The Family Portrait

- Taken on Valentine’s Day in 1990 by Voyager 1, this is a composite “family picture” of the planets and the only such image we have (Mercury and Mars are in the glare of the Sun).
And where would they all be?
Planets and Atmospheres

- **Moon**
  - Diameter: 3,476 km
  - Atmosphere: none

- **Jupiter**
  - Diameter: 142,980 km
  - Atmosphere: several thousand of km

- **Earth**
  - Diameter: 12,756 km
  - Atmosphere: more than 500 km

- **Mars**
  - Diameter: 6,794 km
  - Atmosphere: 1% of the earth's
The Inferior Planets (feat. Pluto)
Other Stars

- Sun
- Sirius
- Pollux
- Arcturus

Jupiter is about 1 pixel in size.
Earth is invisible at this scale.
Still Other Stars...

Betelgeuse

Antares

Jupiter is invisible at this scale

Sun (1 pixel)

Sirius, Pollux, Arcturus, Rigel, Aldebaran
The (Second) Largest Known Star
VY Canis Majoris – a Red Hypergiant Star in the Canis Major Constellation

The Largest Known Star
UY Scuti – a Red Hypergiant in the Scutum Constellation

Exploring the Solar System

• I hope to someday update this slide, but for now humans have been to exactly one planet.
  – This one. Earf.

• We have, however, landed probes on each of our closest two neighbors:
  – Venus – Our Sister Planet*: Venera and Vega Probes.
  – We’ve also probed Jupiter’s atmosphere (intentional crash landing), Titan, and a couple asteroids and comets.
    • And the Moon. For reals.

*Not really. Venus is our sister like a paper clip is a quarter’s sister. Same size-ish; very different.
The Venera Missions

• In 1982, Venera 13 sent back the first color photograph from Venus:
  – There had been black-and-white photos before.

http://www.space.com/images/i/000/023/794/original/venera13-left.jpg?1353363094
The Venera Missions

Color as seen on the surface of Venus

Color with atmospheric effects removed

VENERA 13

http://www.lpi.usra.edu/publications/slidesets/venus/images/03.gif
The Venera Missions

• Venera 14 sent high-res images:

http://4.bp.blogspot.com/-16bU720IepU/Ulr-U5eKm2I/AAAAAAAAcFA/kY4hn_b40k8/s1600/venera14.jpg
The Vega Crafts

• Two USSR-launched Vega crafts dispatched probes to Venus in 1985 and did flybys of Halley’s Comet in 1986.
• One of the two probes failed and did not return data.
• The other probe lasted 56 minutes and indicated pressure of 91 atm and temperature of 736 K.
  – That’s 865 °F, and the highest pressures on Earth barely get above 1 atm.
  – Fun fact: The probes also detected sulfuric, hydrochloric, and hydrofluoric acids in the atmosphere.
The Venera Missions

• So why don’t we have more pictures? How come they sent so many probes?
  – There are several answers.
• Some Venera missions outright failed.
  – A few exploded and many failed to get out of Earth’s orbit.
    • Escape velocity, anyone?
  – One even crash landed in Kecksburg, PA (near Pittsburgh), and made people think a UFO had landed.
    • Like, serious Cold War-era panic.
The Venera Missions

• Some failed to operate.
  – Notably, *Venera 12* dropped its probe arm right onto...its lens cap.
    • Oops.

• Most notable for us, however:
  – Venus’s atmosphere is 94x thicker than Earth’s, and the temperature averages 864 °F.
    • The probes pretty much got crushed. Literally.

• *UniverseToday*: What is the Hottest Planet in the Solar System?

• *UniverseToday*: Why is Venus so Horrible?

Venera 13 which is identical to Venera 12
Average Planetary Temperatures

- This should make it fairly clear why Mars is most deserving of attention when it comes to possible life elsewhere.
  - Note that these are averages, so as we’ll soon note, Mars gets quite comfortable during summer days.
Venus is a Hot Mess

• Turns out that whole atmosphere thing is a theme throughout the solar system.
• Venus also has some other quirks too:
  – Its axis has only a 2° axial tilt, virtually eliminating the possibility of seasons.
  – It rotates clockwise once every 243 Earth days (synodic day) or once every 117 Earth days (sidereal).
    • That’s a really long day, and it’s retrograde rotation.
    • The Sun rises in the West and sets in the East.
    • There is no magnetic field due to the slow rotation.
    • For comparison, a Venusian sidereal year is only 224.7 days.
    • In terms of solar days, Mercury has a longer day than year.
Martians and Venusians

- Venus represents a very different world from our second nearest neighbor, Mars.
  - FYI, we’re closer to Venus than to Mars:
    • Venus averages 0.28 AU away.
    • Mars averages 0.52 AU away.
- Venus is about our planet’s size, but Mars, despite being only half the diameter of Earth, has many similar properties to us.
Mars

We’ve sent a few probes and rovers to Mars:

– Viking 1 and 2 (1976-1982)
  • Orbiters/Landers
– Mars Pathfinder and Sojourner (1997)
  • Lander/Rover
  • Rovers
– Phoenix (2008)
  • Lander
– Curiosity (2012 – )
  • Rover

Mars as seen from Viking 2 in 1976.
Mars Surface Features

• So what have we learned from all those spacecraft?
• For one, Mars has a rather large gouge near its equator much like the Grand Canyon.
  – It’s named Valles Marineris after the *Mariner* spacecraft.
  – Earth’s Grand Canyon:
    • 500 miles long, 1 mile deep.
  – Mars’ Valles Marineris:
    • 2500 miles long, 4 miles deep.

The Martian Climate

• A big part of the interest surrounding Mars is that it’s been shown to have water on its surface.
  – Near Mars’ equator, the temperature can reach as high as 50 °F and there are features that look like riverbeds.
  – Even so, most water on Mars has been lost to space.
• Atmosphere becomes an important theme of the solar system in general, so this is where we leave our closest planetary friends behind and begin to explore the rest of the neighborhood.
  – UniverseToday: Why is Mars Red?
Evidence for Martian Water?
Aside: *Martian Canals?*

- This is Percival Lowell, a rather stately gentleman.
- Lowell learned of linear markings on Mars observed by other astronomers.
- Because he had an active imagination, he put forth the idea that there were cities on Mars and the canals (as he called the lines) were used to transport water as the resource began to become exhausted.
- Then he claimed the same thing on Venus, despite the thick atmosphere obscuring the surface.
  - No one else could confirm what he saw, even after telescopes got better.
  - What was going on?

Percival Lowell
1855-1916

http://upload.wikimedia.org/wikipedia/commons/3/3e/Percival_Lowell.jpg
Aside: Martian Canals?

• In 2002, an optometrist studying Lowell’s telescopic “setup” noticed that his equipment looked strikingly like the equipment the optometrist used to view the interior of patients’ eyes.

• Turns out, Lowell was looking at his own retina:

The Habitable Zone

• Around every star is a region known as the **habitable zone**.
  – A habitable zone is like porridge to Goldilocks – it has to be not too hot and not too cold.
  – Water needs to be *able to be* a liquid.

• The habitable zone is tuned to life as we know it on Earth and it’s very much an estimate.
  – For an example of the debate surrounding the dimensions of the habitable zone: *Earth is only just within the Sun's habitable zone* article
Atmospheres

• Recall that Earth’s gravity is sufficiently great enough to maintain an atmosphere around the planet.
  – That’s a good thing for us. An atmosphere acts as a safety net for collisions with space debris like, you know, meteoroids.

• As a result, planets with thick atmospheres (like Earth and Venus) have relatively young surfaces unscathed by too many craters.
Atmospheres

- Not all planets, however, maintain such atmospheres, and the ones that do don’t have the same molecules.
- Mercury has none, and Mars has *almost* none. And none for dear forgotten Pluto.
  - So places like Mercury and the Moon are heavily cratered and their surfaces are old.
  - Mars would have more craters, but it had water and is volcanically active.
- Jupiter, Saturn, Uranus, and Neptune have rather massive atmospheres.
The Martian Atmosphere

• In May 2015, *Curiosity* sent back images of the Martian sunset, tinted blue from the dust in the air:

[Image of Martian sunset]
Gas Giants

• Because of their enormous sizes and thick/dense atmospheres, the outer four planets are known as the **gas giants**:
  – Jupiter
  – Saturn
  – Uranus (technically an **ice giant**)
  – Neptune (technically an **ice giant**)

• We’ll start with the most imposing of the planets as we take a tour of defining features throughout the solar system.
The Titius-Bode Law oddly seems to predict the spacing of the planets.

- That each planet is twice as far from the Sun as its closer-to-the-Sun neighbor.
- It’s a weird mathematical quirk with no explanation.
Jovian versus Terrestrial

• The gas giants have very little in terms of surface.
  – A lot of atmosphere and sometimes liquid metal, but not really rock.
  – Because Jupiter is a great example of that, we call the gas giants the Jovian Planets (Jovian = Jupiter-like).

• All of them have lower densities than the inner planets.
  – Among the gas giants Saturn is the least dense (~31% less dense than even water).

• So, first a video:
  – UniverseToday – Interesting Facts About Saturn

• And then an activity:
  – Density and Composition of the Planets
Jovian versus Terrestrial

• The inner planets (Mercury through Mars) are known as **terrestrial planets**.
  – Cause they’re, you know, rocky and stuff, with a fair amount of iron.

• Earth is the densest planet in the solar system, so it packs a lot of gravity into a relatively smaller frame.
  – “I’m not massive, I’m just big-gravitied.”
Jupiter: Atmosphere

- Jupiter is by far the largest planet, able to fit all the other planets inside it, combined.
- It has no surface that is solid the way Earth’s is.
  - Instead, Jupiter has a lot of atmosphere made mostly of hydrogen and helium (much like that of a star – no surprise).
  - Pressures build to 40,000x that of Earth and temperatures reach over 63,000 °F.
- The most famous feature of Jupiter’s atmosphere is the Great Red Spot – a hurricane more than 3x the size of Earth that has been brewing since its discovery 400 years ago.
Jupiter: Great Red Spot
Neptune: Great Dark Spot

- Neptune has its own version of the Great Red Spot – appropriately called the **Great Dark Spot**.
  - It’s also a storm but is a bit more tornado-like.
  - It was first observed in 1989 but disappeared by 1994, replaced by a spot in a different location.

http://media-1.web.britannica.com/eb-media//95/4295-050-4283B41B.jpg
Planetary Atmospheres

- Mercury is too small to have an atmosphere.
- Venus has a mixture of acids and a lot of carbon dioxide.
  - You know Earth.
- Mars barely has an atmosphere.
- Jupiter and Saturn have atmospheres of mainly hydrogen and helium with just traces of methane.
- Uranus and Neptune have hydrogen and helium atmospheres too, but get their bluish colors from methane.
- Pluto is weird.
  - Its atmosphere only exists when it gets relatively close to the Sun and the heat sublimes ices into gases like $\text{N}_2$, $\text{CH}_4$, and $\text{CO}$.
  - When it’s at aphelion, its atmosphere freezes and falls back to the surface.
    - For our purposes, this doesn’t count as an atmosphere.
Jupiter: Magnetic Field

• The only thing that can be considered surface-y on Jupiter is metallic hydrogen.
  – Yes, metallic hydrogen. Freaky.
  – UniverseToday: What’s Inside Jupiter?

• Jupiter also happens to have a ridiculously strong magnetic field, which probably emanates from that metallic hydrogen “core,” which rotates quite rapidly.
  – All the planets have magnetic fields except Venus and Mars, but Mercury’s is rather weak.
What’s Inside Jupiter
According to Adler Planetarium, Chicago
Magnetospheres

• Here on Earth, the magnetosphere protects us from a constant flow of solar radiation known as the solar wind.

• Earth’s magnetic field also guides those charged solar particles into the upper parts of the atmosphere, generating the aurora borealis (Northern Lights).

• Video: Solar Wind

http://www.ucl.ac.uk/mssl/space-plasma-physics/plasma-science/aurora
http://helios.gsfc.nasa.gov/magnto.html
Aside: Southern Lights?

• The *aurora borealis* is named for the North wind.
• The Southern Lights go by a different name:
  – The *aurora australis*.
• Furthermore, colors indicate something:
  – Green is collisions with oxygen up to 150 miles up.
  – Red is collisions with oxygen above 150 miles.
  – Blue is collisions with nitrogen up to 60 miles.
  – Purple is collisions with nitrogen above 60 miles.
• Videos: *Aurora Borealis* and *ISS Earth Time-Lapse*

http://science.howstuffworks.com/nature/climate-weather/atmospheric/question471.htm
Aurora Borealis

Hydrospheres

• Here on Earth, the **hydrosphere** is the water-containing part of the planet.
  – So it’s the oceans, rivers, lakes, streams, *and* clouds/rain, *and* groundwater.

• Because of its essential role in supporting life, water has been sought out across the solar system.

• Here’s what we know about water in our neck of the galaxy...
Hydrospheres

• Planets with water besides Earth:
  – Mercury (ice in dark craters)
  – Mars (evidence at the surface, may be underground)

• Moons with water:
  – Earth (orbiters have found ice crystals and a water cycle)
  – Saturn (Enceladus, Mimas, Titan)
    • Titan also has its own atmosphere.
  – Jupiter (Europa, Callisto, and Ganymede)
  – Neptune (Triton?)

• Other Stuff: (more on this next lesson)
  – Ceres (dwarf planet in the Asteroid Belt)
  – Comets
  – Pluto?
Ring Systems

• Also containing water are the ring systems of the gas giants.

• Each one is made of small bits of debris and ice fragments orbiting the planet.
  – Remember that Jupiter, Saturn, Uranus, and Neptune all have ring systems.

http://solarsystem.nasa.gov/multimedia/gallery/9bg.jpg
Saturn’s Rings Up Close
Saturn’s Rings Up Close

Ring Systems

- As a heads-up for you, ring systems usually are divided into individual rings and identified by letters (Saturn), Greek letters (Uranus), or position/names (Jupiter/Neptune).
  - UniverseToday: Which Planets Have Rings?
  - UniverseToday: Where Did Saturn’s Rings Come From?
Volcanism

• Speaking of Mars, the Red Planet also holds the record for highest mountain in the solar system.
  — It happens to be a volcano — no surprise...

• **Olympus Mons** is an active volcano that is three times the height of Mount Everest.
Olympus Mons

http://skywalker.cochise.edu/wellerr/students/olympus-mons/project_files/image007.jpg
Olympus Mons

http://36.media.tumblr.com/dc14c0347678ecb48279ae292f45899e/tumblr_my9s7kyolD1qa0uujo1_1280.png
Volcanism

• Notice how the mountain appears to be stuck to the surface of Mars, rather than be rising out of Mars’ surface?
  – That’s because there is no tectonic activity on the planet.
  – Mount Everest was lifted up by the Indian tectonic plate slamming into the Asian plate.

• Olympus Mons erupts and makes itself bigger every time, since the land underneath doesn’t shift like on Earth.
  – Better climb it now before it gets bigger.

http://skywalker.cochise.edu/wellerr/students/olympus-mons/project_files/image007.jpg
Volcanic Activity in the Solar System

• Obviously Earth and Mars have volcanoes.
• We also can find magma volcanoes on Venus.
• But the most volcanically active place in the solar system is Io, a moon of Jupiter.
  – That’s because nearby Jupiter’s gravity causes distortions inside the core of Io, thus heating it.
  – It’s also on your textbook’s cover.

Voyager 1’s view of two volcanic eruptions on Io.

http://solarsystem.nasa.gov/multimedia/gallery/Io_Volcano-browse1.jpg
The eruption of volcano *Prometheus* as seen by the *Galileo* spacecraft.
Water Volcanoes?

- Turns out there’s even a weird combination of volcanoes and water: **ice geysers**.
  - Better known as **cryovolcanoes**.
- These weirdo water-volcanoes provide a means to get water up to the surface from underground.
  - Enceladus, a moon of Saturn, and Triton, a moon of Neptune, have prominent cryovolcanoes.
- Uranus and Neptune are thus sometimes called **ice giants**.

[Image: Ice geysers on Enceladus, feeding Saturn’s ring system.](https://solarsystem.nasa.gov/multimedia/gallery/PIA08386_full.jpg)
Enceladus Close-up

• This view of Enceladus (from Cassini-Huygens, as usual) shows a geyser field.

http://photojournal.jpl.nasa.gov/jpegMod/PIA17183_modest.jpg
On Another Note: Years*

*Sidereal Years

• Ever wonder how many years it takes other planets to revolve around the Sun once?
  – Mercury: 88 days (0.241 Earth-years)
  – Venus: 224.7 days (0.616 Earth-years)
  – Mars: 687 days (1.882 Earth-years)
  – Jupiter: 4,331 days (11.866 Earth-years)
  – Saturn: 10,747 days (29.444 Earth-years)
  – Uranus: 30,589 days (83.805 Earth-years)
  – Neptune: 59,800 days (163.836 Earth-years)
  – Pluto: 90,588 (248.186 Earth-years)
Origins

• All these planets and features beg a logical question.
  – I’ll give you a hint – it’s kinda like a question you may have asked your parents when you were younger, but this one’s much less uncomfortable.
• Where’d they come from?
• Better yet, where’d the whole solar system come from?
It begins with a cloud...

• ...4.6 billion years ago.
• It turns out that clouds between stars – interstellar clouds – are common in the galaxy.
  – They’re made of gas and tiny dust particles called interstellar grains.
• Remember, even though these things are small, they still have gravity.
  – That’s important.
Grains and Gases

• Eventually, the mixing and spinning grains and dust collapsed inward, powered by their mutual gravitational attraction.
  – “Eventually,” meaning “over a few million years.”
Grains and Gases

- This collapse formed our Sun as a bulge in the middle and the planets as a disk spinning around it – the solar system.
- We call this concept the **solar nebula theory** (or the **nebular hypothesis**) and we’ve seen it elsewhere in the universe, too.

http://www.astro.umass.edu/~myun/teaching/a100_old/images/solarnebular.jpg
Other Terminology

• That spinning disk = **protoplanetary disk**.
  – Not to be confused with a **planetary nebula** (dying star ejecta).
• That early star = **protosun**.
• The process of little particles sticking together to form large particles = **accretion**.
• Small, planet-like accretions of particles = **planetesimals**.
• Finally, how did we get two “kinds” of planets?
  – The planetesimals closest to the Sun took on rocky/iron forms (terrestrial planets) because they were hotter and iron/rocky stuff didn’t vaporize (it could condense).
  – The planetesimals farthest from the Sun also incorporated ice and took on icy/rocky/iron forms (gas and ice giants), because lighter substances could condense only in the colder outer regions.
  • **Non-Solar Differentiation - How Did the Solar System Take Shape** article
Continued Accretion

• For the outer planetesimals, there is more ice around than the particulate matter nearer to the Sun.

• As they grow ever larger, the outer planets can attract more and more of an atmosphere of their own.
  – That helps explain why they became “giants” that bear some similarity to the Sun’s composition.
  – In fact, many astronomers feel that Jupiter was on its way to becoming a star, but it never quite got enough energy.
Pause for heat.

• Jupiter’s got just short of the amount of hydrogen needed to be a star.
• It’s got a ton of mass, though it’s short in that department, too.
• What else?
  – It (and the other gas giants) gives off heat.
• Unlike Earth and the terrestrial planets, all the Jovian planets give off more heat than they absorb.
  – Cool.
    • Er, warm, I guess.
Back to Planet Formation:
Further Stages

• **Runaway accretion** occurs as planetesimals gain mass.
  – More accreted particles = more mass = more gravity =
    more accreted particles = more mass...

• **Oligarch accretion** follows, in which the biggest
  planetesimals (**oligarchs**) begin absorbing smaller
  planetesimals.

• The last phase is the **merger phase**, in which oligarchs
  disturb each others’ orbits and collide.

• **Key:** All of these collisions increase heat within the
  planetesimals, melting their cores.
  – They are now known as **protoplanets**.
Solar Nebula Theory
Summary Slide

- Spinning gas and dust particles coalesce and begin accreting into a protoplanetary disk.
- At the center of the disk is a protosun, a center of the collapse.
- Accretion rates increase until small planet-like bodies become apparent (planetesimals).
- Planetesimals grow into protoplanets after collisions melt their cores.
  - Runaway accretion followed by oligarch accretion followed by the merger phase.
Solar Nebula Theory

- Or, in one image:

http://lifeng.lamost.org/courses/astrotoday/CHAISSON/AT315/HTML/AT31502.HTM
Competing Theories

• An alternative explanation, and one that is not so generally-accepted, is **catastrophe theory**.
  – Here, stars collide and fragments formed the planets.
  – That’s kind of a rare event, so it’s unlikely to have formed the many solar systems we’ve found.

• Catastrophe theory does kinda explain the formation of our Moon, however.

• Let’s take a look at *Cosmos’s* view of both the solar nebula theory and catastrophe theory in action.
  – *Cosmos – Solar Nebula Theory and Catastrophe Theory*
Formation of the Moon

- The Moon is likely to have formed from a collision of a Mars-sized planetary body with Earth when the Earth was still early in development.
  - Ouch. That’ll leave a mark.
- The body that hit the Moon is known as Theia.
- Another view of the Moon’s formation, sans narration:
  - *The Birth of the Moon*
- Article: *How the Moon Formed – Violent Cosmic Crash Theory Gets Double Boost*
Moons

• Ever wonder how many moons there are for each of the planets/dwarf planets?
• Here’s your answer, with major moon names in (parentheses).
  – Mercury and Venus: 0.
  – Earth: 1.
  – Mars: 2 (Phobos and Deimos).
  – Uranus: 27 (Oberon, Titania, Ariel, Umbriel).
  – Pluto: 5 (Charon, Nix, Hydra, Kerberos, Styx).

“The Planet Moon…”

- Despite what Isaac Mizrahi would tell you, moons aren’t planets.
- That said, they can get rather large, like Ganymede, a moon of Jupiter, which is the biggest, or Titan, a moon of Saturn, both of which are bigger than Mercury.
“The Planet Moon…”

- In the other direction, the largest moon relative to its host planet is the, you guessed it, Pluto’s moon Charon:
Hi-Res View of Charon
via New Horizons, 2015

http://www.nasa.gov
How to Pronounce “Charon”

• Sometimes it’s pronounced like “Karen,” sometimes it’s pronounced like “Sharon.”
• Which one is correct?
  – Both!
    • Really, Here’s How You Pronounce Charon – Probably article
    • A bump in the night article
• Charon (“Karen” or “Gheghron”) is the mythological ferryman of the newly dead across the rivers Styx and Acheron.
• Charlene is the name of Charon’s discover Jim Christy’s wife, so he made a fun choice.
• Or maybe not...here’s a depiction of Charon:
End-Stage Planetary Formation

• Think of the formation of the solar system like a season of professional ice hockey.
  – There may be a little violence here or there throughout the early stages of the season (formation).
  – However, the real action happens when you get rid of all the lesser teams (smaller planetesimals) and it becomes a competition of only the best (biggest) teams (planets).
End-Stage Planetary Formation

• What I mean by this is that if you look at the timeline of solar system formation, you see lots of tiny collisions early on...
• ...followed by the buildup of large bodies...
• ...followed by massive collisions later on as the gravity of large protoplanets bring them together. Thus:
  – The formation of many moons.
  – The tilt of Uranus.
  – The relative lack of crust on Mercury.
  – The buildup of asteroids and comets (see next lesson).
Planets Beyond Our Solar System

• Are we the only system of planets orbiting a star?
  – For a long time, the answer had to be yes.

• Starting in the 1990s, however, astronomers started discovering all kinds of **extrasolar planets**, also known as **exoplanets**.
  – *New exoplanet in our neighborhood* article
  – *Journey to a Star* video
  – These are typically planets orbiting a star other than our Sun, but may refer to planets *not* orbiting a star.

• Discovering them, as you may remember a grunting, tennis-playing astronomer told you, requires a bit of indirect detection.
Exoplanet Detection Methods

*Good to Know*

- **Astrometric Detection**
  - Spotting a “wobble” in the star being orbited due to gravity.

- **Radial Velocity (most common means)**
  - Spotting a change in light wavelength coming from a star due to the movement of the star being orbited – a visual Doppler Effect.
  - *Extrasolar Planets Interactive*
  - *Doppler Shift Interactive*
Exoplanet Detection Methods

*Good to Know*

- **Transit (least common means)**
  - Seeing the light from a star being orbited dim periodically with the passing of a planet in front of it.

- **Microlensing**
  - The visual of a star is warped by the gravity of an object in its way.
    - A little like how the corner of a fish tank distorts the image of 1 fish into 2.
  - *Gravitational Lensing Interactive*
Planets That Are Detected

• As you might guess, these detection methods are a bit biased toward large planets.

• In this context, you’ll often hear the term, “Jupiters,” which is a generic term for large planets (not necessarily with the properties of Jupiter, though).

• In some cases, you’ll also hear of “hot Jupiters,” which are Jupiters close to their parent stars, thus, hot.

  – Our Jupiter? Not that hot. Saturn can do better.
Problems with Hot Jupiters

• Turns out, hot Jupiters are quite unexpected.
• In other words, there shouldn’t be big planets that close.
  – It’s a product of the physics of the nebular hypothesis – remember that?
• According to the solar nebula theory, massive planets should be very far from their stars.
The Elephant in the Room

• At some point we need to discuss Pluto.
  – Might as well get it over with.
    • “Pluto, why don’t you have a seat? We need to talk.”
• Pluto has a lot of odd characteristics for being a member of our solar system.
  – Its orbit is tilted.
  – Its moons are big enough that it wobbles noticeably.
  – There’s a lot of junk in its tru– I mean, neighborhood.
    • UniverseToday – Why Pluto is Not a Planet
Pluto’s Neighborhood is Crowded

[Diagram showing Pluto and its neighbors, labeled as Pluto, Haumea, and Eris, with a path marked as 'New Horizons’ Path']. 
Dwarf Planets

• Since 2006, we’ve classified Pluto as a **dwarf planet**.
• Other dwarf planets in our solar system include Ceres, Eris, Haumea, and Makemake.
  – *And Sleepy, Bashful, Dopey...*
• Ceres is by far the closest to us, located between Mars and Jupiter.
  – The rest are out past Neptune.
• Eris is the only one bigger than Pluto in mass (not volume) and it also has a moon (Dysnomia).
  – Fun fact: Eris takes 557 years to make a trip around the Sun.
    • Endless summer, anyone?
What’s a planet, anyway?

• After all of this, you may have noticed I never defined what a planet is in the first place.

• A **planet**:
  – Orbits the Sun (that eliminates moons).
  – Is round in shape (that eliminates asteroids and comets).
  – Has cleared its neighborhood of smaller objects (again eliminating asteroids, comets, ...and Pluto).

• A **plutoid** is a dwarf planet outside Neptune’s orbit (so not Ceres).
Dwarf Planets

• We ended last lesson by talking a lot about Pluto.
  – *Lest we forget*…

• And one of the major arguments against Pluto’s planetary status is that there’s a lot of other stuff out there with it, making Pluto not so unique.
  – *If everyone’s special, then no one is*…
Dwarf Planets

- Among lots of smaller debris, which we’ll discuss in a few moments, Pluto is joined by a few other **dwarf planets**, a term I first used last lesson.
  - Dwarf planets are essentially very large **asteroids** – also a term we’ll get to – but don’t quite meet the requirements of being a planet.
  - Reminder: Planets need to be rounded by gravity, orbiting the Sun, and clear of any massive neighbors in their orbit paths.
Dwarf Planets

• There are five dwarf planets out there you should know, ranked from smallest mass to largest:
  – Ceres (discovered 1801 by Giuseppe Piazzi)
    • The only one located within Neptune’s orbit (in the asteroid belt between Mars and Jupiter).
  – Makemake (discovered 2005 by Mike Brown)
    • It’s also got a moon – MK 2.
  – Haumea (discovered 2004 by Mike Brown)
    • It’s got two moons – Namaka and Hi’iaka.
  – Pluto (discovered 1930 by Clyde Tombaugh)
    • Moons: Charon, Nix, Hydra, Kerberos, Styx.
  – Eris (discovered 2005 by Mike Brown)
    • The only one bigger than Pluto.
    • It’s also got a moon – Dysnomia.
Dwarf Planets

In 2006, the organization responsible for classifying celestial bodies, the International Astronomical Union (IAU) decided that a new class of objects was needed. Pluto, considered a planet since its discovery in 1930, was reclassified into the new "dwarf planet" category. To date, five dwarf planets have been found, although some astronomers expect there may be as many as 50 in the solar system.

<table>
<thead>
<tr>
<th>Dwarf Planet</th>
<th>Year of Discovery</th>
<th>Diameter (mean)</th>
<th>Orbital Period (Earth years)</th>
<th>Distance from Sun (times Earth's Distance)</th>
<th>Orbital Inclination (degrees)</th>
<th>Rotation Period</th>
<th>Moons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eris</td>
<td>2005</td>
<td>1,445 miles 2,326 km</td>
<td>561.4</td>
<td>68</td>
<td>46.9</td>
<td>25.9 hours</td>
<td>1</td>
</tr>
<tr>
<td>Pluto</td>
<td>1930</td>
<td>1,430 miles 2,302 km</td>
<td>247.9</td>
<td>39.5</td>
<td>17.14</td>
<td>6.39 Earth days</td>
<td>5</td>
</tr>
<tr>
<td>Haumea</td>
<td>2003</td>
<td>892.3 miles 1,436 km</td>
<td>281.9</td>
<td>43.1</td>
<td>28.2</td>
<td>3.9 hours</td>
<td>2</td>
</tr>
<tr>
<td>Makemake</td>
<td>2005</td>
<td>882 miles 1,420 km</td>
<td>305.34</td>
<td>45.3</td>
<td>29</td>
<td>22.5 hours</td>
<td>0</td>
</tr>
<tr>
<td>Ceres</td>
<td>1801</td>
<td>591.8 miles 952.4 km</td>
<td>4.6</td>
<td>2.8</td>
<td>10.59</td>
<td>9.1 hours</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: NASA

http://i.space.com/images/i/000/023/868/i02/dwarf-planets-121120b-02.jpg?1353517196
Surrounding our solar system like a...uh...belt...is the **Kuiper Belt**, named for one of its “proposers,” Gerard Kuiper.

- Technically, he suggested it didn’t exist.

It should be noted that Kenneth Edgeworth *independently* proposed the same thing at the same time.

- Perhaps it should have been called the “Edgeworth Edge.”

Also notable is that Fred Leonard may have proposed the same thing about 10 years before these other two.

- The “Leonard Line?”

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http://mail.colonial.net/~hkaiter/aa_newest_images/edgeworth.jpg
http://www.windows2universe.org/people/images/kuiper.gif
Kuiper Belt

- As you can see, the Kuiper Belt is a flat disc at the edge of the solar system, filled with debris:

http://scienceblogs.comstartswithabang/files/2013/10/Kuiperbelt-1.jpg
Kuiper Belt

- Notice from the image that the Kuiper Belt is relatively flat, like the rest of the solar system.
- Also notice that Pluto’s orbit takes it kinda over and under the Kuiper Belt, but certainly out far enough.
- Pluto and other objects out there are known as Kuiper Belt objects (KBOs) or trans-Neptunian objects (TNOs).
- Despite being really friggin’ far away (“really friggin’” = 30-50 AU), the Kuiper Belt has immediate effects on life on Earth.
  - Like, giant space rock to the face, immediate.
Kuiper Belt

- Gravitational attraction on the part of the outer planets (gas giants) can sometimes fling an asteroid or comet our way.
  - They may also be flung further out into space.
Some Trans-Neptunian Objects

Largest known trans-Neptunian objects (TNOs)

- Pluto
- Eris
- Makemake
- Haumea
- Sedna
- 2007 OR₁₀
- Quaoar
- Vanth
- Orcus

https://upload.wikimedia.org/wikipedia/commons/9/91/EightTNOs.png
Oort Cloud

- Named for Jan Oort, the **Oort Cloud** is a shell of icy objects orbiting very far from the Sun.
- Like the Kuiper Belt, gravitational interactions can occasionally sling an icy rock toward the inner solar system.
  - Usually these effects are driven by other stars or passing nebulae instead of by planets, though.


Jan Oort
1900-1992
Oort Cloud

• There are two main differences between the Oort Cloud and the Kuiper Belt:
  – The Oort Cloud is **much** farther away.
    • Kuiper Belt = 30-50 AU.
    • Oort Cloud = 10,000-100,000 AU.
  – The Kuiper Belt is flat; the Oort Cloud is like a spherical shell.
    • Much like the celestial sphere.

• *Those are good to know.*
Dodgin’ Space Rocks

• Either region may send something our way, and there are three main classes of space objects that may be directed on a collision course toward us:
  – Asteroids
  – Meteoroids
  – Comets

• They each have their own details, so let’s explore them.
Asteroids

• As we saw in a video a little while ago, astronomers in the 1800s starting discovering what they thought was a whole raft of planets in between Mars and Jupiter.

• Today, we know them to be **asteroids** orbiting the Sun in the **Asteroid Belt**.
  – The root word “aster-” means “star,” since early astronomers couldn’t tell the difference (they’re small).

• There are occasionally asteroids spotted elsewhere in the solar system but the belt is the most common place.
  – Seriously, there are around 1.1-1.9 million asteroids greater than 1 km in diameter, and millions more that are smaller than that.

https://solarsystem.nasa.gov/planets/profile.cfm?Object=Asteroids&Display=OverviewLong
Asteroids in the Solar System

• Below is NASA’s diagram of NEAs (near-Earth asteroids) and PHAs (potentially hazardous asteroids).
  — Yikes.

https://solarsystem.nasa.gov/multimedia/gallery/PHA.jpg
Asteroid Size, Types, and Companions

• Asteroids are leftovers from the formation of the solar system.
• Ceres (dwarf planet) is the largest of the asteroids at 950 km in diameter (590 mi).
• The smallest are under 1 km (0.6 mi).
  – Combined, all their mass is less than the Moon, and Ceres is 1/3 of it.
• Speaking of moons, some have them, as seen at the right.
• They’re very widely spaced out (1-3 million km average).

NASA’s Dawn spacecraft’s view of Vesta, one of the largest asteroids.

NASA’s Galileo spacecraft’s view of 243 Ida and its moon Dactyl.
Asteroid Size, Types, and Companions

- There are three *main* types of asteroids*:
  - **C-type asteroids** (chondrite) are made of carbon-based stuff (clay and silicates).
    - They’re dark colored.
  - **S-type asteroids** (stony) are made of silicates and nickel-iron.
  - **M-type asteroids** (metallic) are made of nickel and iron.
- Each discovered asteroid is individually named and, among others, there are funny ones out there (like Mr. Spock) or tributes (like Annefrank).
  - [http://www.minorplanetcenter.net/iau/lists/MPNames.html](http://www.minorplanetcenter.net/iau/lists/MPNames.html)

*Depends on whom you ask. This stuff is hard to categorize.*
Asteroid Types

Different Asteroid & Meteorite Types

Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html

Chondritic Stony Meteorite
Iron Meteorite
Pallasite Meteorite
Achondritic Stony Meteorite

Asteroid Type C
Asteroid Type M
Asteroid Type S

License: Wikimedia Creative Commons
Other Asteroid Locations

• Like I said earlier, the majority of asteroids are in the asteroid belt.
• There are, however, a few other regions of concentrated asteroids.
  – Trojans
  – Hildas
  – Apollo asteroids
  – Near-Earth asteroids
• Let’s take a look...

Trojan Asteroids

- The Trojan asteroids orbit just ahead of, and just behind, the orbit of Jupiter.
  - The Sun and Jupiter’s pulls combine to keep them in place.
- The locations of the Trojan asteroid swarms are known as the $L_4$ (ahead) and $L_5$ (behind) Lagrangian Points.
  - The points are 60° ahead/behind.
- FYI, the Jupiter Trojans are best-known, but Mars and Neptune have Trojans, too.

http://ase.tufts.edu/cosmos/pictures/Chapter13/Fig13_1.jpg
The Earth Trojan?

- In 2011, NASA announced the discovery of a single Earth Trojan asteroid.
  - You read that right.
- Earth’s Trojan has the incredibly sexy name of 2010 TK7 and is only about 1 km in diameter.

Hildas

• The **Hildas** are one of many other asteroid families out there.

• They exist in a 3:2 orbital resonance with Jupiter, which means they orbit three times for every two orbits of Jupiter and keeps them in their own gravitational lock.
Apollo Asteroids

- The **Apollo asteroids** are the scary ones.
  - They’re the ones that pass across Earth’s orbit, but there are only about 700 of them and are typically under 1 km in diameter.
    - Still, they hit the Earth once every 10,000 years on average.
- They may be dead comets.

http://astronomy.swin.edu.au/cosmos/a/apollo+asteroids
Near-Earth Asteroids

• Remember a few slides ago when I showed you NASA’s visualization of NEAs and PHAs?
  – The one up there in the corner?
• The Apollo asteroids are just the largest of a few groups of NEAs and one of two groups of Earth-crossing asteroids.
• There are also the Atens and the Amors, along with IEOs (Inner Earth Objects) that don’t cross Earth’s orbit.
Other Space Debris

• So if those are all asteroids, what are meteoroids?
• Asteroids are generally larger than meteoroids.
  – A large meteoroid could be considered a small asteroid.
  – A large asteroid could be considered a small planet.
• In contrast, meteors are asteroids or meteoroids that burn up in Earth’s atmosphere.
  – Known to many as “shooting stars,” though if they were actually star-sized they’d be “shooting to kill.”
• Fun fact: if a meteor explodes in the atmosphere it’s called a bolide.
And what about meteorites?

- If one of those space rocks should make it through the atmosphere and land on Earth’s surface, however small, it’s known as a meteorite.
  - So, 65 million years ago, an asteroid (because it was so big) became a meteor before it became a meteorite and wiped out the last of the dinosaurs.

- Want to collect your own meteorites?
  - Evidence suggests that microscopic meteorites can be “harvested” with a magnet in a rain gutter over several weeks.
Meteors and Meteoroids of Note

• On February 15, 2013, a superbolide (big fiery meteor that blows up) entered the atmosphere over Russia and exploded about 18.4 miles up.
  – It became known as the Chelyabinsk meteor.
• The light was brighter than the Sun and those that were close enough could feel heat from the blast.
• 1500 people were injured from effects of the blast (mainly broken/flying glass).
• Thankfully, no one was killed and the incident was caught on a large number of cameras.
  – Chelyabinsk Meteor – February 15 2013 video
The Tunguska Event

• The Chelyabinsk meteor was only around 20 m (100 ft) in diameter, but it weighed more than the Eiffel Tower.

• Bigger still was an explosion in 1908 by something suspected to be either a comet or asteroid, known as the Tunguska event.
  – It landed in Siberia and cleared an entire forest with a blast estimated at 1000x the energy of the atomic bomb dropped on Hiroshima.
Meteor Showers

• Throughout the year, regions of Earth are treated to a sometimes-astounding light show known as a meteor shower:

The Geminid meteor shower
Meteor Showers

• Meteor showers are named for their apparent constellation of origin:
  – The Perseids (August) come from…?  
    • Perseus, and that’s the biggest one.
  – The Leonids (November) come from…?  
    • Leo.
  – The Geminids (December) come from…?  
    • Sagittarius.
    • Just kidding. It’s Gemini.

• But they don’t actually come from the constellation, so what causes them?
Meteor Showers

- The majority of meteor showers are triggered by comets.
  - As we’ll see in a few slides, comets shed a bunch of debris into which Earth may then pass.
  - Dates are predictable and they’re viewable with the naked eye, so have yourself a nighttime meteor picnic if you want:
    - [http://stardate.org/nightsky/meteors](http://stardate.org/nightsky/meteors)

- And this all provides a great segue into the next topic, comets.
Comet Orbits

• Comets fit into two different classes:
  – **Short-period comets** take less than 200 years to orbit the Sun and come from the Kuiper Belt.
    • Because they come from the relatively flat Kuiper Belt, short-period comets orbit in a plane similar to that of the solar system.
  – **Long-period comets** take more than 200 years to orbit the Sun and come from the Oort Cloud.
    • Because they come from the spherical Oort Cloud, long-period comets orbit on random planes.
Kuiper Belt Comet Orbits

Short Period

https://www.awesomestories.com/images/user/bb9048c84ec9fef6bd1f57920ae6db66.jpg
Oort Cloud Comet Orbits
Long Period

http://lcogt.net/files/styles/twocol/public/sroberts/orbits_Jon.jpg?itok=akVpsVom
Comet Structure

• First off, the “core” of the comet is known as its **nucleus**.
  – It’s made of ice, dust, and frozen gases and is usually around 10 km in diameter.
  – It’s also generally very dark, giving it the common name “**dirty snowball**,” but recent evidence suggests it’s more of an “**icy dirtball**.”

• Immediately around the nucleus is the **coma**, which is a cloud of gas...but that’s about it.
  – Possibly up to 100,000 km in diameter, but very little actual mass.
Comet Structure

- Surrounding and much, much larger than the coma is the **hydrogen envelope**, which is invisible and slightly irregularly-shaped due to the **solar wind**.
- And then, of course, there are the **tails**.
  - Yes, tails. More than one.

http://pages.uoregon.edu/jimbrau/BraulmNew/Chap14/7th/AT_7e_Figure_14_08a.jpg
Comet Tails

• Comets generally have two tails:
  – The **dust tail** is **usually curved** and generally faces directly away from the Sun.
    • It comes from sunlight pushing dust particles off the comet in a form of sublimation.
    • *Sublimation demo!*
  – The **ion tail** is **usually straight** and faces directly away from the Sun.
    • It comes from solar wind radiation that ionizes (charges) gases in the coma, so it often gives off its own light.
Comet Tails

• In both cases, the tails become larger when the comet is closer to the Sun.
  – The tails may even grow to be close to an astronomical unit in length, which is, you know, kinda big.

• The tails may be absent at perihelion.

http://www.tivas.org.uk/solsys/images/comet_hale-bopp.jpg

Comet Hale-Bopp in 1997.
Comet Tails

http://www.newtonsapple.org.uk/comet-bart-simpson/
Comet Tails

http://www.newtonsapple.org.uk/comet-bart-simpson/
Comets
Comets of Note

- [comet etymology]
- Comet 67P/Churyumov-Gerasimenko
- Halley’s Comet
- Shoemaker-Levy 9
- Hale-Bopp
Aside: Comet Etymology

• Historically, comets were associated with bad things:
  – Famine.
  – War.
  – Death of rulers. (you get the idea)
• The “bad star” is so strongly associated with disaster that we actually get the word disaster from it.
  – “Dis-” = bad.
  – “-aster” = star.
Comet 67P/Churyumov-Gerasimenko

- In 2014, the European Space Agency (ESA) successfully landed a probe on the surface of a comet.
  - Like, whoa.
- Let’s talk about the comet first, then a little about the probe.
- The comet is called Churyumov-Gerasimenko (or, boringly, 67P), and while you may think of it as probably very small, it’s not.
Scale of Churyumov-Gerasimenko

http://d1jqu7g1y74ds1.cloudfront.net/wp-content/uploads/2014/08/67P-LA-anosmicovni-credit-BEST.jpg
That said, comets generally have low escape velocities.
  - You could jump off comets.
  - That’s why tails “leak” material.

As a result, when the *Rosetta* orbiter deployed the *Philae* lander, the lander bounced several times before landing, failing to harpoon the comet to hold itself in place.
  - *Philae* is now on its side and out of power.
  - It should be able to recharge if sunlight hits it at the right angle.
Churyumov-Gerasimenko from *Rosetta*

Halley’s Comet

- Halley’s comet has a 75-76 year orbital period and last appeared in 1986 (good year).
  - It’s named for Edmond Halley, who concluded that a comet seen in 1531, 1607, and 1682 was actually the same one.
  - He predicted it would again appear in 1758 and was right, though he died before it returned.
- Remember him? He also observed the movements of the star Arcturus and concluded that the stars move.

Edmond Halley (1656-1742)