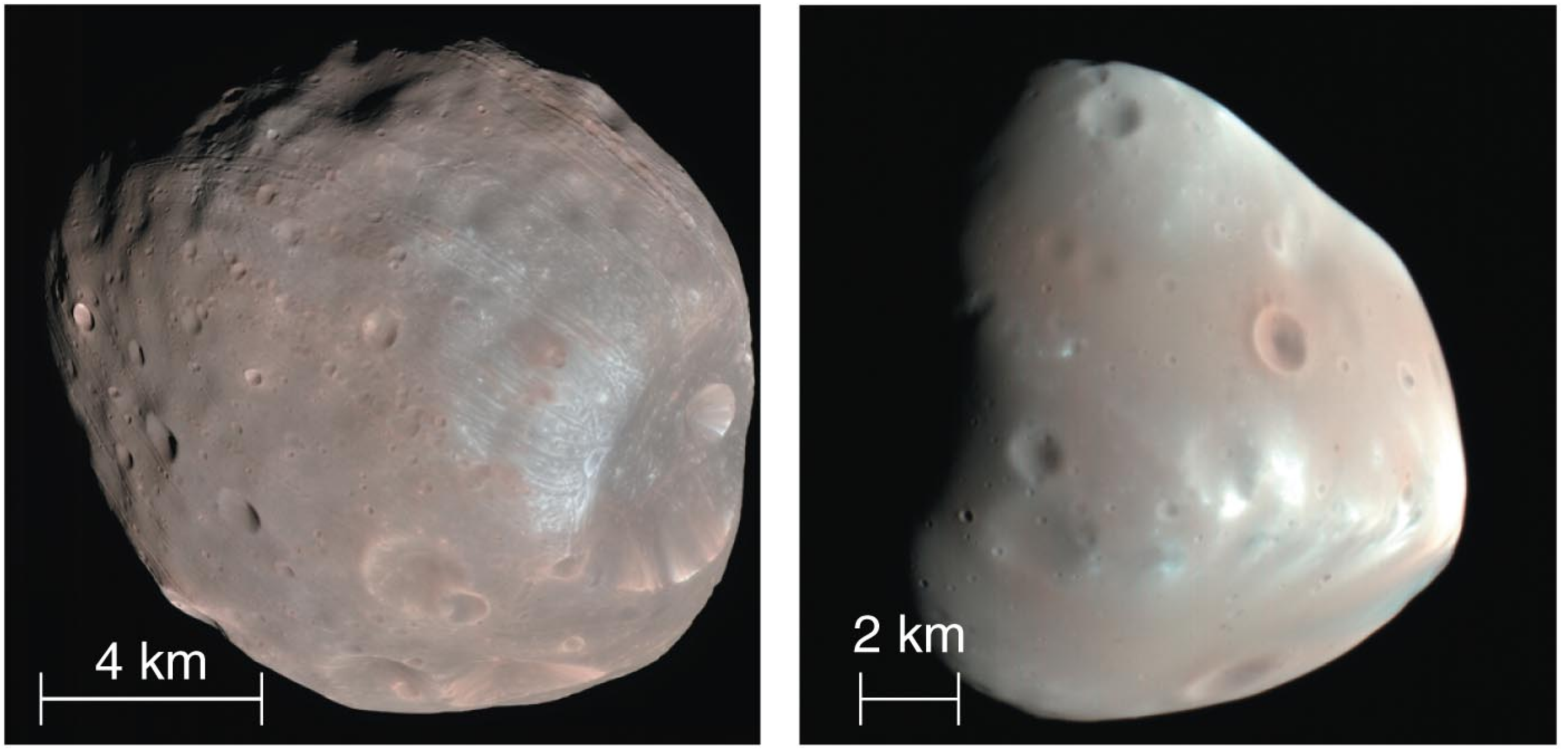
- Leftover planetesimals bombarded other objects in the late stages of solar system formation.
- Earliest hints of life on Earth are from just after the last phase Did life emerge repeatedly only to be snuffed out?



Origin of Earth’s Water

- Water may have come to Earth by way of icy planetesimals.
But this is controversial; part of the controversy has to do with the ratio of deuterium to hydrogen

Captured Moons

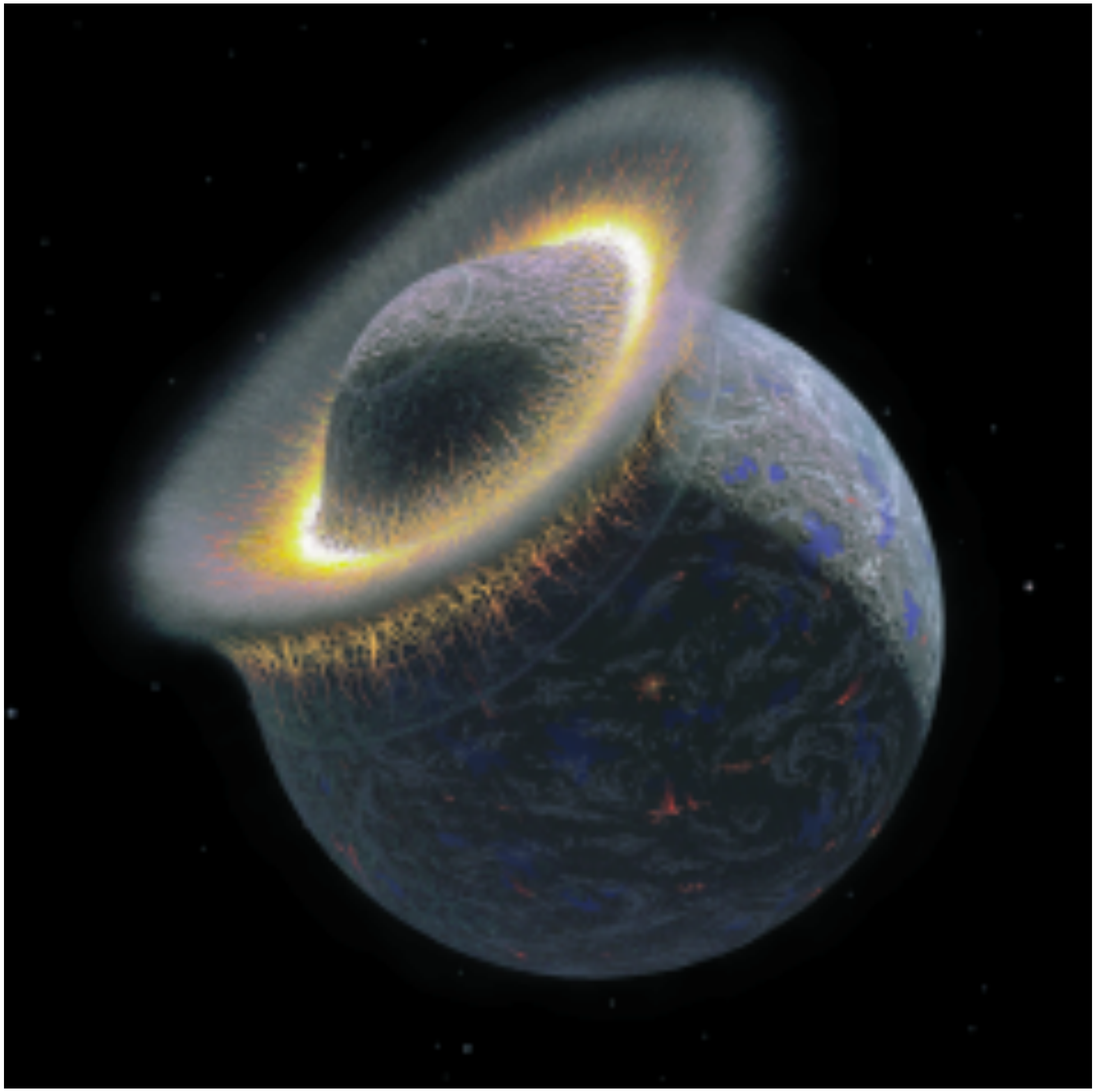


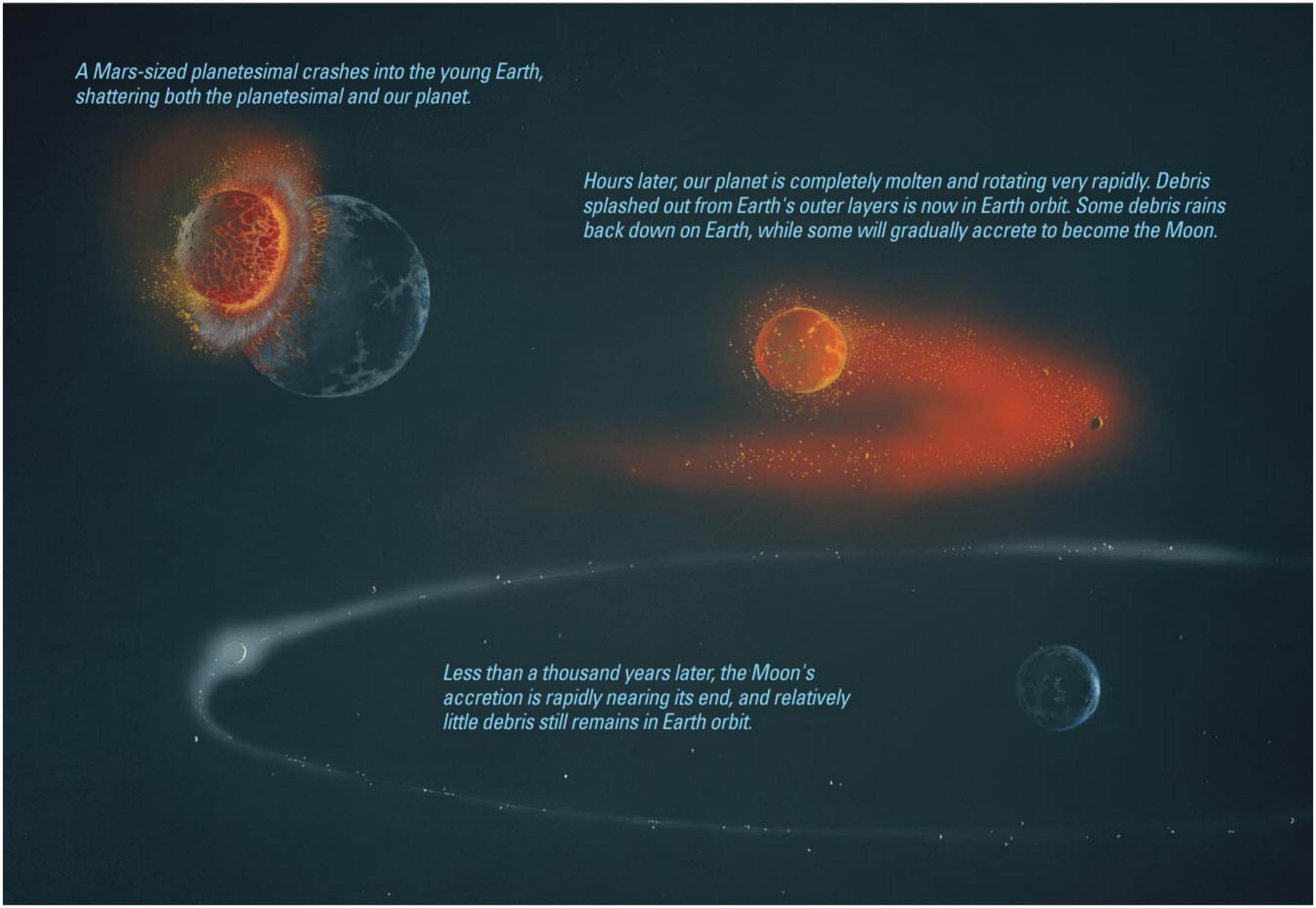
a Phobos **b** Deimos

- The unusual “irregular” satellites of some planets may be captured planetesimals.

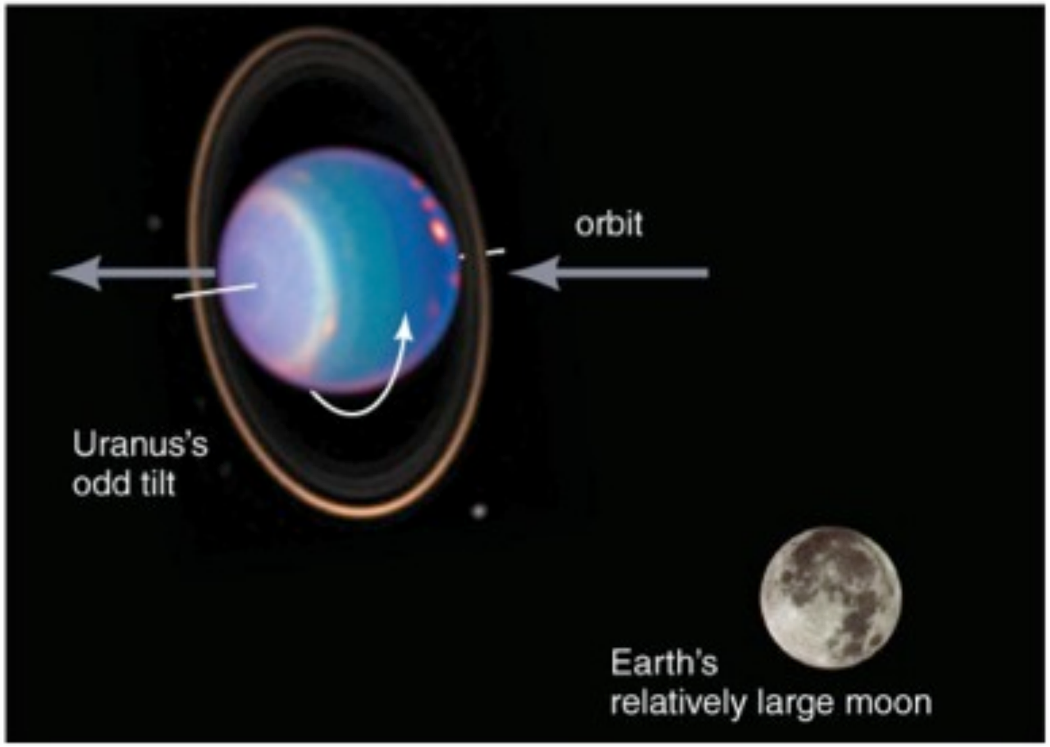
Giant Impacts

- Earth's Moon was probably created when a giant planetesimal slammed into the newly forming Earth.




A Mars-sized planetesimal crashes into the young Earth, shattering both the planetesimal and our planet.
Hours later, our planet is completely molten and rotating very rapidly. Debris splashed out from Earth's outer layers is now in Earth orbit. Some debris rains back down on Earth, while some will gradually accrete to become the Moon.
Less than a thousand years later, the Moon's accretion is rapidly nearing its end, and relatively little debris still remains in Earth orbit.

Odd Rotation



- Giant impacts may also explain the different rotation axes of some planets.
- Resonances can explain others
  E.g., Saturn is tilted by 26 degrees; our own Prof. Doug Hamilton explained that by a resonance with Neptune!

Review of nebular theory