The origin of the Solar System

Astronomy 101
Syracuse University, Fall 2022
Walter Freeman

November 15, 2022

Announcements

- Homework quiz retakes / makeups:
    - Today at 4:30pm, room 206
    - Tomorrow at 2-5 pm, Physics Clinic

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- Exam 3 is being graded now
- Extra extended help hours this week (room 112 or 215):
  - Today, 4pm-5pm
  - Wednesday, 2pm-5pm
  - Friday, noon-2pm

Grade concerns

In this class I ask you to do difficult things, and the grading scale is built around this.

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We cannot prognosticate your grade; you still have time left to learn and show us what you've learned.

But we will do our best to ensure people learn as much as they can.

If you are concerned about your grade, we will have "catch-up sessions" during the three weeks after Thanksgiving.

These will be times for you to come learn the things you have missed and make sure you are well prepared for the final.

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- The special role of atmospheres – **the greenhouse effect and climate change**
- The rest of the Solar System: what else is out there, and what might live there

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... and where we've been and where we'll go:

- Travel to the Moon; the current state of spaceflight
- How we might get to the stars
- ... and what we might find living there once we do

Your final projects

A few reminders:

- If you're working in a group, remember you *must* submit a proposal to me telling me:
  - What you're doing, and why you need a group of that size
  - What each person in the group will be doing
- You're encouraged to send me proposals for any project idea you would like feedback on, or advice on how to make it connect to astronomy/science better

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- People doing visual art or poetry: remember you need to submit a companion piece with your project

Deducing the origin of the Solar System: what do we have to work with?

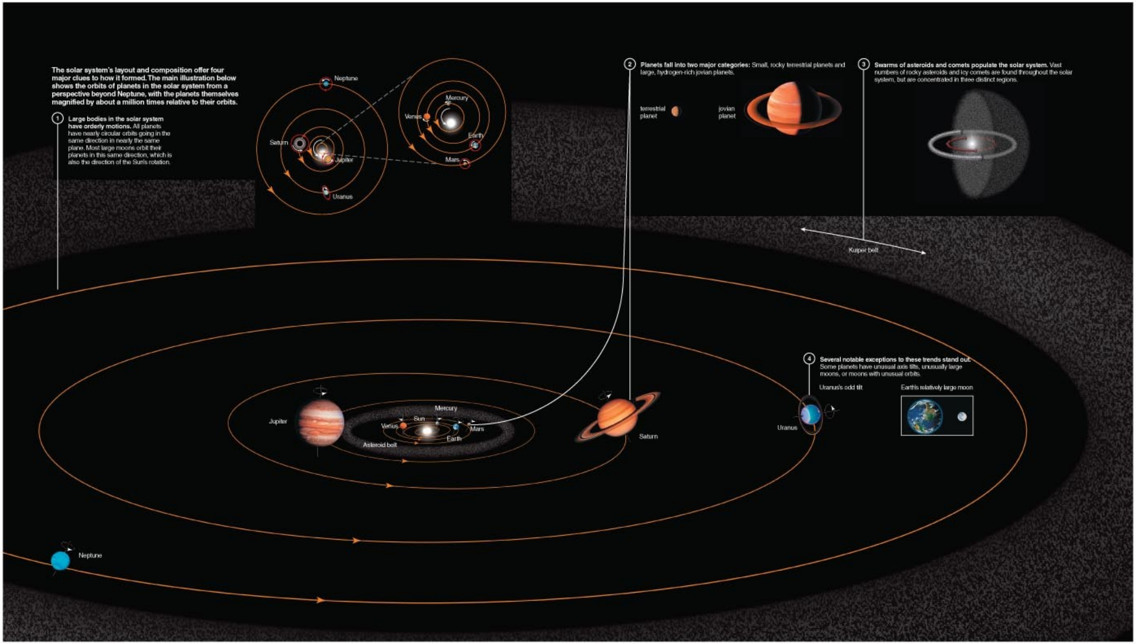

TABLE 6.1 The Planetary Data[a]

Photo	Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/cm^3)	Orbital Period	Rotation Period	Axis Tilt	Average Surface (or Cloud-Top) Temperature[b]	Composition	Known Moons (2013)	Rings?
	Mercury	·	0.387	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night)	Rocks, metals	0	No
	Venus	•	0.723	6051	0.82	5.24	225 days	243 days	177.3°	740 K	Rocks, metals	0	No
	Earth	•	1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
	Mars	·	1.52	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
	Jupiter	●	5.20	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds[c]	67	Yes
	Saturn	●	9.54	60,268	95.2	0.70	29.4 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds[c]	62	Yes
	Uranus	●	19.2	25,559	14.5	1.32	83.8 years	17.2 hours	97.9°	60 K	H, He, hydrogen compounds[c]	27	Yes
	Neptune	●	30.1	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds[c]	14	Yes
	Pluto	·	39.5	1160	0.0022	2.0	248 years	6.39 days	112.5°	44 K	Ices, rock	5	No
	Eris	·	67.7	1200	0.0028	2.3	557 years	1.08 days	78°	43 K	Ices, rock	1	No

[a]Including the dwarf planets Pluto and Eris; Appendix E gives a more complete list of planetary properties. [b]Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed. [c]Includes water (H_2O), methane (CH_4), and ammonia (NH_3).

What patterns do we see?

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- An enormous hydrogen/helium star, with trace elements, at the middle
- Four small, rocky planets around it, including our own
  - No large moons here, except Earth's

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Even further out:

- The Kuiper belt:
  - Lots of small icy bodies (Pluto and Eris among them)
  - Orbit roughly along the plane of the solar system
- The Oort cloud:
  - Contains trillions of comets
  - More distant than the Kuiper belt
  - Roughly spherical

Organized motion

All the planets orbit in the same plane in nearly circular orbits going in the same direction. Most rotate in the same direction, too. Why might this be?

A: Long ago all the planets were in contact with each other

B: Kepler's laws require this

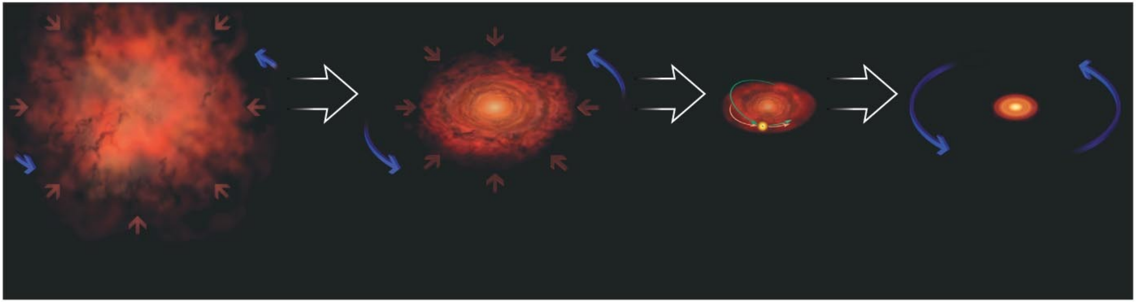
C: Over time the Sun's gravity pulls the planets into circular orbits and synchronizes their rotation

D: The planets all formed from the same chunk of the Sun that was knocked off billions of years ago

E: It's just a coincidence

Organized motion

The Solar System formed out of a cloud of gas that collapsed under its own gravity.



What should happen to its rotation as it shrinks?

A: It should slow down, because of friction between the gas

B: It should slow down, because of the mutual gravitation between the different pieces

C: It should speed up, because spinning things that shrink in size spin faster

D: It shouldn't change, because nothing is applying a twisting force to it

E: It should slow down, because spinning things that shrink in size spin slower

Angular momentum

Physics is very fond of conservation laws. We already met one: the conservation of energy.

Another conserved quantity is *angular momentum*. The angular momentum of an object is the product of:

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Another conserved quantity is *angular momentum*. The angular momentum of an object is the product of:

- Its mass, multiplied by
- ... how quickly it spins, multiplied by ...
- ... how far its mass is from its center.

Since angular momentum is conserved, it doesn't change unless an external agent applies a twist to something.

We can also get to Kepler's second law from here!

The primordial universe contained only hydrogen and helium. Where do you think the heavier elements ("metals") came from?

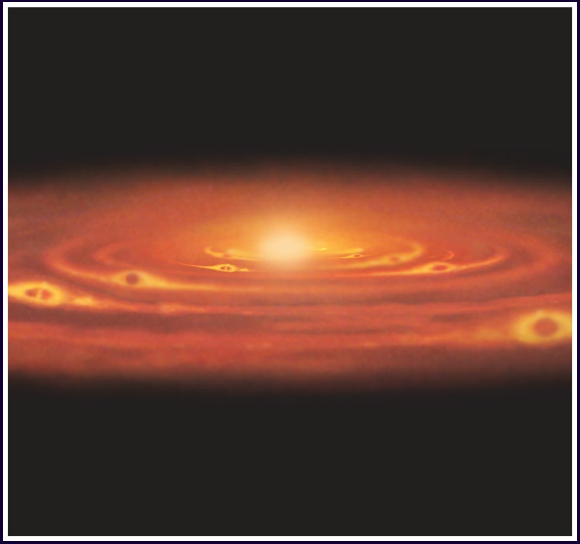
A: They're needed for life, and our solar system is special; they aren't found in other solar systems

B: All stars contain small amounts of metals

C: Nuclear fusion in the Sun builds them out of hydrogen and helium

D: Nuclear fusion in earlier stars forges heavier elements out of lighter ones; those stars have since exploded

A spinning cloud of gas



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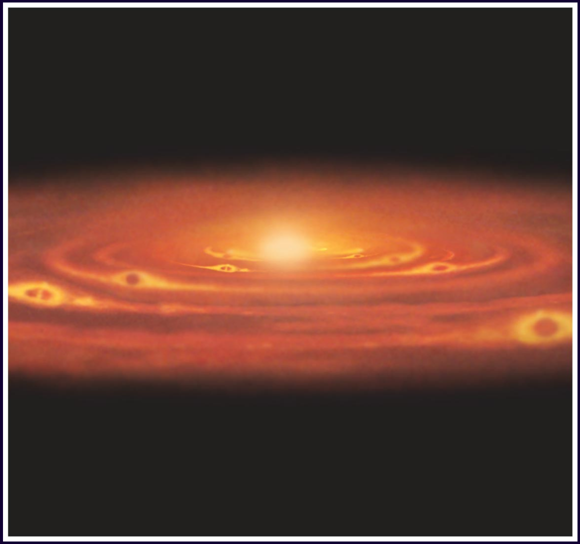
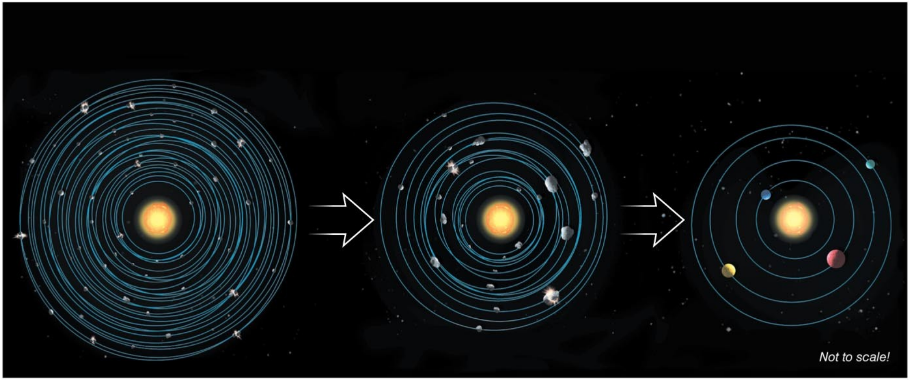


At the center, where the gas is most dense, hydrogen accumulated, until gravity was strong enough to kindle fusion. The Sun was born.

What about the planets?



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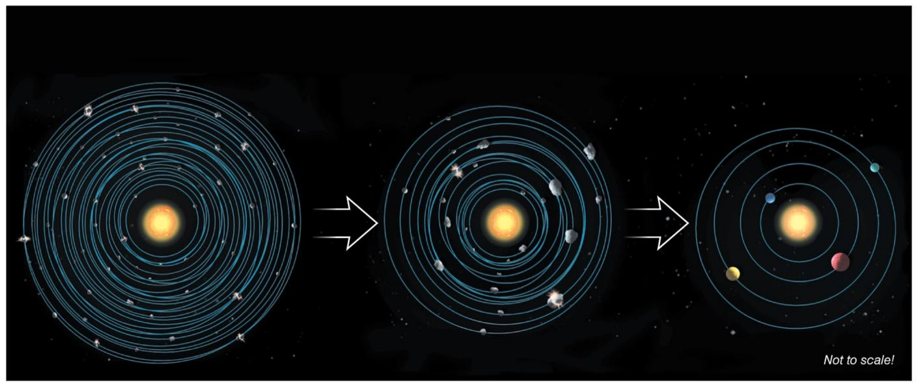


The planets condensed out of bits of dust that first formed by static electricity, then as they grew larger, by gravity.

The gas giants were large enough that they accreted a great deal of gas as well.

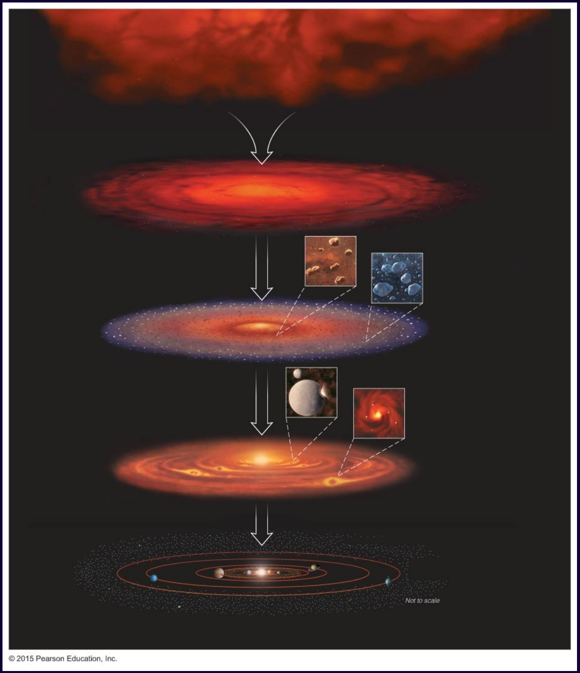
Why are there different sorts of planets?

The primordial nebula contained different constituents which condense at different temperatures:

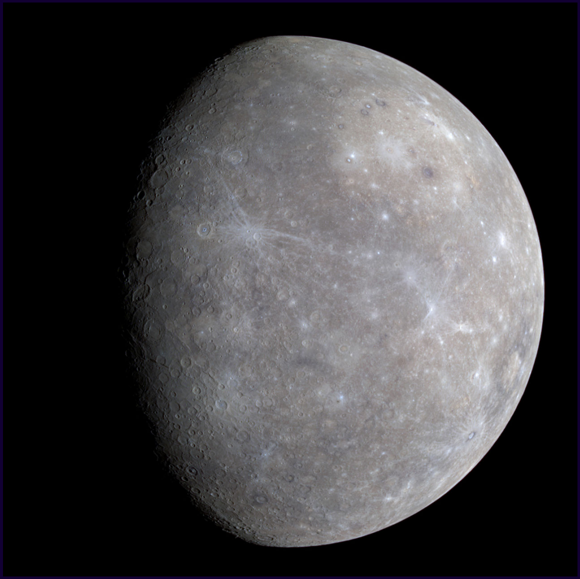
- Hydrogen and helium: never condense in the nebula (98%)
- Hydrogen compounds (water, methane, ammonia): condense at less than 150K (1.4%)
- Rocks: condense at 500-1300K (0.4%)
- Metals: condense at 1000-1600K (0.2%)

Further out it is colder, and those hydrogen compounds could condense to form the jovian ("Jupiter-like") planets.

So here we are...



Mercury, the fleet messenger god, whizzing around the Sun...



https://www.youtube.com/watch?v=CilfBWvCSXI

Agile, lively Mercury...

Mercury's surface is pockmarked with craters. This tells us:

- It clearly has been hit by asteroids.
- It didn't have an atmosphere when this happened
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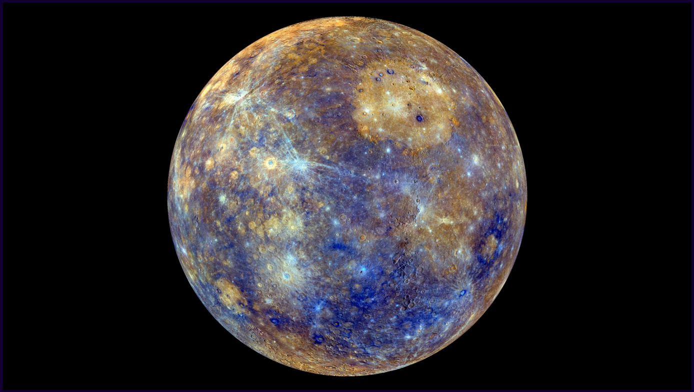
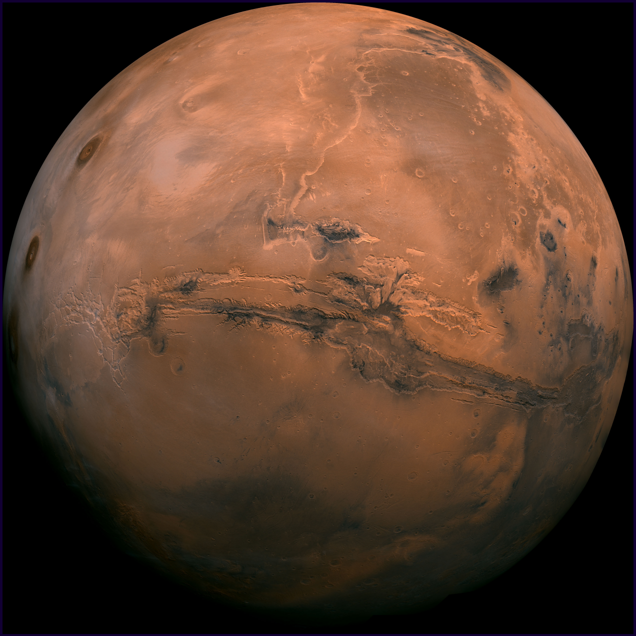


Mars, the cruel god of war...



https://www.youtube.com/watch?v=cX0anvv4plU

Bloodthirsty, violent Mars...

We've sent robots to Mars that have explored it some detail. We find:

- Rocks with rust in them, making it red
- Only a thin atmosphere, mostly CO_2
- Large volcanoes, none active
- Evidence of interior heat, but not like Earth and Venus
- Evidence that liquid water once ran on its surface
- Evidence that it once had an atmosphere of water and CO_2
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- Evidence that was once much warmer than it is today
- ... what happened?

Rusty, peaceful Mars...

- Something happened around three billion years ago
- Mars lost its atmosphere
  - Decline in interior heat $\rightarrow$ less volcanism?
  - Solar wind stripping the atmosphere away?
  - Still an area of active research
- This caused it to cool (no more greenhouse effect!)

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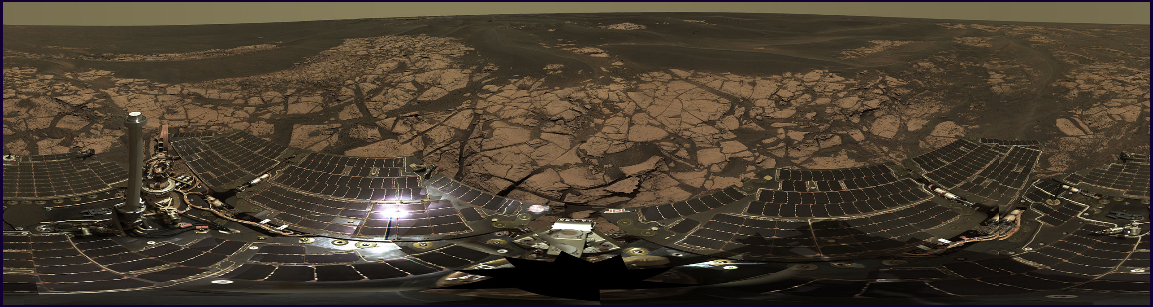
- ... and robots!

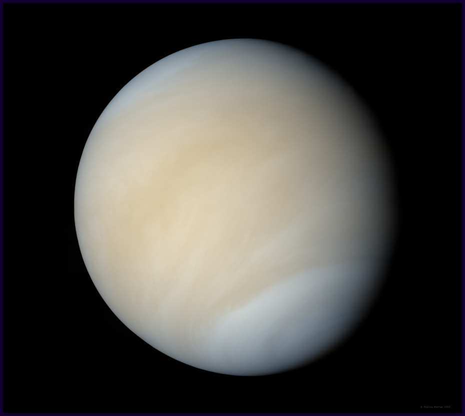
Mars, the robots' domain...

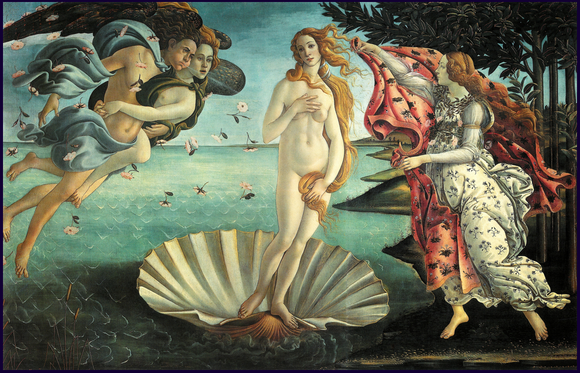
NASA sent two small rovers to Mars that landed in 2004.

- These two little robots, named *Spirit* and *Opportunity*, were supposed to last 90 sols...
- *Spirit:* stuck after 2274 Martian days (6.4 years). `https://xkcd.com/695/`
- *Opportunity:* unresponsive after a dust storm after 5,250 Martian days (14.7 years)



Venus, the goddess of love and beauty...





https://www.youtube.com/watch?v=PyBkzZoMYN4

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- The atmospheric pressure is high enough to crush bone
- ... if there is a Hell in our solar system, it is Venus. What in Hell – literally – happened?

Horrifying, poisonous Venus...

- Visible light doesn't go through this atmosphere well
- ... radar does!
- We've used radar to map the Venusian surface
- It has some interesting geology
- You can read about it in your book

Earth, cradle of life...

https://www.youtube.com/watch?v=MbHQ6eWANIo (not by Holst!)

Earth, our home...

- Active volcanism throughout its history
- Large amounts of liquid water on surface
- Stable climate: most of surface between 273 K and 373 K (freezing/boiling) for a long time
- Atmosphere with significant oxygen, nitrogen, some CO_2

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- Large amounts of liquid water on surface
- Stable climate: most of surface between 273 K and 373 K (freezing/boiling) for a long time
- Atmosphere with significant oxygen, nitrogen, some CO_2
- Surface covered by self-replicating, reactive, diverse, beautiful, *aware* machines, made of carbon compounds: *life!*
- Atmospheric oxygen from the byproducts of plant metabolism
- Hot core generates a magnetic field that shields atmosphere from solar wind

Our large Moon...

- The Moon appears to have similar composition to Earth
- ... but it lacks active geology or an atmosphere

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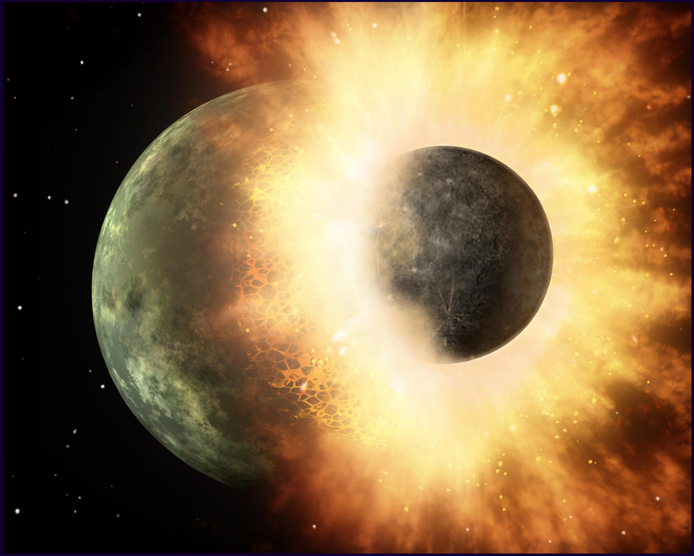
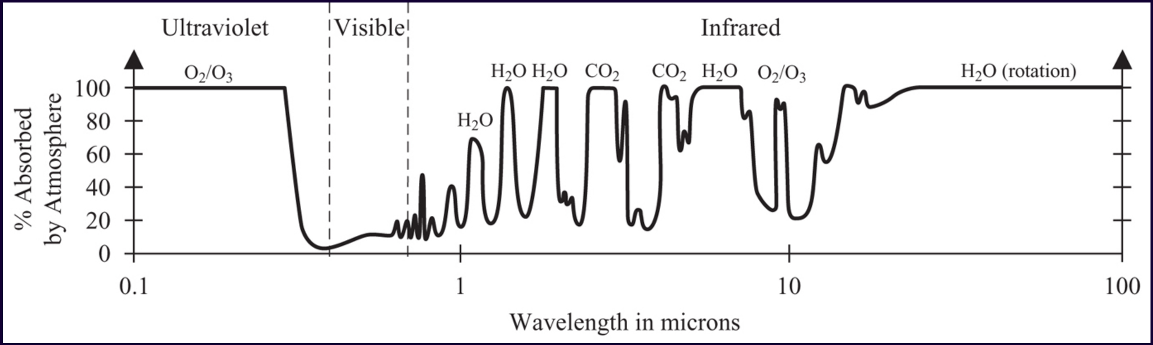
- Shortly after the formation of Earth, something the size of Mars hit us
- Some of the resulting fragments broke off and orbited the Earth
- They coalesced into the Moon



The greenhouse effect



- As you saw/will see in lab this week: planets' temperature set by radiation balance:
  - Incoming thermal radiation from Sun – visible
  - Outgoing thermal radiation from planet – infrared
- What happens if you have an atmosphere that reflects IR, but not visible light?
- The outgoing thermal radiation is greatly reduced!

This is called the *greenhouse effect.*

The greenhouse effect

Venus has a *tremendously thick* atmosphere and a powerful greenhouse effect.

- Its atmosphere contains a great deal of CO_2, which reflects IR strongly
- The thermal radiation that would carry heat away from Venus can't get out
- It is over 400 K hotter than was predicted by the calculation you are doing this week

Earth has a *thinner* atmosphere.

- Nitrogen doesn't absorb strongly at any relevant wavelengths
- H_2O and CO_2 are strong greenhouse gases, but they are only a bit of the atmosphere
- We are about 20 K warmer than predicted by that crude math
- These gases are very important for determining Earth's temperature!