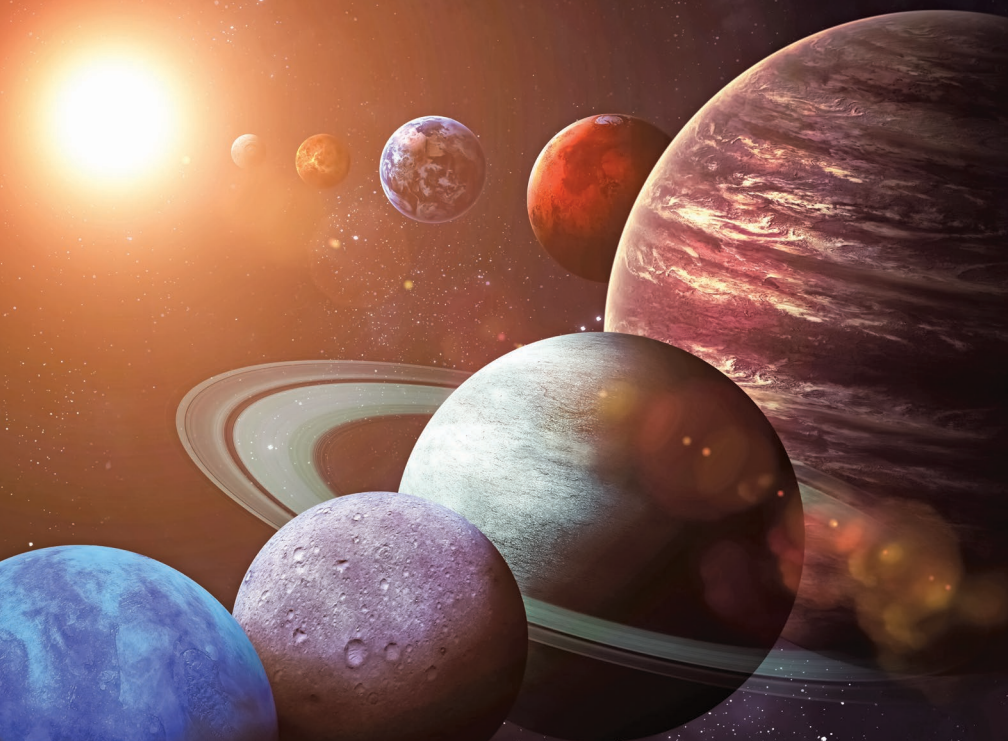


A Field Guide to the Planets

Course Guidebook

Professor Sabine Stanley
Johns Hopkins University



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SABINE STANLEY, PHD

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Sabine Stanley is a Bloomberg Distinguished Professor in the Morton K. Blaustein Department of Earth and Planetary Sciences at Johns Hopkins University. She received a HBS degree in Physics and Astronomy from the University of Toronto and then completed MA and PhD degrees in Geophysics from Harvard University. Prior to joining Johns Hopkins, Professor Stanley was a postdoctoral researcher at the Massachusetts Institute of Technology and a professor at the University of Toronto. At Johns Hopkins, she also holds appointments in the Henry A. Rowland Department of Physics and Astronomy, the Applied Physics Laboratory's Space Exploration Sector, and the Hopkins Extreme Materials Institute.

Professor Stanley has received several honors and awards for both her research and teaching. Her research honors include the American Geophysical Union's William Gilbert Award for her major theoretical contributions to the study of planetary magnetism, a Sloan Research Fellowship as an early career scientist of outstanding promise, and a Canada Research Chair. Her teaching awards include the Ranjini Ghosh Excellence in Teaching Award and the Dean's Outstanding Teaching Award, both from the University of Toronto.

Professor Stanley's research involves investigations of planetary interior processes and evolution. She focuses on studying planetary magnetic fields and uses high-performance computing to study the dynamo process, in which convection in electrically conducting fluid regions inside planets generate self-sustaining magnetic fields. Professor Stanley's research includes studies of the magnetic fields of Earth, Mercury, Mars, Saturn, Uranus, Neptune, and exoplanets. She is also a coinvestigator on NASA's Mars InSight mission.

In addition to her research work, Professor Stanley has written articles for *Bloomberg View* and *Eos*. She has also appeared several times on Canada's CBC Radio show *Quirks & Quarks*. Professor Stanley has served as the editor of the *Journal of Geophysical Research: Planets* and has chaired the Women in Physics Canada Conference. She also tweets about science and life as a scientist as @PlanetSabine.

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NAVIGATION TIP

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On a tablet, use the bookmarks panel.

A Field Guide to the Planets

This course provides a tour of all the planets and other smaller planetary objects in our solar system and beyond. If you were suddenly transported to Mars, what would you experience? What's it like to float through Saturn's rings? Through experiential examples, you'll discover the wonders of our solar system while also learning about the planetary science behind these wonders.

The tour involves trips to all the planets in the solar system, from Mercury to Neptune. What are the differences between worlds that are close to the Sun and those that are far from the Sun? Why do planets have the surface features they do? How were planets different in the past? Why are planets' atmospheres so different? The course ventures through the atmospheres, over the surfaces, and deep into the interiors of the rocky and giant planets in our solar system to answer these questions.

But you'll visit more than just planets. You'll travel to the asteroid belt between Mars and Jupiter; to the extensive moon systems of the giant planets; to the Kuiper belt, home of Pluto and other dwarf planets; and to comets coming from the far reaches of the solar system. You'll also investigate the influence of the Sun in defining and shaping what we call the solar system—from gravity, to beneficial heat and light, to hazardous radiation and high-energy particles.

You'll also examine the origins and evolution of our solar system, so you'll also venture backward in time, to the era when our solar system was just forming, to see how the system we take for granted all began.

You'll also travel to so-called exoplanets—the planets that orbit other stars—where there are worlds that are vastly different from those in our own solar system as well as some solar system analogs. Have we found Earth 2.0? Lessons from exoplanets will have us rethink our understanding of how our own solar system formed and lead us to explore a solar system conundrum known as the late heavy bombardment, when the number of impactors in the early solar system increased 1000-fold some 500 million years after the solar system “finished” forming.

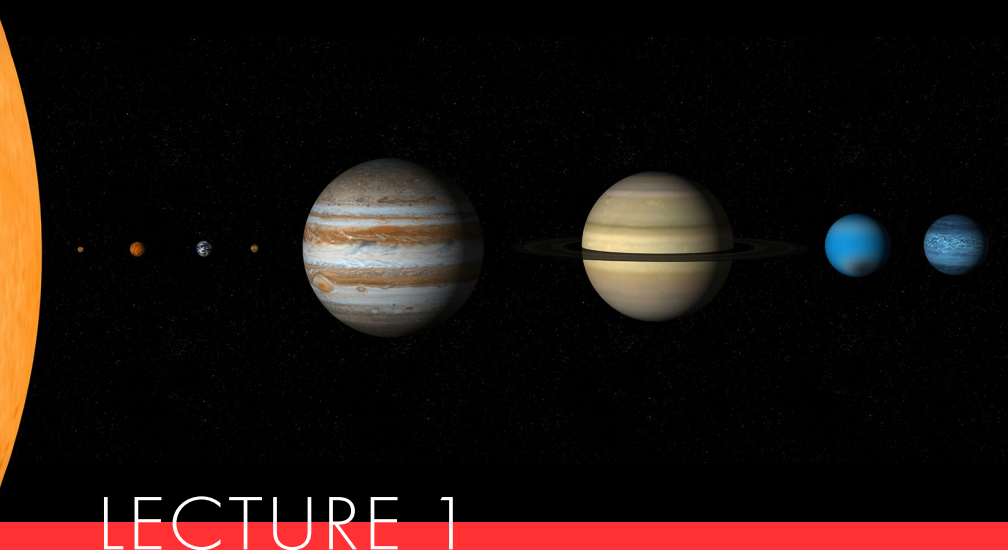
There are some common themes throughout the lectures in this course:

- 1** Water seems to be ubiquitous in the solar system, appearing on world surfaces, like Earth, as well as in the deep interiors of Uranus and Neptune and in the permanently shadowed craters of Mercury and the Moon.
- 2** How planets cool affects their surface and atmospheric features. Volcanoes, canyons, earthquakes, magnetic fields, and giant storms are all related to the fact that planetary bodies are cooling to space.
- 3** Collisions shape the planets. Giant collisions are responsible for everything from the formation of the planets, to Earth's large Moon, to impact craters strewn over planetary surfaces. They are also responsible for bringing water to Earth and may be responsible for the axial tilts of some of the planets.

In this course, you'll explore some of the surprising, even bizarre, features of our solar system, such as pancake volcanoes on Venus, a giant hexagonal storm on Saturn, and the icy "heart" on Pluto. And you'll discover why the Sun sometimes changes direction in Mercury's sky, why we always see the same side of the Moon from Earth, and why Neptune and Pluto never collide even though their orbits cross.

In addition to exploring the features found on planetary bodies, you'll also learn about the fundamental physical, chemical, and geological processes that are responsible for generating the observed features. These lessons will be scientifically detailed but accessible to nonexperts. No previous expertise in math, physics, chemistry, or geology is needed, but important principles in these fields will be taught when they are relevant.

Throughout this course, lectures incorporate the latest discoveries from planetary spacecraft missions. You'll rove over Mars with the Curiosity rover, explore the moons of Saturn with the Cassini mission, and even reach interstellar space with Voyagers I and II. In the end, you'll focus on the next big ideas for exploring and understanding our solar system by considering the future of spacecraft propulsion, the potential terraforming of Mars, and the exploration of subsurface oceans in outer solar system moons to look for life.



LECTURE 1

How the Solar System Family Is Organized



There are 8 planets that orbit the Sun at distances ranging from 40% of Earth's distance to 30 times Earth's distance. Then there are dwarf planets, such as Pluto, that are in orbit around the Sun and comets, whose orbits take them close to the Sun. The solar system also contains moons—more than 200 in total—that orbit planets and even some dwarf planets and asteroids.

Spacecraft have explored every planet in the solar system and have visited smaller bodies, such as moons, asteroids, and comets. Earth has been studied from space and compared with all the other worlds in our solar system; all of these missions together have made it possible to assemble a field guide to the planets and other bodies of our solar system.

ORGANIZING THE SOLAR SYSTEM

- + Our solar system is enormous, and the Sun is pretty much at the center of it, at a distance of 150 million km, or 93 million mi, from Earth. The Sun has a diameter of almost 1.4 million km, or 870,000 mi, which is 1% of the distance between Earth and the Sun—in other words, Earth is roughly 100 Suns away from the Sun! The Sun's diameter is more than 100 times bigger than Earth. In terms of Earth's diameter, the distance from Earth to the Sun is roughly 10,000 Earths. The Sun also makes up 99.8% of the solar system's mass; everything else in the solar system is a tiny ant trying to stay out of the Sun's way.
- + The solar system is typically separated into inner and outer regions based on the type of planet found in each. The inner region of the solar system contains 4 planets: Mercury, Venus, Earth, and Mars. They are all extremely small compared to the Sun. Earth is the largest inner planet, and Venus is almost as large, while Mars is only 50% of Earth's diameter, and Mercury is only 40% of it. These inner planets are called terrestrial planets. They are primarily composed of 2 types of materials: rocks (like what forms from cooling lava or sediments of sand) and metals (mostly iron).
- + The outer solar system contains 4 giant planets: Jupiter, Saturn, Uranus, and Neptune. Jupiter is the biggest of all the planets, and it's more massive than all the other planets combined. The giant planets are not only much bigger than the terrestrial planets, but what they are primarily made of is also quite different.
- + The 2 innermost giant planets, Jupiter and Saturn, are gas giant planets. This means they are primarily made of hydrogen and helium—not just in the atmosphere, but deep into the planet as well.

✦ The outermost planets, Uranus and Neptune, are often called ice giants because they are primarily composed of ices. They each have vastly more water locked away than is found on Earth.

In planetary science, the category called ices refers not only to water, but also to ammonia, methane, and other materials that are volatile because they have low temperatures for melting and evaporation. Moreover, while these ice materials might be solid, they can also be liquid or gaseous.

✦ **So there appears to be an organized architecture to the solar system.** Terrestrial planets,

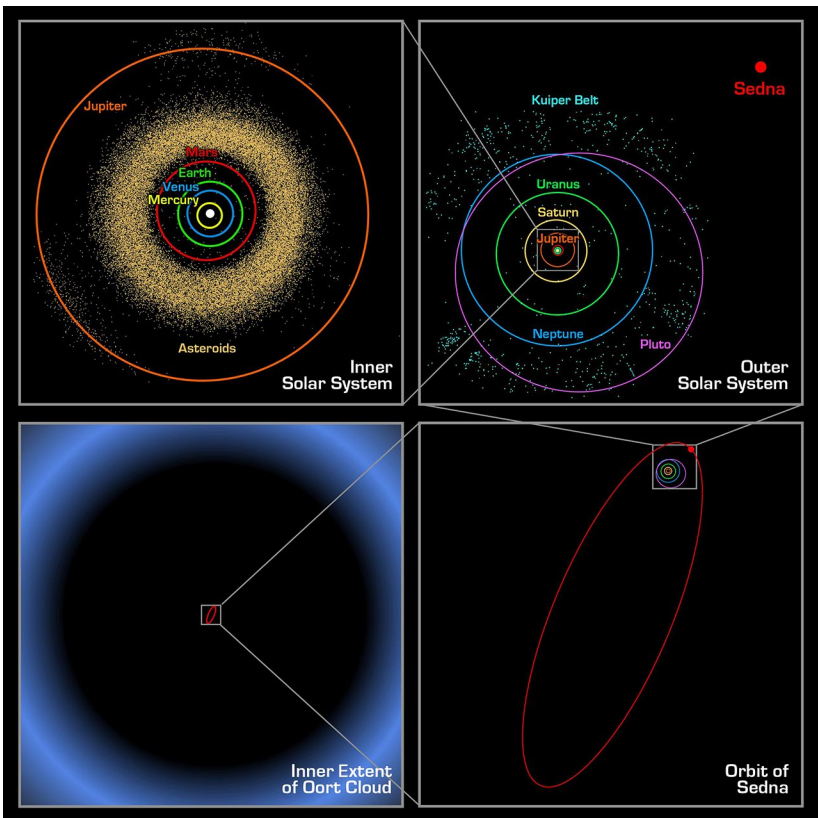
which are closest to the Sun, are dense with heavy materials, starting with a substantial iron core. That core is then surrounded by silicate rocks, typically built from silicon, oxygen, magnesium, other metals, and many trace elements.

✦ Farther from the Sun are the gas giants, made of the lightest atoms, hydrogen and helium. Farthest from the Sun of all are the ice giants, built mostly with molecules comprised of carbon, oxygen, and nitrogen, all mixed with hydrogen.

✦ This pattern isn't a coincidence. **The locations of planets are related to the temperatures in the solar system when and where they formed.**

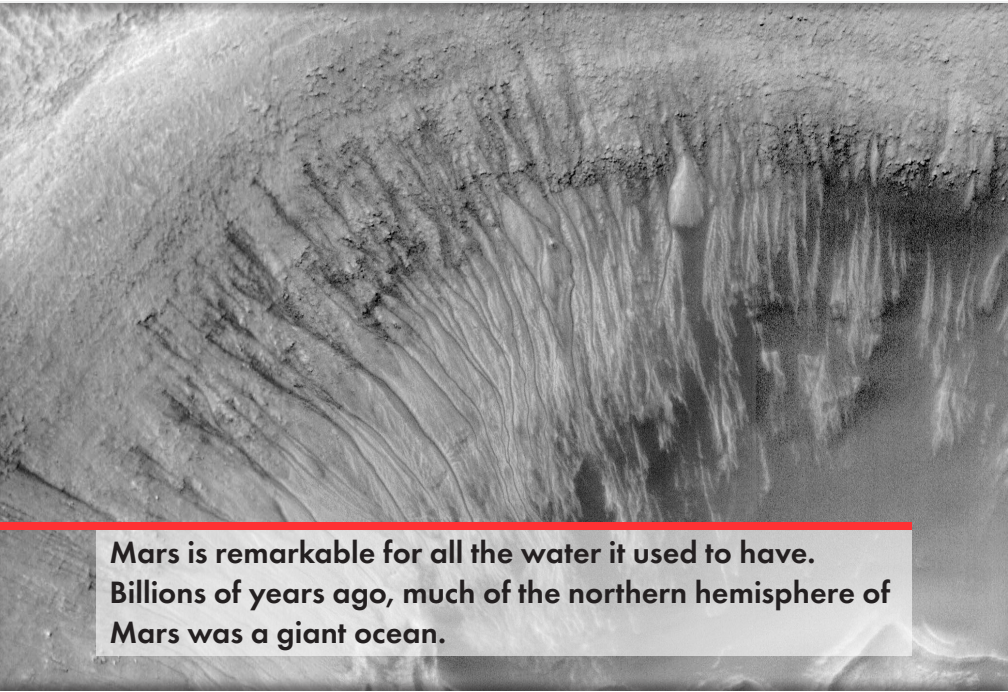
✦ When planets were forming, the inner solar system temperatures were so hot that only metals and rocks could condense from a gaseous disk to make the building blocks of the planets. In the outer solar system, temperatures were cooler, so ices could condense as well as rocks and metals. This meant that there was a wider range of material to build planets in the outer solar system. And Jupiter and Saturn grew so big that their icy-rocky cores could also attract vast amounts of hydrogen and helium—the most common atoms in the universe—eventually becoming gas giant planets.

- But our solar system doesn't end at the farthest planet, Neptune. In fact, Neptune's orbital distance is less than 0.1% of the distance to the farthest solar system inhabitants. The farthest objects are the small icy bodies in the Oort cloud, which are gravitationally bound to the Sun but orbit it 50,000 times farther than Earth's orbit around the Sun.



WATER IN THE SOLAR SYSTEM

- ✦ There are certain overarching phenomena that occur throughout the solar system. The first is the surprising prevalence of water in the solar system. Water is so important because liquid water is one requirement needed for a planet to be habitable, or able to support life—at least life as we know it.
- ✦ On Earth, water takes many forms: fog, rain, snow, streams, lakes, underground aquifers, oceans, etc. **Earth is the only place in the solar system that has standing bodies of liquid water on its surface, but there are many places in the solar system with frozen water ice on the surface.**
- ✦ Almost all of the moons in the outer solar system are covered in shells of frozen water ice. Mars also has frozen water. It's concentrated in the polar ice caps. Mars has a north pole ice cap that's around 1000 km, or 620 mi, across and about ½ the volume of the Greenland Ice Sheet.
- ✦ Frozen water ice is even found in the most unexpected places in the solar system. Mercury's surface has temperatures that can reach 800°F (427°C), yet there is frozen water hiding in permanently shadowed craters near the poles. That's because Mercury doesn't have an atmosphere, so these shadowed regions can stay cold enough for the ice to not sublimate away.
- ✦ And there are liquid water oceans under the surfaces of some other worlds. For example, 3 of Jupiter's moons—Europa, Ganymede, and Callisto—and 2 of Saturn's moons—Titan and Enceladus—have subsurface water oceans. But these oceans are far below the surface, whether several kilometers or hundreds of kilometers. **The subsurface oceans in the outer solar system may be global in scale, creating an entire shell of liquid water below the icy surfaces of the moons.**



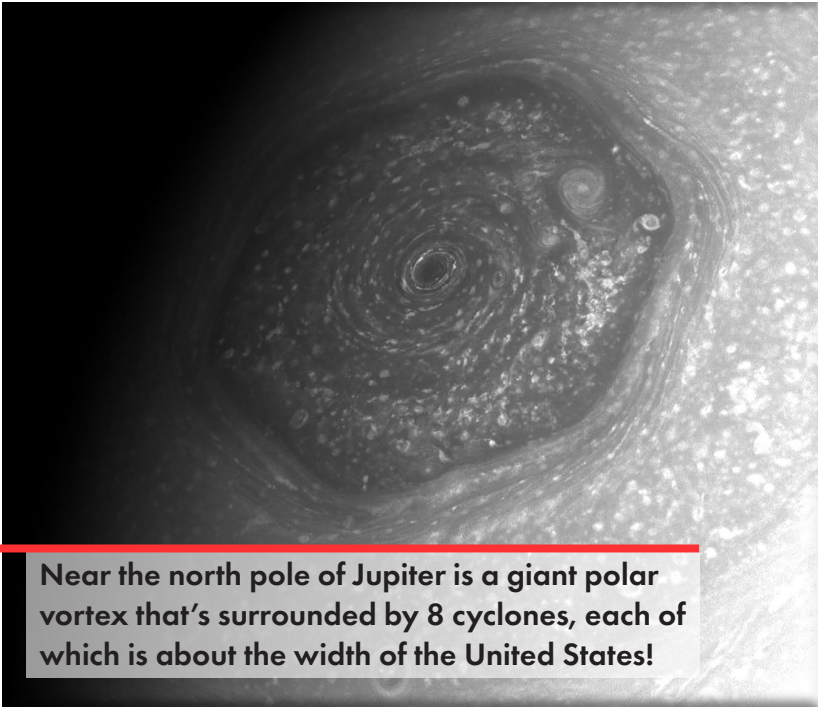
Mars is remarkable for all the water it used to have. Billions of years ago, much of the northern hemisphere of Mars was a giant ocean.

- ✦ **The solar system also gives us water in forms we've never seen on Earth.** Of course, we have snow and ice as solid forms of water. But Uranus and Neptune are the true water planets, because they are made mostly of water. Both planets even look like water worlds, but their blue and blue-green colors are from methane. Their water is locked below as ionic water, and in their deepest interiors, water transforms into the superionic phase.
- ✦ This is a new phase of water that occurs under the extreme pressures and temperatures in the deep interiors of Uranus and Neptune. The pressure reaches more than a million bars about halfway deep into Uranus and Neptune, and the temperatures at these depths reach several thousands of degrees. Here, the hydrogen and oxygen that make up the water molecule

(H₂O) rearrange themselves into a new structure. The oxygen atoms bond into a lattice, while the hydrogen atoms flow freely through the cage-like lattice structure. That's water unlike any we've experienced.

COOLING

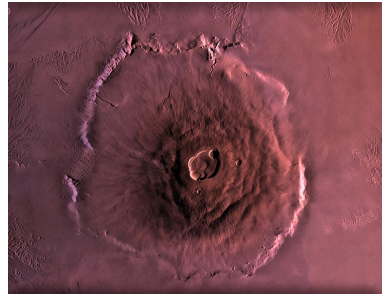
- ✦ A second overarching phenomenon that is encountered across the solar system is the role of cooling. **All planetary objects are cooling to outer space because their interiors are hot.** And that cooling manifests in a variety of ways that you might not consider cooling.
- ✦ Atmospheric storms, for example, occur in the layers of the atmosphere where hot parcels of air rise in updrafts, causing turbulent mixing of the atmosphere. This can cause strong winds, cyclones, and hurricanes.
- ✦ The most impressive storms happen on the gas giant planets. Jupiter, which is covered in storms, has the Great Red Spot, a giant oval-shaped hurricane that has lasted since at least 1830. It's larger in horizontal extent than the entire planet Earth and is about 200 mi deep. Its wind speeds reach more than 250 mph—which is much faster than the Category 5 winds of the most devastating hurricanes on Earth.
- ✦ Storms on Saturn behave quite differently from Jupiter's storms. The Great White Spot on Saturn formed in 2010, broadened out in longitude until it encircled the whole planet, ate its tail, and then died within a year. And similar great storms are seen on Saturn about every 30 Earth years. This is similar to Saturn's year, so the planetwide storms on Saturn seem to be seasonal, like our hurricanes. Saturn's polar storms are also bizarre. For example, the winds surrounding Saturn's north pole form a giant hexagon, each side of which is bigger than the diameter of Earth.



Near the north pole of Jupiter is a giant polar vortex that's surrounded by 8 cyclones, each of which is about the width of the United States!

- + **But the most severe planetary storms we know of don't happen in our solar system.** Some planets around other stars orbit much closer to their parent stars than Mercury orbits our Sun. Traveling so close to a star means the planet's surface temperatures can reach thousands of degrees. The superhot temperatures mean the “clouds” on that planet are made of silicates—sand—basically the building blocks of rocks. So precipitation may be in the form of molten-glass rain!
- + Another aspect of cooling on bodies across the solar system is the formation of volcanoes. The solar system is filled with volcanoes, many of which tower over Earth's largest volcano: Mauna Loa on Hawaii.

- ✦ There are places in the solar system that have a much larger number of volcanoes than Earth. For example, Venus is covered in volcanoes. More than 500 volcanoes on Venus are greater than 20 km, or 12 mi, wide, and more than 160 of the volcanoes on Venus are similar in size to, or bigger than, Mauna Loa.
- ✦ Although Venus is covered in volcanoes, they may be taking a very long break. For current eruptions, you'll want to visit Jupiter's moon Io, which is constantly flexed by gravitational tidal forces from Jupiter, heating its interior. That heat manifests as volcanic activity at the surface.
- ✦ Volcanoes don't just erupt molten rock in our solar system; there are other volcanoes that erupt water. The water then freezes into ice on the cold surface to create the volcanic cone. Such volcanoes are called cryovolcanoes or ice volcanoes.



The tallest volcano in the solar system is Olympus Mons on Mars.

COLLISIONS

- ✦ A third phenomenon that helps us understand the solar system is collisions. The solar system can be a chaotic place. Many objects are flying around at fast speeds, and they're always feeling gravitational pulls from all the other objects in the solar system. Sometimes objects get close and collide. **There is evidence of collisions everywhere in the form of impact craters—the remnants of violent collisions that occur as meteors hit a planet's surface.**

- ✦ Impacts occur all the time. The solar system is full of debris—small asteroid-sized objects floating around in space. There are almost 20,000 known asteroids orbiting near Earth. We keep a careful watch over them to see if any pose threats of hitting the Earth in the future.

The Chicxulub crater in Mexico is about 150 km (or about 93 mi) across and was caused by a meteor that hit Earth around 66 million years ago. That date coincides with a massive extinction event on Earth—the one that killed the dinosaurs.
- ✦ And there are many impact craters in the solar system that dwarf those on Earth. Just look up in the sky at the Moon. **All of those circular features on the Moon are impact craters.** For example, the dark spots on the near side of the moon are impact craters that were filled in with lava billions of years ago.
- ✦ **And the existence of the Moon itself is now understood to be a sign of an even larger impact that occurred early in solar system history.** About 4.5 billion years ago, a Mars-sized object referred to as Theia hit the proto-Earth at an angle, causing a combination of material from Earth and Theia to be ejected into orbit around the Earth. Material in orbit from that gigantic collision eventually accreted back together to form the Moon.

READINGS

Carney, *Planets*.

Hartmann and Miller, *The Grand Tour*.

Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.



LECTURE 2

Mercury, the Extreme Little Planet



Mercury is a planet of extremes. It's the smallest planet in the solar system and the closest planet to the Sun. It travels around the Sun much faster than any other planet—60% faster than Earth—at average speeds of more than 100,000 mph. Mercury has incredibly long days; in fact, a single day on Mercury is almost as long as an entire year on the planet. Mercury's orbit around the Sun is also less circular, or more elliptical, than any other planet.

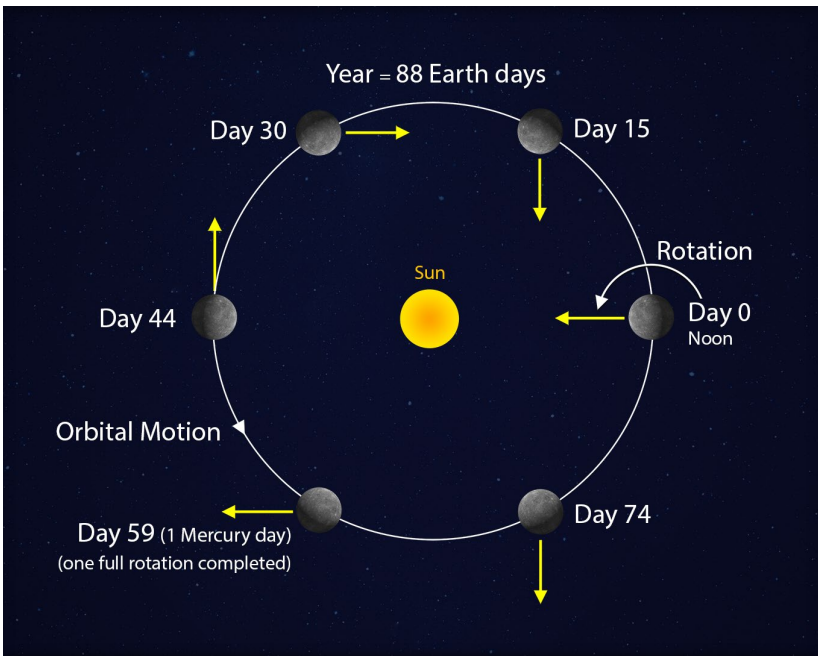
ORBIT AND ROTATION

- + Mercury's distance from the Sun changes a lot during its orbit. At its farthest point, Mercury is 70 million km (or 43.5 million mi) from the Sun, whereas at its closest point, it's only 46 million km (or 28.5 million mi) away. This means that the Sun's measured size in the sky would vary at different points in Mercury's orbit. This is not just an optical illusion. When Mercury is at its closest point to the Sun, the Sun really is about 50% bigger than when Mercury is at its farthest point from the Sun.

On average, the Sun is 2.5 times bigger when measured in the sky from Mercury than from Earth. This is because Mercury is on average 2.5 times closer to the Sun than the Earth is.

- + This elliptical orbit gives Mercury seasons that are very different. On Earth, seasons are due to the 23° tilt of Earth's axis, where winter in the Northern Hemisphere coincides with summer in the Southern Hemisphere, and vice versa. By contrast, Mercury's axis of rotation has almost no tilt, so Mercury's northern and southern hemispheres experience pretty much the same thing.
- + Yet Mercury as a whole does have seasons, of unequal size, because Mercury's elliptical orbit brings the entire planet closer to the Sun for short periods and farther away for longer periods. When Mercury is at its closest point to the Sun, called perihelion, the Sun is twice as bright as when Mercury is at its farthest point, called aphelion. So there are seasons of the year that are hotter and seasons that are colder.

- + A planet where the Sun gets noticeably bigger and smaller depending on the time of year is already strange enough. But the Sun's motion across Mercury's sky is even stranger.
- + First, Mercury's rotation is really slow; put another way, Mercury's day is really long. That's because when a planet is so close to the Sun, the Sun's gravity exerts strong tidal forces on the near and far sides of the planet that have slowed Mercury's spin down significantly. It takes about 59 Earth days for Mercury to complete just one rotation on its axis. The time for one rotation is only barely faster than Mercury's year, which is 88 Earth days. So that means Mercury's year is only 1.5 Mercury days long.



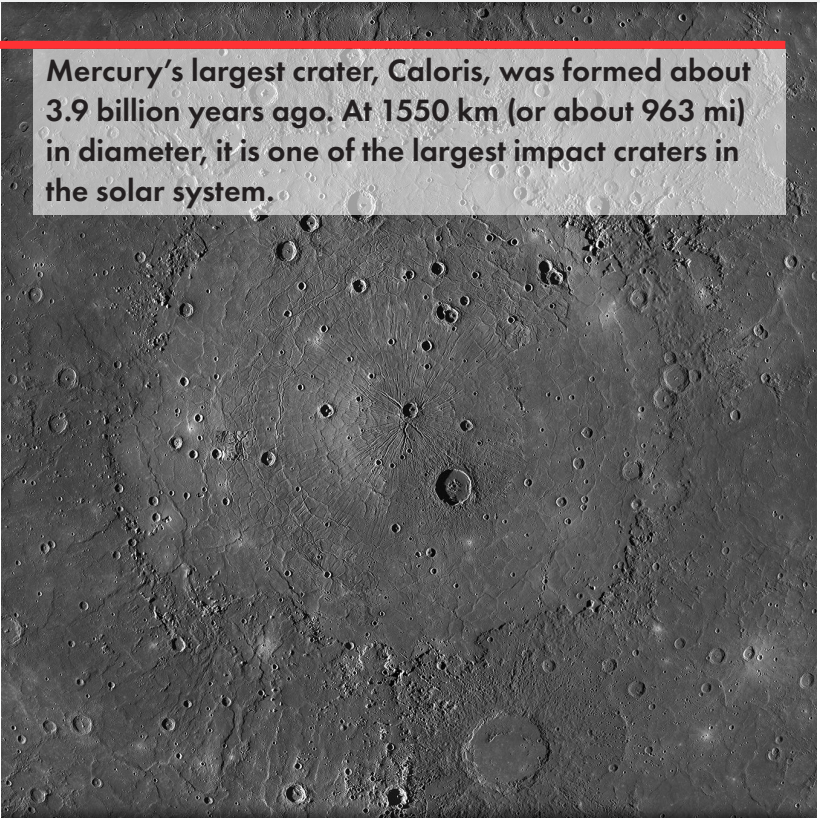
- + Second, the Sun doesn't rise every day. It doesn't even rise every year! On Earth, we are used to our time of day being well marked by the position of the Sun in our sky, but this doesn't happen on Mercury. Ultimately, this is because the length of day is so close to the length of year.
- + Third, the Sun's motion in the sky can change direction. If you were standing on Mercury watching the Sun, it would rise and move westward across the horizon, but at certain intervals along Mercury's orbit, it would stop moving, reverse direction, and move eastward for a while. It would then stop and reverse direction again and continue its normal westward motion across the sky. This happens because of how Mercury's very elliptical orbit combines with the fact that Mercury rotates very slowly. The change in which type of motion is faster—orbiting or rotating—is what causes the Sun to change direction in Mercury's sky.

SURFACE FEATURES

- + **Mercury is densely covered with craters.** More than 30,000 craters with diameters larger than 5 km (or about 3 mi) have been catalogued from images of the planet.
- + Because Mercury is so close to the Sun, objects that impact Mercury are usually moving faster than objects that impact the other planets. All of the fast-moving objects striking Mercury's surface mean that Mercury has more **secondary craters** than other planets. A secondary crater occurs when material that was ejected from Mercury's surface as a meteor hits reimpacts the surface with enough energy to cause another, secondary crater.

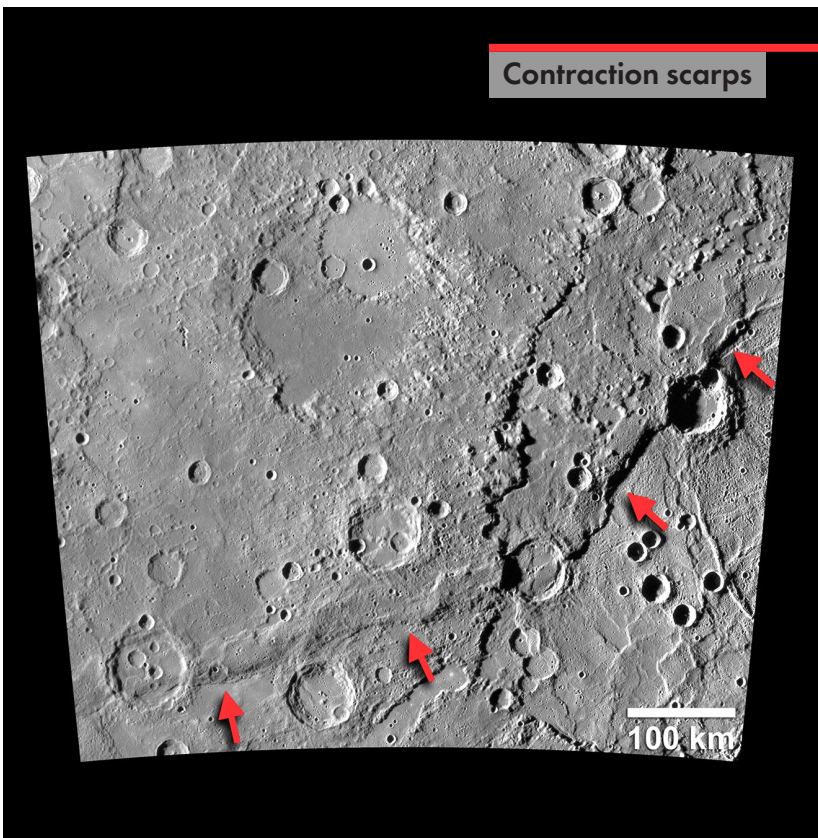
Almost 400 of Mercury's largest craters are named for musicians, writers, and artists. Beethoven is the third largest on Mercury; Rembrandt is the second largest.

Mercury's largest crater, Caloris, was formed about 3.9 billion years ago. At 1550 km (or about 963 mi) in diameter, it is one of the largest impact craters in the solar system.



- ✦ But the sheer number of primary craters also tells us that Mercury's surface is very old. This is actually a general rule of thumb for all rocky planets. Older surfaces have more craters because they've been around longer and therefore have been hit by more meteors. Scientists use this method of [crater counting](#) to distinguish the relative ages of different areas on a single planet and to compare the ages of planet surfaces to each other. Mercury, the Moon, and Mars all have very old surfaces, with some visible features dating back more than 4 billion years. What is seen on the surface of Venus and Earth, by contrast, is much younger.

- + Like all planets, Mercury has cooled over time, but the planet has preserved evidence of this cooling in a quite dramatic way. Close-ups of Mercury reveal some large cliffs or ridges, known as contraction scarps, which are long, wavy cliffs that formed as the planet cooled and contracted, thereby shrinking its volume. But as its volume shrank, its surface area remained the same, resulting in the wrinkling of the surface. These wrinkle ridges are up to 7 km (or about 4 mi) high on Mercury.



- ✦ But the best surface feature is also the most surprising: **Mercury has ice!**
- ✦ Mercury is very close to the Sun, so the daytime surface temperature can get really hot—more than 750°F (400°C). If the planet ever had any water in its past, it would have evaporated from the surface long ago and escaped into space.
- ✦ Yet radar images have found really bright radar spots in certain regions near Mercury’s poles that are best explained by the presence of water ice.
- ✦ **But how can there be water ice on Mercury when we know that any water in its past would have vaporized and escaped? The answer lies in the unique locations of these radar spots.** They are found in portions of crater floors. But the spots don’t cover the whole crater floor. Scientists have realized that these spots are found in regions of crater floors that are in permanent shadow. This can happen in craters in the polar regions because the Sun is never high in the sky. Because Mercury’s axis of rotation has almost no tilt, sunlight never hits the same polar spots, all year round.
- ✦ These permanently shadowed regions experience much colder temperatures than the rest of the planet. This is because Mercury has no atmosphere to transport heat around the planet, so if the Sun doesn’t shine on a particular spot, it’s going to remain extremely cold.
- ✦ Such craters are thought to form by impacts from comets and asteroids, some of which contain water. If a water-rich comet or asteroid impacts in the polar regions, then some of the water may be able to remain on the surface, buried in the permanently shadowed regions of polar craters.

Having access to water is considered a crucial resource for astronauts who want to spend a significant amount of time away from Earth, and Mercury has demonstrated that there is water even in the most unlikely of planets.

STRUCTURE AND COMPOSITION

- + Yet another extreme is that Mercury is small enough to be a moon. Mercury is smaller than Jupiter's moon Ganymede and Saturn's moon Titan. In fact, all of Mercury is smaller than just the iron core that makes up the center of the Earth!
- + Although Mercury is small, it's unusually dense. Mercury's average density is about 5430 kg/m^3 (or about 339 lb/ft^3), suggesting a planet that's mostly rocks and iron. Earth has an average density of about 5500 kg/m^3 (or about 343 lb/ft^3), again telling us that it is mostly made up of rocks and iron.
- + But it turns out that Mercury has a much larger fraction of iron in its interior than Earth does. In fact, Mercury has the largest fraction of iron in its interior of any planet in our solar system. The radius of Mercury's iron core is about 1800 km (or about 1118 mi), which is almost 75% of the planet's radius. By volume, that means Mercury is more than 50% iron core, whereas Earth is only 17% iron core.

CORE AND MAGNETIC FIELD

- + Mercury's large metallic core is also home to another surprising discovery: In the mid-1970s, the first spacecraft to visit Mercury, Mariner 10, discovered that Mercury has a global-scale magnetic field. Before this mission, scientists didn't think Mercury had the right ingredients for dynamo action to produce a magnetic field.
- + Dynamo action occurs when materials that are good electrical conductors can vigorously move around in such a way to create electromagnetic energy from the kinetic energy of the motions. This is the same process

that is at work in a generator. Basically, electrical currents can be generated in moving electrical conductors. And those currents can generate magnetic fields.

- ✦ In a terrestrial planet like Mercury, the metallic iron core is a good candidate for an electrically conducting region. But in order to have the vigorous motions necessary to generate magnetic fields through dynamo action, the iron core needs to be liquid.
- ✦ Early on, scientists didn't think it would be possible for Mercury's core to be liquid, because Mercury is a small planet, and small planets cool faster than big planets because of their larger surface-area-to-volume ratio.
- ✦ Thermal models for Mercury showed that the temperatures in the interior would be below the freezing temperature of iron, so Mercury's core would be solid.
- ✦ But then along comes the Mariner 10 mission, and the more recent MESSENGER mission in 2011, both of which demonstrated that Mercury has a global magnetic field, which is only possible if the core is at least partially liquid.
- ✦ How do we reconcile Mercury's small size with the fact that we know that at least some of Mercury's core is liquid? The answer lies in realizing that Mercury's iron core must have an antifreeze.
- ✦ Iron's freezing temperature can be greatly reduced by adding sulfur to the mix. We know that the cores of planets aren't made of pure iron from our studies of meteorites.

Seismology has also told us that Earth's core is not pure iron. It contains about 10% lighter elements, such as sulfur, silicon, and oxygen.

Scientists have determined that just a few percent of sulfur in Mercury's core could act as a good enough antifreeze to keep a portion of Mercury's core liquid.

- + Another key ingredient for a dynamo is that the liquid conductor has to have vigorous motions. This can occur inside a planet if it's cooling fast enough to transport heat through convection. Because Mercury is a small planet, with rapid cooling, the turbulent churning motions from heat transport can generate the electrical currents that produce magnetic fields.
- + And this magnetic field partially shields Mercury from solar radiation and from high-energy particles emitted from other stars and galaxies. That's better than Mars can offer!

ATMOSPHERE

- + It's true that Mercury has no atmosphere in the sense that balloons and other aeronautical devices will not work there. But that doesn't mean that there aren't particles floating above the surface, gravitationally bound to Mercury.
- + All planets, and even some moons, have particles surrounding them. On Earth, those particles are mostly nitrogen, along with oxygen, plus much smaller amounts of carbon dioxide. The particles are gravitationally bound to Earth, and the number density of the particles is large enough that these particles collide with each other, effectively keeping them up in the air. Such particles in collision with one another behave as a gas. These collisions make possible what we typically think of when the term *atmosphere* is used.

- + Mercury doesn't have an atmosphere in this sense. But there are still sometimes particles surrounding the planet and gravitationally bound to it. It's just that they almost never interact with other particles.
- + Scientists have detected all sorts of elements in Mercury's exosphere—a region of orbiting particles—including hydrogen, helium, oxygen, sodium, calcium, and magnesium. Earth and other planets have exospheres, too, but Earth's exosphere starts far above what we think of as atmosphere, at altitudes where the density becomes low enough that the particles no longer collide anymore. The difference is Mercury only has an exosphere. It's another way that planet Mercury is more like a moon.

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LECTURE 3

Venus, the Veiled Greenhouse Planet



Venus is quite similar to Earth. Some even call Venus Earth's twin planet. Venus's diameter and average density are 95% those of Earth. Venus's orbit is also closest to Earth's orbit, at 72% the distance, which means travel time from Earth to Venus could be less than travel time from Earth to Mars.

ATMOSPHERE

- ✦ At around 50 to 65 km (or about 30 to 40 mi) above its surface, Venus offers some conditions that are surprisingly similar to the surface of Earth. The temperature, atmospheric pressure, gravity, and even shielding from the Sun's radiation are comparable to what we take for granted at Earth's surface.
- ✦ But once we enter the atmosphere of Venus, we can't see anything! There is a veil of highly reflective cloud and haze blanketing the planet.
- ✦ The atmosphere of Venus makes it twice as hot as the highest setting of your kitchen oven. Venus's atmosphere is also much denser and under higher pressure than on Earth. At Venus's surface, the pressure is 92 bars! That's 92 times Earth's atmospheric pressure at sea level.
- ✦ On Earth, the bottom layer of the atmosphere, called the troposphere, extends from the surface up to an average of about 10 km, or about 6 mi. This is the layer of the atmosphere where most of the weather happens. The defining characteristic of the troposphere is this is where temperature decreases with height due to convection.
- ✦ Venus has a troposphere, but it extends from the surface up to about 65 km (or about 40 mi), so it's on average 6.5 times taller! But while Venus has this extremely tall troposphere layer, the other layers are smaller than those on Earth, and the total height of the Venus atmosphere is actually less than Earth.

Compared to Mars or open space, the atmosphere of Venus would have less radiation from the Sun, which would make long-term Venus missions much less hazardous for astronauts and equipment.

- + Venus transitions directly from troposphere to a relatively calm mesosphere, or middle atmosphere. Outermost is an exosphere (similar to Mercury), where particles no longer behave like a gas because the density is too low for collisions to happen. For Venus, the exosphere starts at an altitude of about 220 to 350 km (or about 137 to 217 mi). In contrast, Earth's exosphere starts at an altitude of about 600 km (or about 373 mi). So even though Venus's troposphere is taller, and very dense, the total atmosphere is only $\frac{1}{2}$ the height of Earth's atmosphere.
- + What's in the air is also very different. Venus's atmosphere is overwhelmingly carbon dioxide. Earth's atmosphere is $\frac{3}{4}$ nitrogen.
- + Earth as a planet still has about the same amount of carbon dioxide as Venus; it's just that Earth removes it from the atmosphere. Earth buries carbon dioxide in carbonate rocks, and plants convert it to oxygen in the air. But there is nowhere on Venus for the carbon dioxide to go—except the atmosphere.

GREENHOUSE EFFECT

- + The immense amount of carbon dioxide in Venus's atmosphere is also the reason Venus has a surface temperature of about 850°F (450°C). This is extremely hot, but it's also much hotter than would be expected based on Venus's distance from the Sun.
- + We can estimate the temperature expected at a planet by considering how much solar energy it absorbs at its orbital distance. That absorbed energy is reemitted by the planet in the infrared portion of the electromagnetic spectrum, which we sense as heat. The temperature we get from balancing the amount of absorbed energy with the amount of reemitted energy is known as the equilibrium temperature.

Venus is the brightest object in our sky after the Sun and Moon.



- ✦ The natural trend is that planet equilibrium temperatures are hotter the closer the planet is to the Sun, because the solar energy is greater the closer you are to the Sun. But you also have to account for how reflective the planet is, known as the albedo. Venus is covered everywhere with reflective clouds, giving it the highest albedo of any planet in the solar system.
- ✦ Combining Venus's distance from the Sun with its albedo, its equilibrium temperature is calculated as about -50°F (-45°C). But Venus's actual surface temperature is 850°F (450°C)! The problem is that Venus became the victim of a runaway greenhouse effect.
- ✦ A greenhouse effect occurs when a planet has an atmosphere that contains greenhouse gases, such as carbon dioxide, methane, and water vapor. The surface first absorbs all the sunlight that gets through the atmosphere and then reradiates it in infrared wavelengths. These greenhouse gases absorb the infrared light and reradiate it in all directions. That means that some of that energy gets sent back toward

the surface, so greenhouse gases can effectively trap heat energy close to the planet's surface, increasing the planet's surface temperature above its equilibrium temperature.

On Earth, our equilibrium temperature, without a greenhouse effect, would be about 0°F (-18°C). With these temperatures, water would be frozen on Earth's surface.

But a greenhouse effect on Earth has increased the average temperature to about 60°F (16°C), which has resulted in liquid water being stable over much of the surface.

- + A mild greenhouse effect can be quite beneficial. In fact, it can be a key ingredient in making a planet habitable. But the runaway greenhouse effect on Venus has made it hot enough to melt lead! At these temperatures, there is no liquid or solid water on Venus's surface, and any remaining water that appears on the surface from the interior—say, from volcanic eruptions—would quickly evaporate into the atmosphere. This means that Venus's surface and interior are extremely dry and getting even drier all the time.
- + But even in the atmosphere, Venus has very little water vapor remaining. That's because any water that gets into the atmosphere is quickly broken up into oxygen and hydrogen atoms by interactions with solar light. Hydrogen, being the lightest of elements, then most easily escapes the planet, being blown off by the solar wind.

SULFURIC ACID CLOUDS AND WINDS

- + In addition to fiery temperatures, the hellish atmosphere of Venus even offers brimstone—an old word for sulfur. The clouds that hide Venus's surface from us aren't the friendly water clouds of Earth. The oxygen

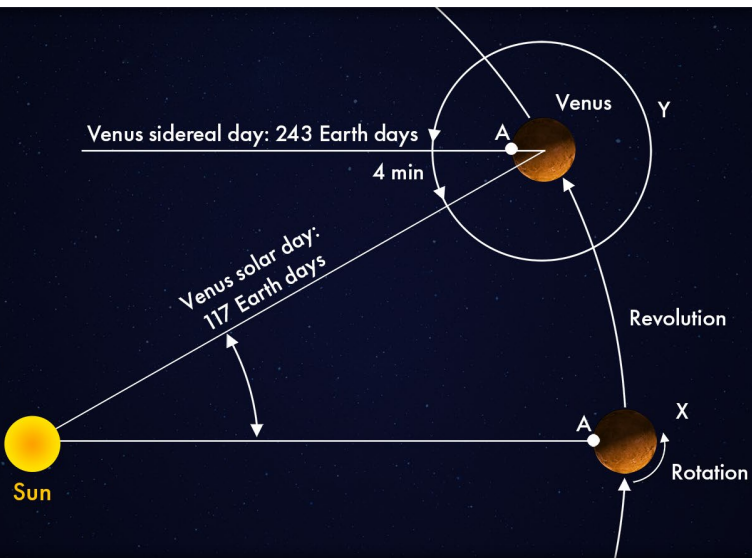
hanging around in the atmosphere pairs up with sulfur erupted by volcanoes to form clouds made of sulfuric acid, also known as vitriol. That's a highly corrosive acid that easily causes severe burns when in contact with skin and can even dissolve metals and stone. This cloud bank exists at heights of around 50 to 70 km (or about 31 to 43 mi) above Venus's surface.

- + We don't have similar clouds on Earth because the composition of our atmosphere is quite different, so different chemical reactions occur.
- + You might think things get better below the cloud level on Venus, but it turns out that, like on Earth, clouds can lead to rain, and the sulfuric acid clouds on Venus lead to sulfuric acid rain down to about 20 to 30 km (or about 12 to 19 mi) in altitude.
- + Down at those altitudes, it's already so hot that the sulfuric acid evaporates and therefore doesn't actually hit the surface. So the surface is safe from sulfuric acid rain, but to get to the surface, you still have to go through sulfuric acid clouds and rain.
- + At around 50 km (or about 31 mi) in altitude are strong westerly winds that travel at about 350 kph (or about 217 mph) at the top of Venus's cloud deck. Those wind speeds are faster than Category 5 hurricane speeds on Earth. And those winds are about 60 times faster than Venus's rotation speed, which is 243 Earth days for just one Venus day. This is known as atmospheric super-rotation.
- + For Venus, the winds get slower as you go deeper in the atmosphere. That's because it takes a lot more energy to move the denser atmosphere.

Venus has the slowest rate of rotation anywhere in the solar system, at 243 Earth days for just one Venus day.

UPSIDE-DOWN ROTATION

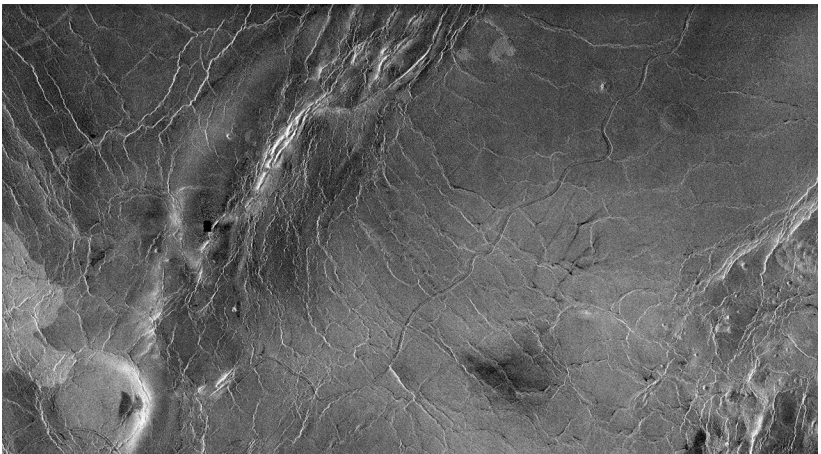
- + Venus not only spins on its axis more slowly than all the other planets, but it also spins opposite the direction that all the planets orbit around the Sun! That means the Sun rises for Venus in the west and sets in the east.
- + Venus's axial tilt goes all the way upside-down. One theory for this tilt is that it was caused by impacts. Early in Venus's history, if an object hit it in a glancing impact, it could have changed its spin axis, tilting it somewhat. Another theory is that Venus's thick atmosphere was the culprit. Winds in the atmosphere driven by solar heating could push on the planet's surface. With enough pushing in a constant direction, they might have actually worked to flip the planet over!
- + Venus's rotation rate is also very slow, which means the length of the day is very long. The sidereal day—the length of time it takes for Venus to complete a full 360° rotation—is 243 Earth days. The year on Venus is 225 Earth days, so for Venus, the sidereal day is longer than the year!



SURFACE AND INTERIOR

- ✦ Using radar, scientists have been able to penetrate Venus's pesky opaque clouds to reveal its full surface. Radar tells us that most of Venus is covered in smooth volcanic plains. There are 2 highland regions, covering about 20% of the surface. They're kind of like uplifted, deformed continents, though not surrounded by any trace of ocean. The continents also feature mountains.
- ✦ All rocks are much closer to their melting points on Venus, and hot rocks help explain the number, variety, and sheer size of volcanoes on Venus. There are 167 volcanoes on Venus whose diameters are more than 100 km (or about 62 mi) across.
- ✦ Some of these volcanoes appear a lot like Earth's volcanoes, except bigger. These are like Earth's shield volcanoes, with an incline rising to a large hole, or caldera, we expect at the top of the volcano.
- ✦ Venus also has some unique volcanoes. First, there are the enormous pancake volcanoes. Some are 10 to 100 times larger than lava dome volcanoes on Earth. Those on Venus are unique because they tend to be very circular and have a very flat, broad dome—hence the name *pancake*. They are spread across Venus but typically in small groups.
- ✦ Next are the arachnoid volcanoes. These look kind of like spiderwebs, due to starlike fractures in both radial and concentric directions. Almost 100 of them have been found. They range in size from 40 to more than 200 km (or from about 25 to 125 mi) in diameter. They might have formed when magma upwelling below the crust forms fractures in the surface.

- + Finally, the coronae volcanoes are circular fractured features. Magma pushes up the crust, but then after the magma is released, it's thought that the crust collapses back down, leaving the crumpled circular edge.
- + Coronae have been found on one other world in the solar system: Miranda, which is the moon most stretched and squeezed by the gravity of Uranus. But pancake volcanoes and arachnoid volcanoes have not been seen on any other body in the solar system. This tells us that something unique is happening in Venus's crust and interior. High surface temperatures and pressures may be responsible. Or the lack of water in Venus's interior could affect how magma flows in the crust.
- + Another surface feature on Venus is impact craters. The largest crater on Venus is called Mead, with a diameter of 280 km (or about 174 mi). It's similar in size to the largest crater on Earth, the Vredefort crater, whose diameter is around 300 km (or about 186 mi).



Venus has the longest channel anywhere in the solar system: Baltis Vallis, which stretches about 4200 mi. Baltis Vallis is slightly longer than the Nile River on Earth and has an average width of 1 mi.

- + Venus has fewer large craters (more than 5 km, or about 3 mi, in diameter) than either Mercury or the Moon. This tells us that Venus's surface is much younger than Mercury's or the Moon's, with a surface age that's more similar to Earth's. We don't even find craters smaller than about 5 km (or about 3 mi) in diameter on Venus. But this is because smaller impactors just completely burn up in Venus's dense atmosphere.
- + Like Earth, Venus formed about 4.5 billion years ago, so the surface is at least 3.5 billion years younger than planet Venus as a whole. But unlike Earth, the young surface of Venus is believed to be the result of one or more global resurfacing events. Essentially, the entire surface collapsed back into the mantle and was replaced by a massive infill of magma.
- + Venus's average density is 5240 kg/m^3 (or about 327 lb/ft^3), which is quite similar to Earth's. This means that Venus is made of silicate rocks and iron. The fraction of iron is similar to that of Earth. Yet Venus does not have a global magnetic field today. That tells us that the iron core is cooling slowly, without the vigorous fluid motions called convection needed to generate a dynamo that creates the magnetic field.

Based on counting large craters, Venus's surface is between 200 million years and 1 billion years old.

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LECTURE 4

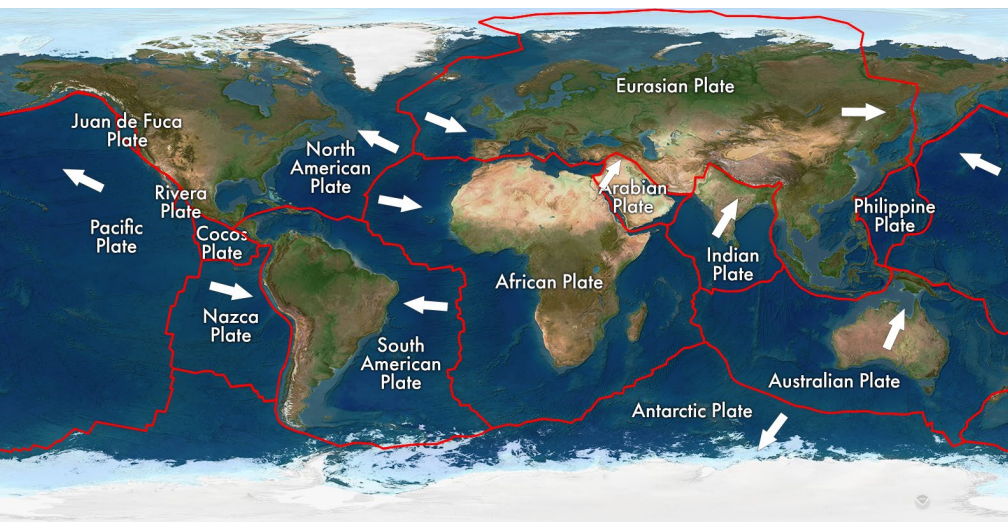
Earth: How Plate Tectonics Sets Up Life



Earth is our home-base example of a terrestrial planet, a category of similar-sized planets that includes Mercury, Venus, and Mars. But Earth has some significant differences. It's the biggest and most massive of the terrestrial planets. Compared with smaller planets like Mercury or Mars, Earth's stronger gravity makes it much easier to retain an atmosphere. Thanks to the insulating blanket provided by this atmosphere, Earth's distance from the Sun turns out to be perfect for providing surface temperatures that allow liquid water to be stable at Earth's surface. And uniquely on Earth, there is life everywhere. But all these unique features may have also depended on yet another major difference between Earth and other terrestrial planets: Earth's surface never stops moving.

PLATE TECTONICS

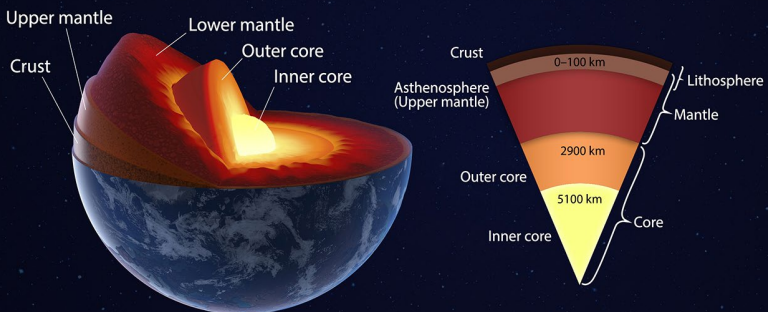
- ✦ Tectonics refers to large-scale processes that cause geological structure on a planet's surface. In that sense, every planet has tectonics. On Mercury and Venus are craters, volcanoes, mountains, and faults. These are all caused by tectonics.
- ✦ Earth has a special kind of tectonics called plate tectonics. Earth's outermost rigid shell, called the lithosphere, is broken up into a series of plates. The key feature of plate tectonics is that these rigid plates move relative to each other.



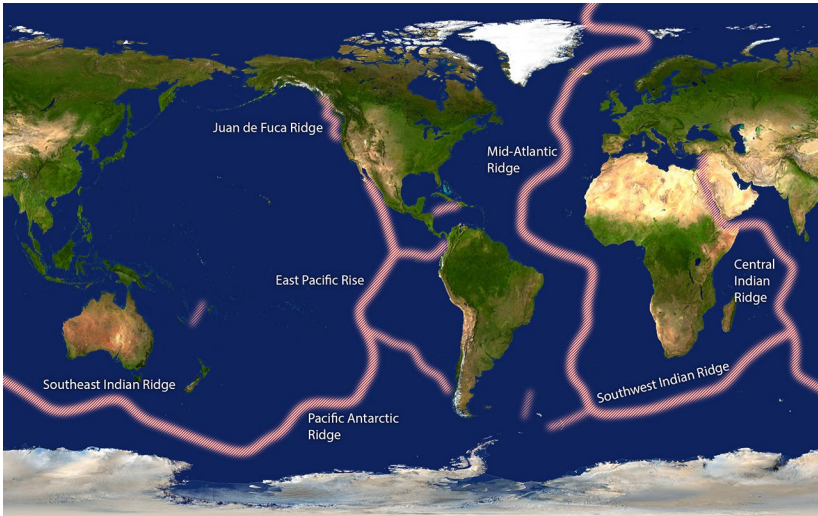
- ✦ There are 7 large plates and many smaller plates. The names of the plates tend to be related to continents, but they also extend out to portions of the ocean floor. And the largest plate, the Pacific Plate, doesn't contain any continent.

- + About 250 million years ago, the plates seem to have been arranged so that Earth had one supercontinent. But the plates are always moving. That's why the supercontinent called Pangea drifted apart, and other collisions took place, leaving (for now!) the continental shapes we're familiar with today.
- + These plates define the rigid layer called the lithosphere, which is about 100 km (or about 62 mi) thick, on average. The shifting plates are situated on top of a weaker layer called the asthenosphere, also called the upper mantle. This weaker rock layer in the Earth is more easily deformable than the plates but is still solid.
- + You can picture the surface plates as floating on the asthenosphere, just like icebergs float on water. And just like icebergs, the plates move relative to each other. The motion of the plates is quite slow by human standards, with speeds of just a few centimeters per year—about the rate at which a fingernail grows.

It's a misconception that the hot rock in Earth's mantle is molten; in fact, the rocks in the mantle are solid.



- ✦ But because each plate is moving relative to all the others, the **boundaries between plates can be quite dynamic**. Sometimes that motion has plates sliding past one another, called a **transform boundary**. On the western coast of the United States, the Pacific Plate is sliding northwest relative to the North American Plate. The San Andreas Fault is a famous example of part of the boundary between these 2 plates. **The lateral, sliding motion along the San Andreas Fault causes some of the strong earthquakes that California is famous for.**
- ✦ Plates can also move apart from each other, called a **divergent boundary**. When plates diverge, a fissure opens up on the Earth's surface. This opening depressurizes the mantle layer below, and the reduced pressure allows it to melt and allows the now-melted material to come to the surface. As this happens, the melted material cools to create new surface material.
- ✦ This is happening right now in the middle of the Atlantic Ocean in 2 places: The African and South American Plates are moving apart, and the Eurasian and North American Plates are moving apart. This divergence of the plates in the mid-Atlantic, and the opening created for volcanic eruptions, has led to the growth of a giant mountain range that's more than a mile high in the middle of the Atlantic Ocean known as the Mid-Atlantic Ridge.
- ✦ What happens to the new plate material created at ridges? Over time, as the plates keep moving apart, newly created lithosphere moves farther and farther from the ridge. During this time, the new material on the surface is also cooling down because the surface is much colder than Earth's interior. As it cools, it becomes denser.



The Mid-Atlantic Ridge may be largely invisible from space, yet with a length of about 10,000 mi, it is the longest mountain range on Earth.

- ✦ Eventually, that dense plate material encounters another plate boundary. Often, that's a boundary where 2 plates are moving toward each other, called a convergent boundary. When that happens, if a plate is dense enough, then it can descend below the other, into the mantle. This happens in many places around the Pacific Plate, such as near New Zealand and Japan.
- ✦ Regions where plates descend back into the Earth are known as subduction zones, and they, too, are famous for being very geologically active. A strong earthquake in Japan might be the result of a rigid plate that's being pushed and pulled into the mantle of the Earth, which causes fracturing.

+ In addition to causing strong earthquakes, the subducting plate is also being exposed to higher temperatures and pressures as it goes deeper into the Earth. This can cause melting and volcanism on the overriding plate that sits above the subducting slab.


Volcanoes are found all along the rim of the Pacific Plate, where subduction is occurring. This has given the west coast of North and South America and the east coast of Asia the nickname the "Ring of Fire."

- + When a plate descends into the Earth at a subduction zone, it continues to sink because it's colder, and hence denser, than the rock in the mantle. Eventually, some plates get to the bottom of the mantle, where they sit on top of the core-mantle boundary. Because Earth's core is made of iron, which is always much denser than mantle rocks, the subducting plate can't sink into the core.
- + But this isn't a fast process. The mantle of the Earth is solid, and the mantle rocks slowly deform as the denser plate moves downward through the mantle. It takes about 200 million years for a subducting slab to go from the surface to the bottom of the mantle.
- + But as the plate gets deeper and deeper into the mantle, it will start warming up because its surroundings get warmer as depth increases. Eventually, the subducted plate warms up to ambient temperature and is then just part of the mantle, like the rest of the rock there.
- + At the same time, new mantle rock is reaching the surface at mid-ocean ridges, where new surface plates are being created. This new surface plate material will cool down over time as it's exposed to the relatively cold temperatures at the surface of the Earth.

- + This whole process is known as **mantle convection**. In this way, the Earth cools down over time and also constantly recycles its surface. This recycling means that there is very little “old” surface left. Even the best-preserved continental regions are subject to constant weathering through precipitation and winds—very different from the Moon, or Mercury, or other pristine places with no atmosphere.
- The oldest crust on the ocean floor is only about 180 million years old.
- + That means **the history of Earth’s earliest times is constantly being erased, little by little, making it harder to study**. It’s one of the reasons why studying the other terrestrial planets with old surfaces is so important. We can learn about Earth’s early history from their early history.

PLATE TECTONICS AND CLIMATE

- + Plate tectonics plays an important role in Earth’s climate.
- + First, there are local effects. **Because plates move on the Earth, they can change their latitude over time**. Around 200 million years ago, India and Australia were close to the South Pole. Only later did they slowly move northward to their current locations.
- + **And the deformation that occurs at plate boundaries**, such as where the Indian Plate collided with the Eurasian Plate, **can cause mountain building**, such as the Himalayas. Regions that were once coastal or even underwater can end up thousands of feet high as the continental crust crumples.



Portions of the Appalachian Mountains on the East Coast of the US used to be ocean floor!

- + The locations of oceans also change. And that means changing the ocean currents that affect climate.
- + Earth's regional climate system depends on the location of the continental plates. As the plates continue to move, climates in the area will continue to change, too.
- + But plate tectonics also has larger global effects on the climate. Because of a central role in Earth's carbon cycle, plate tectonics determines how much carbon dioxide is in the atmosphere. One of the main reasons carbon dioxide gets removed from our atmosphere is that it mixes with rain to form carbonic acid. This acid then weathers rocks on the surface, creating carbonates, such as limestone. All those carbonates eventually settle to the bottom of Earth's oceans. That's all part of the carbon cycle on Earth.

- ✦ The carbonates don't just stay at the bottom of the ocean forever. Oceanic crust eventually gets subducted into the mantle. So carbon from the atmosphere ends up in the mantle.
- ✦ But if that was the whole story, the Earth's atmosphere would eventually lose all of its carbon dioxide to the interior of the planet. And if that happened, Earth would be a frozen ice world.
- ✦ Here is where plate tectonics (usually) saves the day: **The eruptions from volcanoes that occur on overriding plates at subduction zones include carbon dioxide from the subducting slabs underneath, effectively replenishing the atmosphere.**
- ✦ And those volcanoes are responsible for replenishing more than just carbon dioxide. Volcanic activity also brings other volatiles, such as water, back to the surface. It's possible that a significant amount of the water we have on Earth's surface came from volcanic outgassing early in Earth's history.

PLATE TECTONICS AND LIFE

- ✦ Plate tectonics may also have implications for life itself.
- ✦ **Plate tectonics plays a role in creating Earth's global magnetic field.** The magnetic field, in turn, creates a magnetic bubble in space called the magnetosphere. This magnetic bubble in space protects us from the solar wind, which is a continuous flow of plasma and charged particles released from the Sun; that is, the magnetosphere helps shield the planet from the radiation and high-energy particles emitted from the Sun and from deep space. Because ionizing radiation is blocked, water vapor in Earth's atmosphere can avoid being ionized into pieces and blown into space by the solar wind.

- + To generate a magnetosphere, a big terrestrial planet like Earth needs to cool its core quite rapidly. But the core is surrounded by the mantle, so the core can only cool as fast as the mantle cools. Here's where plate tectonics comes in: With plate tectonics constantly opening the mantle, Earth's core can cool fast enough for turbulent motions that generate a dynamo. Rapid cooling generates a magnetic shield that makes Earth more suitable for life.
- + **Plate tectonics may also have had a role in the evolution of complex life on Earth.** That's because plate tectonics is responsible for much of the mountain building on continents. Continental rocks are so buoyant that they don't subduct back into the Earth, so the only place for them to go during continent-continent collision is up. When new mountains form, however, they are more susceptible to erosion, which brings important minerals, such as phosphorus and calcium, to the oceans. These minerals can act as nutrients and building blocks for life. Plate tectonics can also change sea level in local regions, and scientists think that shallow waters might be an ideal location for life to flourish.
- + **Also, some scientists believe that there might even be a connection between major evolutionary events in the fossil record and plate tectonics.** For example, around 540 million years ago, during the Cambrian Period, life on Earth went from being mostly simple, single-cellular organisms to a vast array of complex multicellular animals. And this all happened in about 20 million years—a blink of an eye in geologic terms. What could have spawned such a rapid change and growth in life? It's possible that adding more nutrients to the ocean could have fed phytoplankton, which then, through photosynthesis, created more oxygen. A rise in oxygen level may have been involved in what is now called the Cambrian explosion.

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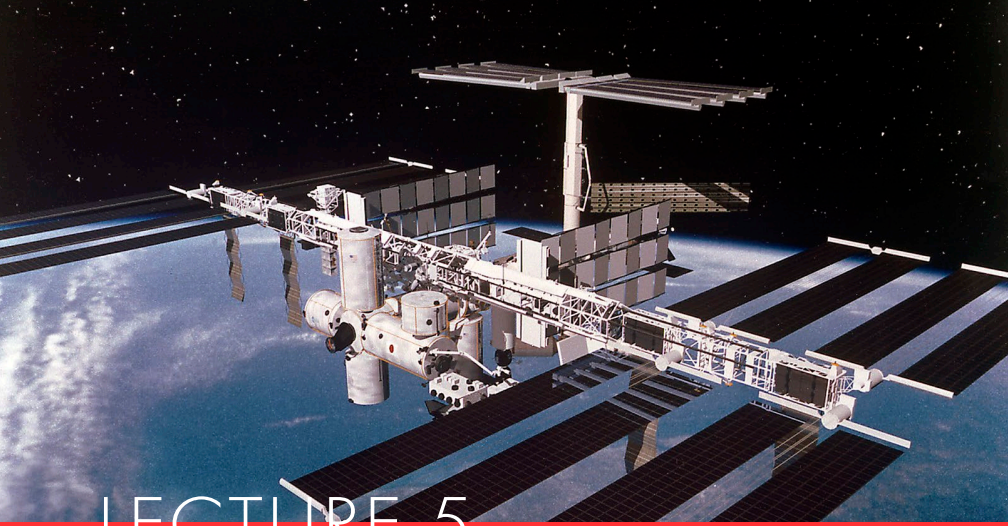
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LECTURE 5

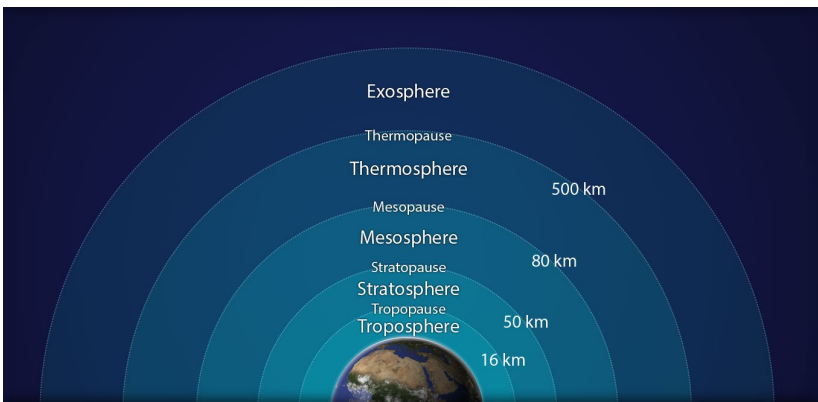
Orbiting Earth: Up through the Atmosphere



There's no clear-cut answer to where Earth ends and where space begins, but there are ways to define boundaries between Earth and the rest of the solar system. Wherever the outermost boundary of Earth is located, the regions of space around Earth are not empty. And we can't ignore these regions. Our rockets have to pass through them to get to the rest of the solar system. The regions of low, medium, and high Earth orbits can also be very useful to us. They're a great place to put up space telescopes and satellites that can communicate across the globe as well as monitor the Earth's climate and tectonic changes.

TROPOSPHERE

- + The lowest layer of Earth's atmosphere is called the troposphere. It starts at Earth's surface and ends at an average of about 10 km, or roughly 6 mi, in altitude. The troposphere is where all of our weather occurs—including winds, thunderstorms, tornados, hurricanes, and blizzards—and where most of our clouds form.
- + And all of these result from the convective overturning of air that occurs in this layer, along with the fact that this layer is where water goes through all of its phases—from the water vapor creating humidity on hot summer days on the East Coast of the US, to the rain that drenches Seattle, to the snow that blankets the northern states in winter.
- + **The overturning, or vertical mixing, in the troposphere happens because the troposphere is hottest at the bottom.** The average temperature at Earth's surface is about 60°F (15°C). As we head upward in the atmosphere, the temperature decreases until we reach the top of the troposphere, a boundary known as the tropopause, where the average temperature is about -75°F (-60°C).



- ✦ The air density and pressure also decrease with altitude. In fact, the majority of the atmosphere's mass, about 80%, resides in this thin lowermost layer. By the time you reach the tropopause, the pressure is 5 times lower than it is at the surface.

STRATOSPHERE

- ✦ Above the troposphere begins a new layer in the atmosphere, the stratosphere. This layer is stratified, so it doesn't experience all the mixing and overturning seen in the troposphere. The stratosphere goes from its base at about 10 km (or 6 mi) in altitude at the tropopause up to about 50 km (or 31 mi) in altitude at the stratopause.
- ✦ The stratosphere is stratified because it has a heat source that causes the temperature to increase with altitude here. If the temperature is increasing with altitude, then parcels of air at the bottom of the layer aren't buoyant and therefore won't rise to cause the convection and overturning experienced in the troposphere.
- ✦ From -75°F (-60°C) at the bottom of the stratosphere, the temperature increases to about 32°F (0°C) at the top of the stratosphere. But although the temperature increases by about 100°F (60°C) as you rise up through the stratosphere, the pressure decreases. At the stratopause, the pressure is just one millibar—1000 times less than the pressure at Earth's surface.
- ✦ Commercial airliners typically fly with cruising altitudes around 12 km, or 39,000 ft, in the lowest part of the stratosphere; this puts them above most of the weather in the troposphere that causes the turbulence experienced in airplanes. Giant scientific balloons can also be used to do science studies in the stratosphere.

Flown by NASA in the lower stratosphere, SOFIA (Stratospheric Observatory for Infrared Astronomy) is a Boeing 747 aircraft that has a 100-inch telescope attached.



MESOSPHERE

- + Above the stratopause is an atmospheric layer known as the mesosphere, which extends from about 50 to 80 km (about 30 to 50 mi) in altitude. There is no ozone layer or other heating source here, so temperature falls rapidly with height. The top of this layer, the mesopause, is the coldest layer in the atmosphere, with an average temperature of about -120°F (-85°C).
- + Scientists sometimes refer to the mesosphere as the “ignorosphere” because it’s so poorly studied compared to the layers below or above it. We basically ignore it because it’s hard to gather data there! With pressures ranging from one thousandth of one bar at the bottom of the mesosphere to one millionth of one bar at the top, air is too sparse here for even balloons to visit, yet still too thick for orbiting satellites.

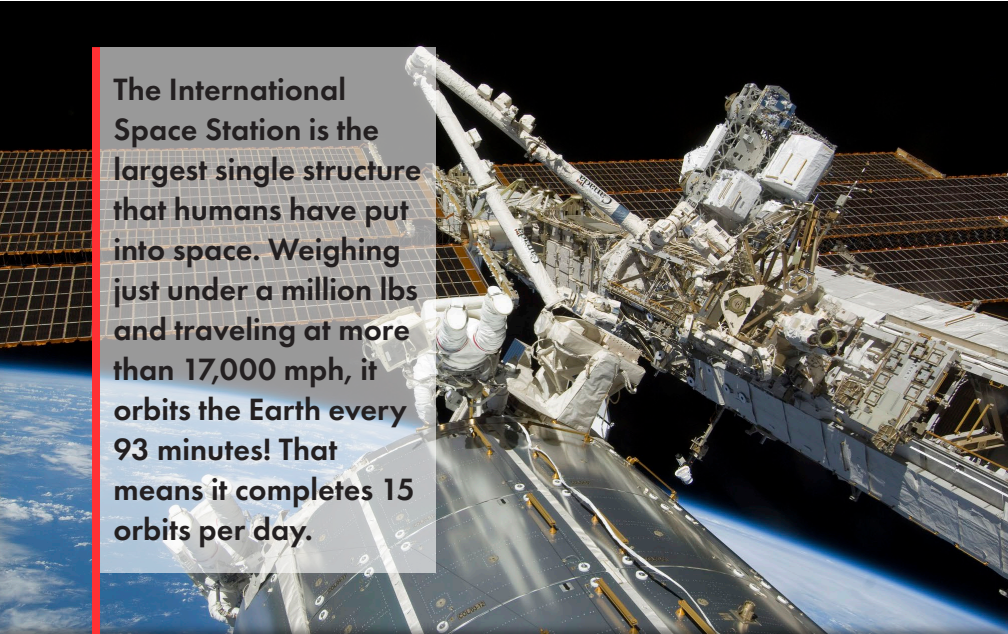
- + Instead, we study the mesosphere by strapping instruments to rockets that are launched from Earth, reach a maximum height somewhere above the mesosphere, and then descend back to Earth again. But that means the rockets only spend a few minutes in the mesosphere taking data.
- + The mesosphere could be a good place to do some risky sightseeing, starting with electrical phenomena such as red sprites and blue jets, both of which are due to lightning in the mesosphere. The mesosphere is also the region of the atmosphere where most meteors burn up. So when you are out on a clear night and you see a shooting star, that trail of light you see is in the mesosphere.

THERMOSPHERE

- + Above the mesosphere, about 80 km (or 50 mi) in altitude, is a much larger layer, the thermosphere, which also varies greatly in height, from 500 km (311 mi) all the way up to 1000 km (621 mi) in altitude!
- + The thermosphere is where the temperature starts increasing with height again, like it did in the stratosphere. But this time, it's because ultraviolet light and x-rays are absorbed by molecules in the thermosphere—heating the layer as well as ionizing the molecules. Anywhere that electrically charged ions dominate is known as the ionosphere, and most of Earth's ionosphere is centered in the thermosphere.
- + Temperatures in the thermosphere vary a lot but can reach several thousands of degrees. It seems strange, then, that you would actually freeze if your skin was exposed in the thermosphere. That's because the density of air is extremely low; an air molecule in the thermosphere may

travel more than a kilometer before colliding with another air molecule. You definitely don't want to try to breathe up here. But it also means you'd never warm up from the high temperatures of those air molecules.

- ✦ The thermosphere is where most of the aurora, or northern lights—wondrous bright flashes of colored light in the night sky—are created.
- ✦ The International Space Station orbits in the thermosphere at altitudes between about 330 and 420 km (about 205 and 260 mi). This football field-sized space station has been inhabited by humans since the year 2000.
- ✦ The International Space Station in the thermosphere is the highest altitude where humans are long-term inhabitants, but there's other technology up here, too: the artificial satellites that we've built and launched into low Earth orbits. For example, the Hubble Space Telescope orbits at about 540 km (335 mi) in altitude.




The International Space Station is the largest single structure that humans have put into space. Weighing just under a million lbs and traveling at more than 17,000 mph, it orbits the Earth every 93 minutes! That means it completes 15 orbits per day.

EXOSPHERE

- ✦ The next layer is the exosphere, which extends to around 10,000 km (or about 6200 mi) in altitude. At these heights, the exosphere merges with the solar wind—the ever-present stream of plasma and charged particles released by the Sun.
- ✦ **Some people consider the boundary between the thermosphere and exosphere as marking the edge of Earth's atmosphere.** That's because atmospheric particles in the exosphere don't really act like a gas. Like the exosphere of Mercury, Earth's exosphere has so few particles that collisions happen extremely rarely. That means the atoms or molecules in the exosphere don't have the typical motions of gases, bouncing around between collisions. Instead, the atoms and molecules are on ballistic trajectories, as if someone had thrown them like baseballs in the high atmosphere.
- ✦ It's this low density of particles that can make the exosphere an attractive location to put satellites into orbit. Lower orbits tend to degrade due to air drag on the satellite, unless the satellite has significant fuel to boost the orbit over time.
- ✦ These days, there are thousands of artificial satellites in Earth orbit, with altitudes ranging from a few hundred kilometers to around 35,000 km (or 22,000 mi).
- ✦ In low Earth orbit, one network is the Iridium satellite constellation, with 66 satellites in polar orbits at an altitude of about 780 km (or 485 mi). It takes about 100 minutes for one satellite to complete an orbit.
- ✦ Satellites in medium Earth orbit, around 20,000 km (or 12,000 mi) in altitude, orbit once every ½ of a day.

- + Far above the exosphere is where the Global Positioning System (GPS) satellites are found; there are about 30 GPS satellites in orbit at any given time.
- + Even higher, there's a very special orbit where satellites can stay in the same location overhead at all times. This can be useful for communication, weather, or other monitoring of a specific location. This is called geostationary orbit, and it's achieved at the altitude where the satellite's orbital velocity is just slow enough to match Earth's rotational velocity: around 35,000 km (or 22,000 mi) above Earth's surface. But it can only be achieved above the equator, so spaces are limited.

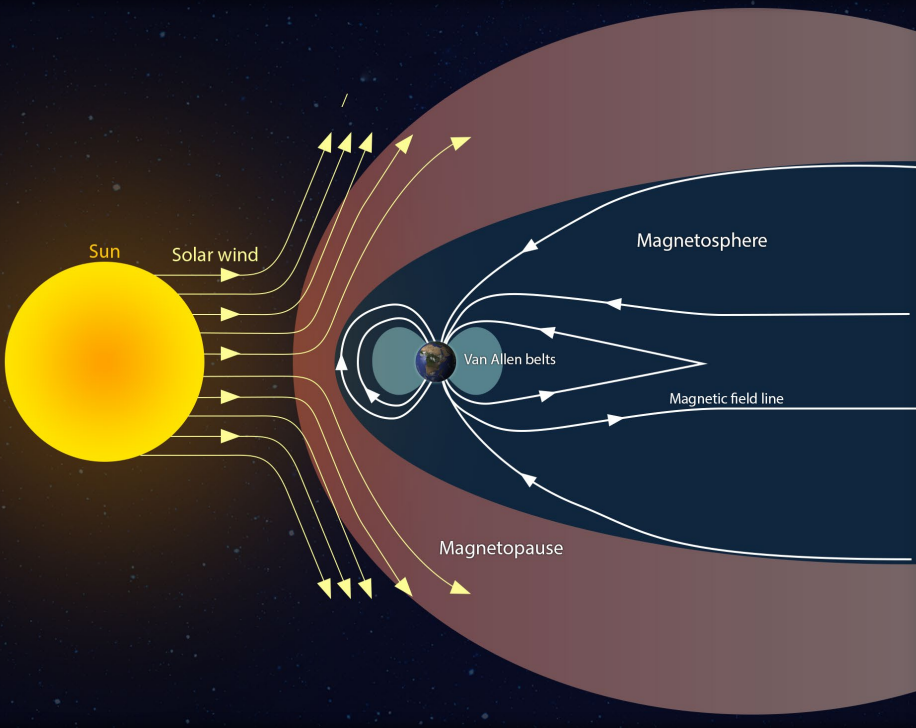


With so many satellites in orbit and more being planned in the future, concerns have been raised about space debris. In 2018, it was estimated that of some 4900 satellites in orbit, only 40% of them were operational. The rest were, essentially, space debris.

In addition, there are also spent rocket stages and bits and pieces from collisions of objects. We can't see or track the smallest of debris, but it's estimated that there are hundreds of millions of debris pieces orbiting Earth.

MAGNETOSPHERE

- ✦ The Sun spews out a continuous stream of high-energy particles through the solar wind. If these particles were to bombard orbiting satellites, their electronics would be severely damaged, rendering them useless.
- ✦ Luckily, **Earth has provided its own shield to the solar wind: our magnetosphere.** Although the Earth's magnetic dynamo operates deep in Earth's core, the magnetic field it generates reaches out to large distances above the Earth's surface. It forms a protective bubble because the high-energy particles from the solar wind are ionized and therefore have a difficult time penetrating strong magnetic fields. Instead, the solar wind gets diverted around the Earth.
- ✦ The size of the magnetosphere depends on both the intensity of Earth's magnetic field as well as the ram pressure from the solar wind. On the side of Earth facing the Sun, the magnetosphere extends out to the distance where the magnetic pressure from Earth's magnetic field equals the ram pressure from the solar wind. This boundary is known as the **magnetopause**. The altitude of the magnetopause varies a lot because the solar wind varies in its intensity, but it is on average around 60,000 km (or 37,000 mi) above Earth's surface.
- ✦ However, the influence of Earth's magnetic field on the solar wind extends to a much greater distance, even beyond the magnetopause. That's because the solar wind has to slow down in order to divert around the magnetopause. The distance where a large drop in solar wind speed occurs is known as the **bow shock**. On Earth, the bow shock is located about 90,000 km (or 56,000 mi) from the surface.



- † On the far side of Earth, the solar wind has been routed around the planet, causing the magnetosphere to form a long tail that reaches even beyond the Moon's orbit. That means the Moon flies through Earth's magnetotail once every lunar orbit.
- † Although Earth's magnetosphere shields us from the worst of the solar wind, some high-energy particles still get into the magnetosphere. They end up creating giant radiation belts around Earth known as the Van Allen radiation belt. Once inside the magnetosphere, ionized particles from the solar wind can get rapidly accelerated by spiraling around Earth's magnetic field lines. It's these particles that create the aurora in the polar regions.

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LECTURE 6

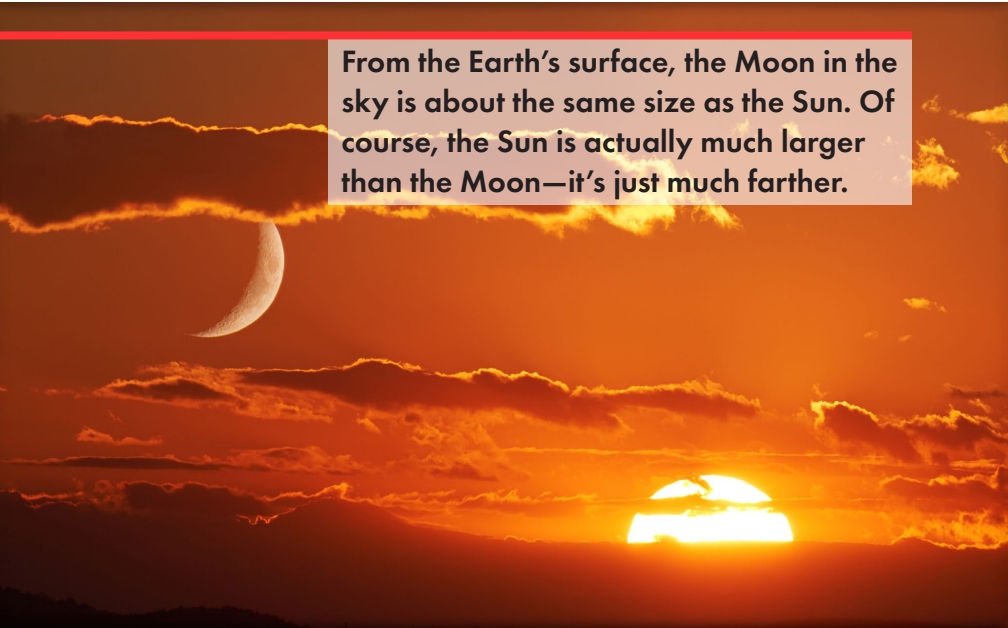
Exploring the Earth-Moon System



Near the top of the list of reasons for what makes Earth so different from Mercury or Venus is that Earth has a Moon. The Earth and Moon are intrinsically coupled as a system, and each body affects the other. The Moon stabilizes Earth's axial tilt, and that stabilizes our seasons and climate. It is responsible for the length of our day and the tides of our oceans, and it provides a source of natural light at night.

COMPARING THE MOON AND EARTH

- + As moons go, ours is relatively close; it's closer than about $\frac{2}{3}$ of all moons to their respective planets. But there are some 50 moons in the solar system that are closer to a planet.
- + What's more unusual about our Moon is how big it is, especially relative to the planet it's orbiting. Earth's diameter is only about 3.5 times larger than our Moon, and that's quite unusual. Not until we get to Pluto will we see a planet—actually a dwarf planet—whose moon is so large relative to the planet.
- + The Moon's composition is quite similar to Earth's, where the biggest difference is that the Moon has so much less iron and therefore a smaller core at the center. Having only a small iron core means the Moon is much less dense than Earth, and that's another reason (besides size) why the Moon has only about 1% of Earth's mass.



From the Earth's surface, the Moon in the sky is about the same size as the Sun. Of course, the Sun is actually much larger than the Moon—it's just much farther.

- + Surface gravity on the Moon is much weaker, but you are closer to the center of the Moon. The net result is that **gravity on the Moon is 17% of Earth's surface gravity**. This low gravity is evident when you watch footage of astronauts on the Moon that seem to float and bounce over the surface, despite wearing suits and equipment that triple their mass.

The Earth and Moon are separated by a distance of about 30 Earth diameters. This distance would fit comfortably inside the Sun 3 times in a row.

THE MOON'S ORBIT AND PHASES

- + We see the Moon as a bright object in the sky. **The light we get from the Moon is reflected light that originally came from the Sun. And the Sun only shines on one side of the Moon at any given time. This is why the Moon has phases.**
- + The Moon makes a full orbit around Earth in 27 days (called a sidereal period), but the Moon's more familiar orbital period to reveal all its phases (called a synodic period) is about 29.5 days.
- + When the Moon is directly between the Earth and Sun, the Sun is only shining light on the side of the Moon facing away from Earth, so we don't see any of that light. That's when we experience a new moon.
- + As the Moon moves along in its orbit a bit, part of the Moon that the Sun is shining on becomes visible from Earth. We first see a waxing crescent moon. It's waxing because the size of the visible crescent will continue to grow until the Earth-Moon line is perpendicular to the Earth-Sun line. This is when the Moon has reached the first quarter, because we are seeing $\frac{1}{4}$ of the Moon's total surface.

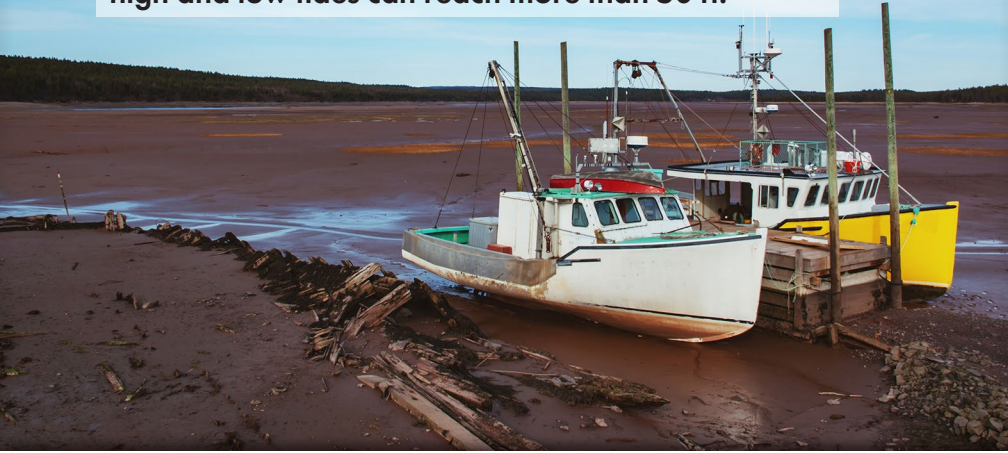
- ✦ From this point on, the inward-curving crescent is replaced by an outward-curving shape called a waxing gibbous moon. This happens until the Moon is directly on the opposite side of the Earth from the Sun, which is called a full moon, where you can see an entire $\frac{1}{2}$ of the Moon.
- ✦ From this point on, we start seeing less and less of the Moon going through the waning gibbous phase to the last quarter. Then there's a waning crescent phase until the Moon is in between the Earth and Sun once again and the cycle repeats.
- ✦ If the Moon orbited the Earth in the same plane as the Earth orbits the Sun, that would mean that we would see a solar eclipse at every new moon (because the Moon would be directly between the Earth and Sun) and a lunar eclipse at every full moon (because the Earth would be directly between the Sun and Moon). But that's not what we see. Earth averages only a few lunar eclipses per year and somewhat less than one total solar eclipse per year. That's because the Earth-Moon orbital plane is tilted by about 5° from the Sun-Earth orbital plane.
- ✦ So the Sun, Moon, and Earth don't really make a straight line during every new moon and full moon. It just looks like they do when you look at the orbits from above.
- ✦ Eclipses only occur when the Moon is at new or full phase at the same time that it is in the same plane as the Earth-Sun orbit. We have a total eclipse only when the Moon is perfectly aligned. The rest of the time, we have partial eclipses, where the Moon isn't exactly in the same plane.
- ✦ At its closest point to Earth, known as perigee, the Moon measures about 12% bigger compared to when it's at the farthest point from Earth, or apogee. Full moons at their perigee are sometimes called supermoons, whereas full moons at apogee are called micromoons.

LUNAR TIDES

- + The Moon's gravity is responsible for the lunar tides. Tides occur because the force of gravity depends on distance. The closer you are to a massive object, the stronger the gravitational force from that object is.
- + The near side of Earth is roughly 59 Earth radii away from the Moon, but the far side of Earth is 61 Earth radii away. Because different locations on Earth are different distances away from the Moon, the force of the Moon's gravity at those locations is different, too. The Moon's gravitational pull is weakest on the opposite side of Earth and strongest when the Moon is closest, which is directly overhead.
- + The difference in the Moon's gravitational force between the near and far sides of Earth is about 7% of the average force, but it's enough to change the sea height by a few feet on average.
- + But the tides are more variable than what you would expect just from the Moon's gravity and motion around the Earth. There are a few complicating factors:
 - 1 The Moon's elliptical orbit means that the Moon's distance from the Earth changes. The closer the Moon, the stronger the gravitational force, so we tend to experience higher tides when the Moon is at perigee.
 - 2 We also experience solar tides! They work exactly the same way as lunar tides, but the high solar tides occur at the points closest to and farthest from the Sun. The Sun is much farther from the Earth than the Moon is, but the Sun is also much more massive. These 2 factors combine such that the solar tidal force is about $\frac{1}{2}$ as strong as the lunar tidal force.

- 3** The shape of the ocean bottom near the shore, and the currents and waves in the region, will also affect how high the tides can be at a particular location.
- ✦ The oceans aren't the only part of the Earth that experiences tides. Even the solid portions of the Earth are affected by the gravitational forces of the Moon. Of course, solids are more resistant to changing their shape when they experience a force than liquids are, so the solid tide heights are much smaller than the ocean tides. They max out at about 1 foot.
 - ✦ The fact that solid material also flexes due to tides means that the Moon also experiences tides due to the Earth's gravitational force. The Moon has a stagnant tidal bulge that is roughly 20 inches on both the near and far sides of the Moon, and it changes only a few inches.
 - ✦ But we've also recorded the tidal forces the Moon experiences in the form of deep earthquakes on the Moon, or moonquakes. We know they're related to tides because they occur in sync with several periodicities of the Earth-Moon system.
- Four seismometers left by the Apollo missions measured more than 7000 seismic events on the Moon that were triggered by tides between 1969 and 1977.
- ✦ Tidal forces also have some unexpected consequences. They cause the days to get longer on Earth and the Moon to move farther away from Earth—at a rate of about 1.5 inches per year. Shortly after the Moon formed, about 4.5 billion years ago, the Moon may have been as much as 7 times closer to the Earth. Back then, Earth was also spinning so fast that the length of Earth's day was only a few hours!
 - ✦ But over time, the spin rate has slowed down as a result of the Moon's gravity. Presently, that rate of slowing is about 2 seconds every 100,000 years, or about 2 milliseconds each century.

The highest tides experienced on Earth occur in the Bay of Fundy between Nova Scotia and New Brunswick in Canada, where the difference between high and low tides can reach more than 50 ft.



- + Tidal forces are also responsible for perhaps the most notable feature of the Moon's orbit: We always see the same face of the Moon from Earth's surface. That means that the Moon's rotation period is equal to its orbital period, called a lunation; in other words, the Moon's year is the same length of time as its day.

THE MOON'S EFFECT ON EARTH'S ROTATION STABILITY

- + In addition to slowing Earth's rotation, the Moon also stabilizes Earth's rotation axis in space. Without the Moon, Earth's spin axis would be more vulnerable to external gravitational forces from other planets. This would change the climate. What we benefit from is the angular momentum associated with the Moon's orbit.

- ✦ Spinning objects, like Earth, have angular momentum. If you want to change the direction of Earth's rotation axis, you have to change its angular momentum. To do that, you have to apply a big force in the direction of the rotation change you want. That's called a **torque**. The larger the angular momentum of an object, the larger the torque you need to change the angular momentum.
- ✦ The Earth and Moon form a system that has angular momentum due to 3 factors: the Earth's spin about its rotation axis, the Moon's spin about its rotation axis, and the Moon's orbital motion (which is a revolution around the Earth). The Moon orbiting the Earth is the largest factor in the Earth-Moon system—4 times larger than the Earth's rotational angular momentum.
- ✦ So to change the Earth's spin axis, you have to apply a much larger torque to overcome the combined angular momentum of the Earth-Moon system than you would if the Earth had no large Moon. **Because the Moon has stabilized our rotation axis, the Earth has experienced more climate stability than it would without a Moon.**

THE FORMATION OF THE MOON

- ✦ **We know that the Moon couldn't have formed as a separate body at the same time as the Earth** because the bodies would be too close and the Earth would have just accreted it during the chaotic solar system formation period, combining into a bigger Earth, with no Moon.
- ✦ **So the Moon must have come later—but not too much later.** The oldest lunar rocks brought to Earth from the Apollo missions have minerals that are 4.51 billion years old; this means that the Moon formed within about 50 million years after Earth's formation.

- + The best theory we have for how the Moon formed is called the **giant impact hypothesis**. The idea is that a giant impact occurred between a Mars-sized protoplanet, given the name Theia, and the proto-Earth. The impact sheared Theia apart, and most of it merged with Earth except for a small amount of material, which ended up in a disk orbiting around Earth. The material in the disk eventually coalesced into the Moon, just like the planets coalesced from a disk around the Sun.
- + Going from the time of the hypothesized giant impact to a Moon-sized body orbiting the Earth took about a month, or maybe a year. That's incredibly fast! For comparison, formation of the Earth probably took millions of years.
- + But the Moon just after the collision would have been hot enough that at least the outermost 200 to 300 km (about 125 to 185 mi) were entirely molten. We know this because the crust of the Moon is primarily made of an igneous rock called **anorthosite**. This anorthosite crust was formed when buoyant rocks floated to the top of the lunar magma ocean.

As the Moon gets smaller in our sky, there will come a time when it's too small to cause a total eclipse of the Sun. That might be 600 million years in the future.

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Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.

QUIZ

LECTURES 1-6

- 1 Why couldn't an ice giant planet form in the inner solar system? [L1]
- a The other terrestrial planets would have gravitationally perturbed it to the outer solar system.
 - b The temperatures in the inner solar system were too hot for ices to condense in the inner solar system.
 - c All of the ices in the solar system were found at Uranus's and Neptune's current orbital distances.
- 2 Active volcanism over the last few decades occurs on which of the following planetary bodies? (Choose all that apply.) [L1]
- a Venus
 - b Earth
 - c Moon
 - d Mars
 - e Io
 - f Ganymede

- 3** How can Mercury have ice on its surface if temperatures reach more than 400°C ? [L2]
- a** Mercury's magnetic field shields the ice from sublimating.
 - b** Mercury's atmosphere keeps regions of the planet cold enough for ice to form.
 - c** Because Mercury has no atmosphere, permanently shadowed regions in polar craters stay cold enough to harbor ice from comet impacts.
- 4** If Mercury's orbit were perfectly circular, rather than elliptical, would there be times where the Sun changes direction in the sky? [L2]
- 5** Why does Venus lack a global magnetic field generated by a dynamo? [L3]
- a** Venus's iron core is not cooling fast enough to generate a dynamo.
 - b** Venus doesn't have an iron core.
 - c** Venus is rotating too slowly to generate a dynamo.
- 6** Why does Venus lack water? [L3]

- 7** Why is Earth's surface younger than the Moon's and Mercury's? [L4]
- a** Earth formed later than the Moon and Mercury.
 - b** Earth experienced a global resurfacing event.
 - c** Earth's surface is recycled constantly through plate tectonics.
- 8** List 3 ways plate tectonics may be responsible for making Earth habitable. [L4]
- 9** What are 2 hazards for satellites in Earth orbit? [L5]
- 10** Why do typical passenger airplanes fly at about 12 km (7.5 mi) in altitude? [L5]
- 11** Solar eclipses are only possible when the Moon is in which phase? [L6]
- a** new moon
 - b** first quarter
 - c** full moon
 - d** last quarter

12 What is the best theory we have for how the Moon formed? [L6]

- a** The Moon formed as a separate planet near Earth's orbit and was gravitationally captured by Earth.
- b** The Moon broke off from the early Earth due to the Earth's early rapid rotation.
- c** The Moon formed when Earth experienced a glancing impact by a Mars-sized body.

Answers can be found on page 297.




LECTURE 7

Humans on the Moon: A Never-Ending Story



The human adventure in space truly began when we set foot on the Moon. From that first step on July 20, 1969, to the end of 1972, 12 astronauts walked on the Moon at 6 different landing sites. The Apollo missions carried out science activities ranging from placing seismometers, magnetometers, and retroreflectors on the surface to collecting lunar samples to return to Earth. The lunar samples collected by the Apollo astronauts have helped unlock scientific mysteries like how old the Moon is, how it formed, and what it's made of.



In 1969, Apollo 11 was the first mission that landed humans on the Moon, and by the end of 1972, there had been 6 successful human-landing missions during just a 4-year period.

THE APOLLO PROGRAM

- ✦ The Apollo program was revolutionary, and signs of the Apollo missions on the Moon persist to this day. Of course, there are the various equipment and spacecraft parts left behind, but even Moon buggy tracks and astronaut walking paths can still be seen on the surface.
- ✦ The astronauts who landed on the Moon became immediately aware that the surface is covered in a layer of loose dust and broken rock known as regolith. This is the end result of the Moon's surface having been impacted over and over again—for 4.5 billion years.
- ✦ The Apollo missions collected 2200 rock samples weighing almost 400 kg (880 lbs) that were all brought back to Earth for analysis. The analysis of those rocks on Earth has helped us determine that the Moon has a similar composition to the Earth's mantle and that the Moon formed very early in solar system history. The Moon has also experienced large impacts and volcanism.

- + One of the most important results was the determination of the age of different parts of the lunar surface. We can tell the relative ages of parts of a planetary surface by looking at how cratered the surface is. But we need radiometric dating of the rocks to tell the absolute age—that is, put a number on the age.
- + Once we know the absolute age of a rock coming from one region and the crater density of that region, we can figure out the ages of other regions on the surface with the same crater density, even if we don't have samples. So we can figure out the ages of large regions of the Moon's surface from just a handful of samples brought back to Earth. And importantly, we can translate that information to figure out the absolute ages of the surfaces of other planets even if we don't have samples.

GEOLOGY OF THE MOON

- + The lighter regions on the Moon's surface are known as the lunar highlands. They are, as advertised, higher in altitude than the darker regions—on average, about 1 to 2 km (or about 1 mi) higher. The highlands are also the oldest regions on the Moon's surface, dating back more than 4.5 billion years, and they are made of a coarse igneous rock known as anorthosite.
- + The dark regions are very flat, low-lying regions on the Moon. Some of them are fairly circular as well. Early astronomers thought they were seas and therefore named these features maria, which is Latin for “seas.” The maria aren't really seas, or even liquid; instead, they are solidified ancient lava flows.

The largest of the maria—Oceanus Procellarum, or “Ocean of Storms”—has about the same area as the 6 largest US states combined: Alaska, Texas, California, Montana, New Mexico, and Arizona.

- ✦ The maria are made up of basalt, a volcanic rock that's also seen in Earth's volcanic regions. The basalts in the maria are darker than the surrounding regions because they have more metallic iron. The lunar maria are generally younger than the rest of the surface. Most of the maria are dated between 3 billion and 3.5 billion years ago, while some of the youngest maria may only be about 1.2 billion years old.

CRATERS

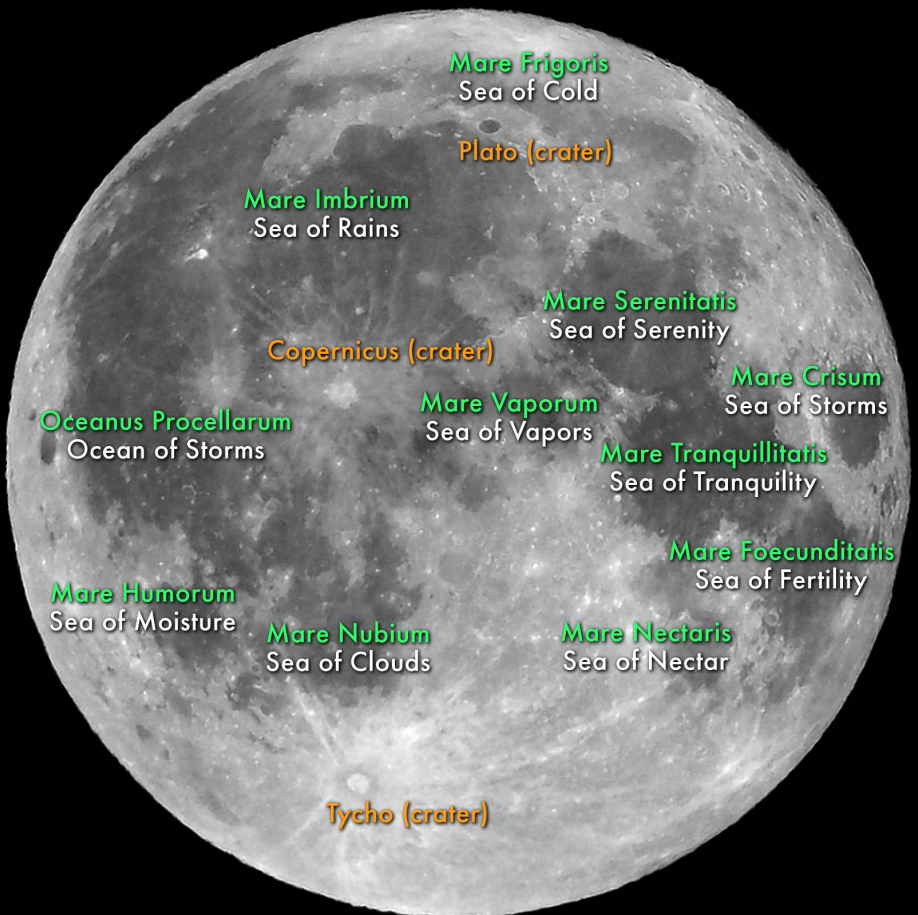
- ✦ **The Moon is covered with impact craters.** Craters can have different shapes and features based on how big they are. That helps us determine the size of the meteor that impacted the surface, forming the crater. On the smallest end are simple craters, which are bowl-shaped craters with sharp rims.

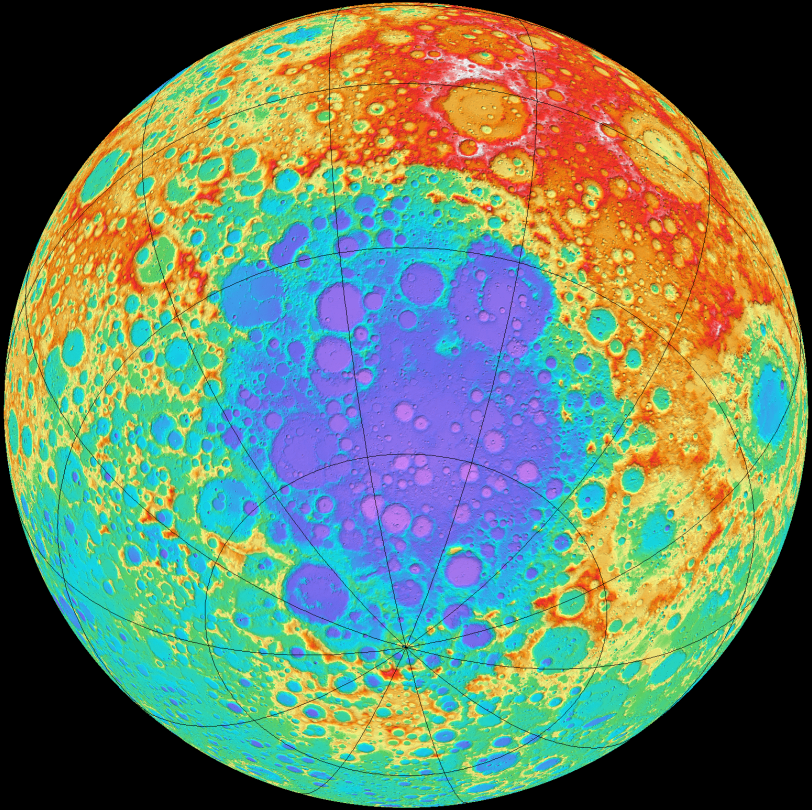
- ✦ Near the southern edge of Mare Tranquillitatis—the site of the first lunar landing by Apollo 11—is a simple crater named Moltke. It has a diameter of 6.5 km (about 4 mi) and a depth of 1.3 km (about 1 mi). Note that the depth of the crater is about 20% of its diameter. It turns out that all simple craters—whether on the Moon, Earth, Mercury, or Mars—have depth-to-diameter ratios in the range of 14% to 20%.

Mare Tranquillitatis, or “Sea of Tranquility,” is not actually a sea. It's an impact crater that was filled in with lava that solidified into rock billions of years ago.

- ✦ **Bigger craters end up having a different shape than simple craters.** For example, Tycho, near the south pole of the Moon, can actually be seen from Earth because it's so bright. It's so noticeable because it's a fairly young crater, only about 100 million years old. The impact ejected much of the older, darker material from the surface, revealing the fresher layer underneath.

- + Tycho is about 85 km (about 53 mi) in diameter, which is more than 10 times bigger than the simple crater Moltke. Tycho has some typical features that occur in craters of this larger size. First, the floor is quite flat, but then there is a peak or mountain at its center. The walls of the crater are also terraced due to slumping of the material at the rim of the crater after it formed. Craters like this are known as complex craters.



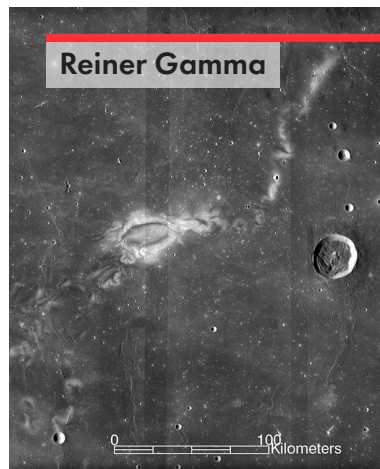


The largest confirmed crater on the Moon—and the second largest in the entire solar system—is the South Pole-Aitken (SPA) Basin, which is about 2500 km, or 1600 mi, in diameter. It would span the distance from New York City to Denver.

- + Interestingly, the point at which simple craters transition to complex craters is different for different planets, based on their gravity. Smaller bodies, like the Moon, where the gravity is only 17% of that on Earth, have simple craters even at larger diameters. On Earth, more intense gravity causes complex craters to form at smaller sizes than are found on the Moon.
- + As craters get even bigger, the features become even more complex. For example, the central peak mountain can become a peak ring of mountains. The bigger a crater is, the more complex its morphology is. The impacts that create the largest craters have a lot of energy that results in lots of melting and deformation, even far away from the crater itself.

LUNAR SWIRLS

- + There are unusually bright features on the Moon's surface called lunar swirls, such as Reiner Gamma, which you can even see from Earth with a small telescope. It kind of looks like a tadpole, with a body region that's around 50 km (31 mi) in diameter and a tail that extends out about another 100 km (62 mi). The bright parts are also kind of swirly—hence its name.
- + What's particularly intriguing is that the body region isn't just a uniform bright spot. Instead, the feature seems to have a sharp, dark oval ring inside of it. And even though the feature is really bright and noticeable, it doesn't



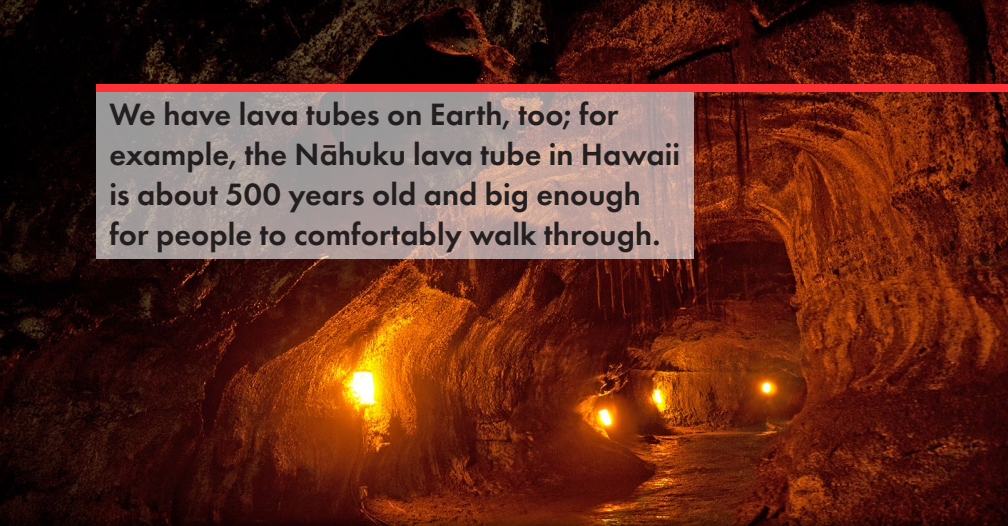
seem to be related to craters, or mountains, or any other tectonic process that might produce a noticeable topographic feature on the Moon.

Lunar swirls are some of the most otherworldly-looking features seen in the solar system. And the only place we've ever seen them is on the Moon.

- ✦ It turns out that lunar swirls are located in places that have strong magnetic fields in the rocks. And these magnetic fields may explain the bright and dark features in the swirls because of how they protect the lunar surface from high-energy particles in the solar wind.

LAVA CHANNELS AND TUBES

- ✦ Long, narrow, meandering depressions called sinuous rilles (which kind of look like dried-up rivers) are signs of the past flow of lava from volcanism on the lunar surface. They tend to be found attached to extinct volcanic vents, where the lava would have originated. We don't fully understand how these depressions formed, but one theory is that they are lava channels. Outcrops in the walls of some rilles show signs of layering, or stratification, a sure sign that material flowed through them.
- ✦ Another possible explanation for sinuous rilles is that they are collapsed lava tubes, which are subsurface empty conduits where lava previously flowed through. They may have started as channels, but the surface of the lava channel solidified while the interior stayed liquid, creating a sort of pipe for lava to flow through.
- ✦ But lunar lava tubes can be much bigger—perhaps hundreds of meters wide and hundreds of kilometers long—than their Earthly counterparts because gravity on the Moon is weaker. It's been suggested that lava tubes that haven't collapsed (and therefore still have their covering roofs) may



We have lava tubes on Earth, too; for example, the Nāhuku lava tube in Hawaii is about 500 years old and big enough for people to comfortably walk through.

be ideal locations for lunar bases. Here under the surface, humans would be shielded from both radiation and meteorites. This type of protection is particularly important because the Moon doesn't have an atmosphere that can provide some shielding from small meteorites and radiation.

WATER ON THE MOON

- + If humans do venture to spend significant time on the Moon, then in addition to a protective base, they'll also need resources, with water being a particularly important one. Without an atmosphere, temperatures on the Moon are directly related to where the Sun is shining. And they can be extreme.
- + Wherever sunlight hits the unprotected surface, the temperature can reach 260°F (125°C), so any water would evaporate away. Where the sun does not strike the surface, the temperature can reach -280°F (-175°C). And keep in mind that a day on the Moon lasts about 13 Earth days, so we don't expect water—whether liquid or solid—to be found in most places on the lunar surface.

- + But it turns out that **there is a bit of water on the Moon**. Water ice has been found at the bottom of some permanently shadowed craters in the polar regions, just like Mercury. There is also water locked up in minerals formed during explosive volcanic eruptions.
- + Interestingly, the fact that there is water in these erupted magmas suggests that **the deep lunar interior may be quite water-rich**. This is unexpected because the impact that formed the Moon involved very high temperatures and a molten Moon in which all of the water should have escaped. This suggests that water may have been brought to the Moon by comets or asteroids shortly after its formation, perhaps while it was still only partially solidified.

THE INTERIOR OF THE MOON

- + Clearly, the lunar interior has hidden some secrets from us. Some of those secrets have been revealed by special equipment left on the Moon by the Apollo missions.
- + First, there are **laser retroreflectors** that are used to study the rotational and orbital motion of the Moon. Using lasers, the distance between Earth and the Moon can be calculated very precisely—down to just a few centimeters! Lasers have been used to figure out the speed at which the Moon is moving away from Earth and to test Einstein's general theory of relativity. **Even changes in the Moon's rotation and wobble in its orbit have been measured and tell us about the deep interior of the Moon**.
- + **The Apollo missions also left seismometers on the surface of the Moon that have given us data about moonquakes**. There are deep moonquakes, likely due to tidal flexing of the Moon, but there are also shallow ones, ranging from 2 to 5 on the Richter scale, that are caused by tidal forces

in combination with the Moon shrinking as it continues to cool. The moonquakes also made it possible to determine that the Moon has a small iron core that is only $\frac{1}{4}$ to $\frac{1}{3}$ the diameter of Earth's iron core.

- ✦ The Moon doesn't have a global magnetic field generated by a dynamo today, but the iron core is at least partially liquid, leaving open the possibility that the Moon did have a dynamo in its past. We think this is likely because of the crustal magnetic field we see in the rocks at the surface. Even some lunar samples are magnetized. Based on the ages of the magnetized lunar samples, scientists have determined that a dynamo was active by at least 4.2 billion years ago and may have lasted until just 1 billion years ago.

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LECTURE 8

Exploring Mars from Space and the Ground



The Red Planet: That's probably the most iconic way of describing Mars. The reddish hue comes from iron oxide minerals—actual rust—that make up its dusty surface.

MARS'S ORBIT, ROTATION, AND SEASONS

- ✦ Mars orbits the Sun from a distance of about 1.5 times Earth's orbital distance, or 1.5 astronomical units. So **the orbit of Mars is roughly 75 million km, or 47 million mi, from the orbit of Earth**—almost 200 times the distance between the Earth and Moon. Because the orbits are not perfect circles, there are rare cases when Mars and Earth can come as much as 25% closer.
- ✦ **But spacecraft that travel from Earth to Mars actually take a much, much longer path**—6 times longer than the average distance between the orbits. The Mars InSight mission, for example, traveled almost 500 million km (or 310 million mi) to get to Mars, and it took more than 6 months.



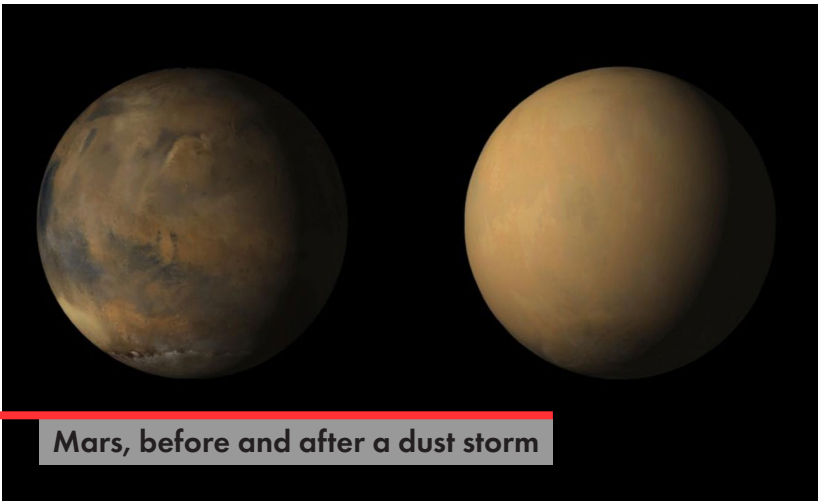
The Mars InSight mission landed on Mars in November 2018 and placed a seismometer on Mars's surface to record earthquakes—or marsquakes—which were first detected in early 2019.

- + That's because spacecraft don't just shoot out and travel in a straight line between Earth and Mars. That would take too much fuel, as the spacecraft would have to overcome the Sun's gravitational field. Instead, spacecraft traveling away from the Sun use what's called a Hohmann transfer orbit to be as fuel efficient as possible.
- + The length of one day-night cycle on Mars, known as a sol, is 24 hours, 39 minutes, and 35 seconds. The fact that this is quite close to the length of a day on Earth is a great coincidence. But it does mean that we wouldn't have to adjust our internal clocks too much if we were to visit Mars.
- + Mars also has seasons because the planet's rotation axis is tilted relative to its orbital axis. The tilt is currently about 25°, quite similar to Earth's tilt of 23.5°. Because Mars's year is almost twice as long as Earth's, this means the seasons are also almost twice as long.

MARS'S ATMOSPHERE

- + Whereas Venus has a very thick atmosphere, with a surface pressure of about 92 bars (which is 92 times Earth's surface pressure), Mars has a very thin atmosphere. The surface pressure on Earth is 200 times that on Mars, which has a surface pressure similar to the lower mesosphere of Earth—too thin to support balloons, but too much friction for satellites. The atmosphere that Mars does have is 95% carbon dioxide, which is very similar in composition to Venus. There's just not much there.
- + Standing on Mars's surface, you would experience the same atmospheric pressure as you would at 35 km (22 mi) in altitude on Earth. Water in the human body boils away at about 6% of a bar, but pressure on Mars is only 1/10 of that critical value (only 6 millibar). The near-vacuum on Mars means human visitors would need pressure suits on the planet.

- + This very low surface pressure also means that it would be very hard to feel the impact of winds on Mars. So even though Mars can have moderately fast winds and storms, with wind speeds around 70 kph (38 mph), those winds probably wouldn't knock over a person or break apart antennas on mechanical equipment, unlike how it's sometimes depicted in sci-fi movies.
- + Even so, the Mars winds can push around dust. And Mars appears to have a lot of dust to push around. For example, Mars has frequent dust devils, or small hurricanes of dust that leave dark streaks on Mars's surface that can even be seen from orbit. The Curiosity rover has caught dust devils in action as well.
- + On a larger scale, Mars also experiences dust storms, where massive amounts of dust are lofted off the surface by winds and get carried around, typically covering a continent-sized area and lasting several weeks. These dust storms happen about once every Martian year, typically when Mars is at its closest point to the Sun and receiving more sunlight.

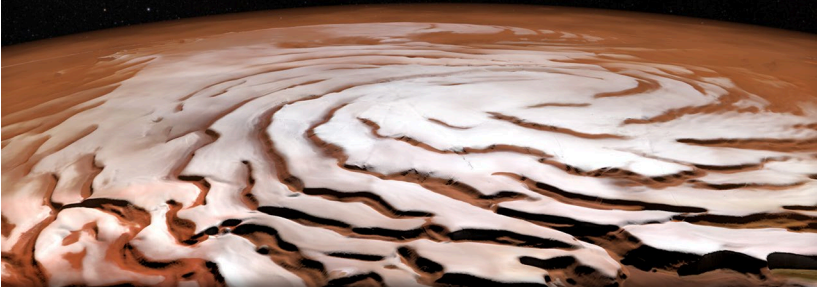


- ✦ But sometimes these local dust storms can become planetwide dust storms. In 1971, the very first mission to orbit Mars, Mariner 9, observed a global dust storm. In all, 7 global dust storms have been detected between 1971 and 2019—and there may have been more!

MARS'S POLAR CAPS

- ✦ **Mars has seasons**, as we can see from the migration of its polar ice caps. **Both of Mars's poles have permanent frozen water ice caps all year long.** The ice cap at the north pole is around 1000 km (600 mi) across in the summer and contains about $\frac{1}{2}$ as much ice as the Greenland Ice Sheet on Earth. The southern polar cap has about the same volume as the northern cap but contained in a sheet that is smaller (at 350 km, or 218 mi, across) yet thicker.
- ✦ On top of these permanent ice caps of water is winter snowfall of carbon dioxide. When winter hits a particular hemisphere, about $\frac{1}{4}$ to $\frac{1}{3}$ of the carbon dioxide in the atmosphere freezes and snows on top of the water ice at the pole. So essentially, a polar cap made of carbon dioxide dry ice is added to the water ice cap each winter.
- ✦ Then, when summer comes along, the dry ice sublimates, putting carbon dioxide back into the atmosphere. And at the same time, the other hemisphere is experiencing winter, and the carbon dioxide in the atmosphere freezes onto the other polar cap. This cycle repeats with each Martian year.
- ✦ The caps are covered in pits, hills, and cracks and have interesting spiral patterns, with dark troughs appearing in the bright ice. This happens because the ice caps were created over time with different layers freezing

Mars's north polar ice cap

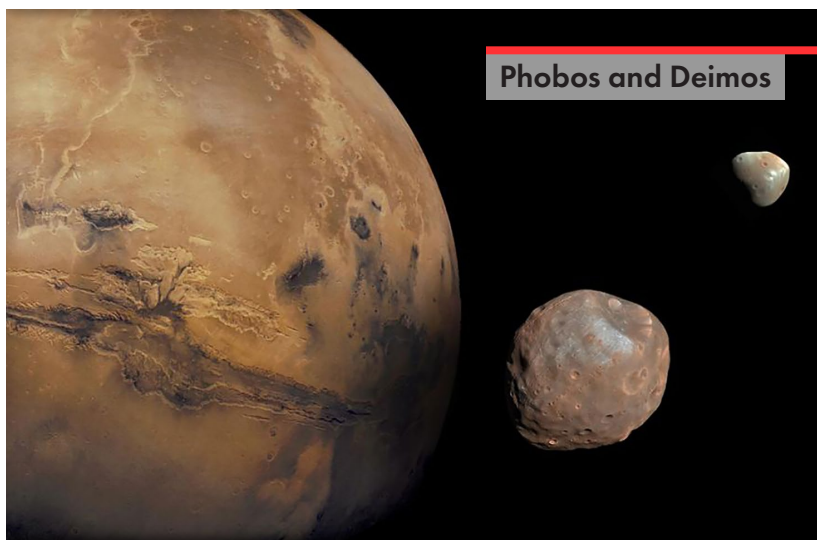


onto the cap each season. Some of those layers have more dust than others. The dustier layers are created when there is a large dust storm. These layers of dust in the ice cap get revealed by wind erosion of the ice.

- + We can use these layers kind of like tree rings to study how the ice cap grew and what the climate was like earlier on Mars. Variations in the layers have been linked to changes in the tilt of Mars's rotation pole, which for the last 5 million years or so has ranged from about a 15° tilt to a 35° tilt—much less and much more than today.
- + The fact that Mars's axis tilt changes so substantially means that **climate on Mars changes substantially**. The tilt of the pole influences how much solar energy reaches the polar regions. In centuries when the tilt is greater, more of the polar region receives sunlight and the polar cap melts and retreats. When the tilt is less, more of the polar cap stays colder and in shadow for longer periods, so the polar cap can grow.
- + **Why does the axial tilt change so much on Mars?** Unlike Earth, Mars doesn't have a large moon to keep the angular momentum of Mars stable. Mars is also especially vulnerable to Jupiter, whose gravitational influence can change Mars's axial tilt.

MARS'S MOONS: PHOBOS AND DEIMOS

- + Mars does have 2 small moons, but they're too small and close by to stabilize against the influence of Jupiter. Phobos is only about 22 km (14 mi) in diameter; Deimos is about 12 km (7 mi) in diameter and 7 times less massive than Phobos.
- + Phobos orbits extremely close to Mars—actually, closer than any other moon orbits a planet in our solar system. At about 6000 km (3700 mi) above the Martian surface, Phobos is 3 times closer to Mars than GPS satellites are to Earth.
- + Because Phobos is so close to Mars, it orbits very quickly, taking less than 8 hours to complete one full circle around Mars. So the moon orbits faster than Mars rotates (a little more than 24 hours). An observer on Mars would see Phobos rise in the west and traverse the sky in a little more than 4 hours. And this moonrise typically happens twice a day!



- + Phobos orbits in the Mars-Sun plane, which means solar eclipses happen every time Phobos passes in front of the Sun—so about twice a Martian day! And even though Phobos is small, it's so close to Mars that it actually blocks a lot of the Sun during an eclipse, but never the whole Sun, so they are partial eclipses. The eclipses last only about 30 seconds.
- + Being so close to Mars, Phobos also experiences significant tidal forces from Mars, and these forces are decreasing Phobos's orbit over time. In about 50 million years, Phobos will be ripped apart by these tidal forces.
- + **Deimos, on the other hand, acts much more like a normal moon.** Its orbit is almost 4 times as far away, more than 23,000 km (14,000 mi) from Mars's surface. Deimos has an orbital period of around 30 hours, which is longer than Mars's rotation period. This means that Deimos rises in the east and sets in the west, just like Earth's Moon does. But because Deimos's orbital period is quite close to Mars's rotation period, Deimos doesn't appear to move very fast in the sky. If you were standing at the equator of Mars, it would take about 2.5 Martian days for Deimos to rise and set.
- + Because Deimos is so much farther from Mars and so much smaller, it doesn't really cause visible eclipses, even though it does pass in front of the Sun regularly. It looks more like a small dot crossing the Sun during one of these eclipses.
- + Deimos also won't suffer the same fate as Phobos. Instead, Deimos is slowly moving away from Mars, just like Earth's Moon is moving away from Earth.

Because Mars has 2 moons in the same plane, Phobos can lunar-eclipse Deimos! The Curiosity rover observed such an eclipse from Mars's surface in 2013.

MARS'S SURFACE AND INTERIOR

- + Choosing a landing site for a Mars rover or lander is quite involved. You have to balance finding a scientifically interesting place to land with a relatively safe place to land. In terms of safety, you want a place that's relatively flat and doesn't have too many rocks or boulders that may cause the lander to tip over while landing.
- + Mars's surface boasts several volcanoes, mountains, and canyons. At about 26 km, or 16 mi, high—almost 3 times the height of Mount Everest on Earth—Olympus Mons is the largest-known mountain in the solar system. This one mountain has an area that is comparable in size to France and larger than Texas and California combined!



Olympus Mons's last eruptions occurred about 115 million years ago.

- + **Mars's surface is also covered with impact craters.** Chryse Planitia (“Plains of Gold”) was one of the first places explored by a Mars lander spacecraft. Visited by Viking 1 in 1976, it is believed to be a large impact crater. There are also signs that water once flowed in the region.

The history of robotic exploration of Mars has been filled with more heartbreaking failures than triumphant successes. In fact, only about $\frac{1}{3}$ of Mars-destined missions made it safely to their destinations.

- + **Mars has a crust, mantle, and core, just like Earth.** The iron-rich core is about $\frac{1}{2}$ the radius of Mars. Mars's mean density is almost 4000 kg/m^3 (or about 250 lb/ft^3). Its radius is about $\frac{1}{2}$ that of Earth and twice that of the Moon. Because Mars is a small planet, its uncompressed density isn't much different from its mean density, only about 8% less. For comparison, Earth's uncompressed density is a very similar 4200 kg/m^3 (or about 262 lb/ft^3). This tells us that Mars's composition is quite similar to Earth's.
- + **Mars has no global magnetic field today.** However, the crust has magnetized rocks, indicating that Mars did have a dynamo in its past. The magnetized rocks appear in the oldest regions of Mars, and based on crater counting of the surfaces that are magnetized, we think Mars's dynamo died about 4 billion years ago.

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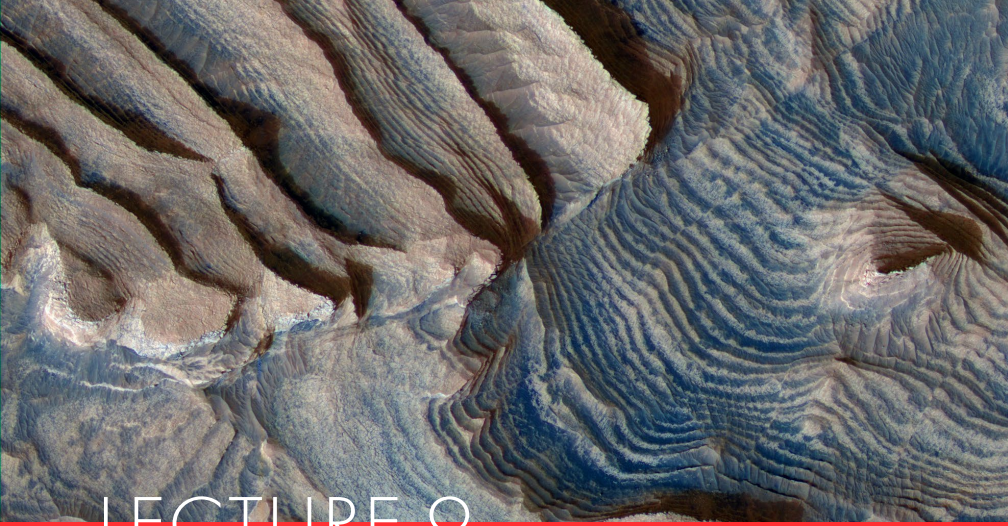
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LECTURE 9

Water on Mars and Prospects for Life



Mars has very little atmosphere, temperatures that make Antarctica look like a tropical vacation spot, and no stable liquid surface water. But Mars wasn't always such a barren landscape. In fact, evidence suggests it used to be quite different, perhaps even much bluer, with warm temperatures, a thicker atmosphere, and even the possibility of water oceans.

WATER AND LIFE

- + There is no evidence for large bodies of liquid water anywhere on Mars today. But there is lots of evidence for frozen water ice. First, there are the polar ice caps. But even in more equatorial regions, there are signs that Mars may have large amounts of permafrost, or icy soils just below the surface. Enough ice has been detected that it would cover the entire surface of Mars in a layer that is 35 m (115 ft) high if spread evenly.
- + But what about liquid water? Because of Mars's low atmospheric pressures and cold temperatures, liquid water is not stable on Mars's surface.
- + We have seen signs of temporary unstable liquid water on Mars's surface. Dark streaks appear on some crater rims and tend to form when the walls of the crater are warmed in the spring and summer seasons. The dark streaks fade as the year goes on and appear again the next season.
- + It's possible that these features, called recurring slope lineae, are formed by liquid water trickling down the slopes of craters. The water comes from melting of the ice that is buried in the shallow subsurface but happens to get exposed in crater walls. But to explain why the water is liquid, it must be very salty, like a brine, because salt reduces the freezing temperature of water.
- + Although salty water near the surface is interesting, the emergence of life probably requires liquid water that is stable for long periods of time. And liquid water could be stable on Mars deep in the subsurface, where the pressures and temperatures are higher. One possible location for subsurface liquid water would be under the polar ice caps, because we already know there is frozen water there.

The Mars Reconnaissance Orbiter has imaged many craters over time, so we can see how they've changed.

- + We believe that water is essential to life—at least life as we know it—because biochemical reactions take place in liquid water. This has led to a Mars exploration philosophy of “follow the water”: Find the places on Mars where liquid water could be stable for long periods of time, because that’s where life could be.
- + So Mars-based life today is challenging. Based on our understanding of the origin of life, it’s no surprise that the planet isn’t covered in it. The key issue is the missing ingredient of stable liquid water. So why do we keep looking for signs of life on Mars?
- + The answer lies in the many clues that suggest Mars used to be much wetter. There is evidence that liquid water was stable on the surface of Mars in its early history. And the only way Mars’s surface could have had stable liquid water is if the atmospheric pressure was higher and the surface was warmer.

GEOMORPHIC EVIDENCE

- + There are 3 types of independent observations that have led to the conclusion that Mars once had stable liquid water on its surface. The first set of observations is geomorphic evidence: shapes on the surface that appear to be the result of flowing water.
- + There are many places on Mars that look like they were formed from water based on our experience from Earth. For example, we see dried-up river valleys on Mars—more than 40,000 of them at last count. The largest and longest is Kasei Valles at about 2400 km (1500 mi) long. In Kasei Valles, we see where the ancient river split into 2 channels. We even see giant dried-up waterfalls, also known as cataracts.

+ Many of the smaller dried-up river valleys show signs of dendritic, branching networks and tributaries, which are typically signs of rainwater runoff on Earth.

+ There are also signs of streambeds, where round and angled pebbles and gravel indicate erosion by fast-moving liquids. Scientists use the shapes and sizes of the stones in the gravel to determine that the water was somewhere between ankle- and hip-deep and must have been flowing about 1 meter per second (3 ft/s).

The 2 largest cataracts in Kasei Valles have vertical drops of about 500 m (1600 ft) and extend horizontally for 100 km (62 mi). That's 10 times higher and 100 times wider than Niagara Falls.

Kasei Valles



- + We can also see evidence of dried-up lakes on Mars. In fact, the dried-up river valleys often lead into dried-up lakes. One of the most breathtaking visuals is in the form of lake deltas. The fan-shaped structure is sediment that was being transported from a fast-moving river into the bottom of the slow-moving lake water. On Earth, this type of structure requires deep water.
- + Another geomorphic sign of past lakes is sedimentary layers, which form when sandy sediment settles out from the water onto the bottom of a lake bed. Over time, each layer gets compressed into hard rock. These layers are abundant in certain areas and can even be seen from orbit. We also have close-ups of sedimentary rocks in Gale crater seen by the Curiosity rover.
- + There is also evidence that most of the northern hemisphere of Mars was once a giant ocean! Data from the Mars Global Surveyor mission shows that much of the northern hemisphere is composed of low-lying regions and is fairly smooth. In fact, there is only one region on Earth that shares this level of surface smoothness: the abyssal plains at the bottom of Earth's oceans. This smoothness of the northern hemisphere topography suggests that sediment has filled in any rough areas. That sediment could have precipitated out of an ocean, just like it does on Earth.
- + We also see evidence of shorelines around the low-lying northern hemisphere region. On Earth, a shoreline is an obvious geologic marker that would appear on surrounding rock at the top boundary of a body of water. It separates the region below, where the rock is in constant contact with water—and hence influenced by water erosion processes—and the region above, which is not in constant contact with water. On Mars, these shorelines extend for long distances around the northern depression.

- + One of the extended shorelines is believed to be about 3.8 billion years old. If you filled the northern depression with water to this shoreline, it would imply an ocean that covered 36% of the surface of Mars.
- + There is also evidence that Mars experienced giant tsunamis more than 3 billion years ago. And the evidence suggests that there were at least 2 mega-tsunamis, most likely created by impact events.

AQUEOUS MINERALOGY

- + The next clue that Mars was once much wetter comes from rocks. Mars is covered in rocks and minerals that can only form in the presence of liquid water. When minerals are exposed to water, they can chemically weather and produce new minerals. Some of these new minerals can incorporate the hydrogen and oxygen from water (H_2O) into their crystal structures. The minerals are then hydrated.
- + Mars seems to have many locations where hydrated minerals are found, especially in equatorial regions, suggesting that water was widespread.
- + We can also determine properties of the water from the types of minerals that form. In some of the oldest regions of northern Mars, we see hydrated clay minerals called phyllosilicates, which formed more than 3.5 billion years ago. These clay minerals are made up of many layers, which is a sign that volcanic rocks were in contact with water for an extended period of time.
- + When we find evidence of hydrated minerals on Mars, we can therefore infer that liquid water must have been present when they formed.

Phyllosilicates



- + Another group of minerals—called aqueous minerals—doesn't contain water (that is, they are not hydrated) yet could only have formed through reactions with liquid water. Aqueous minerals have incredible power to tell us about the conditions of their formation. The types and speeds of chemical reactions in the rocks depend on the pressure, temperature, chemistry, and even pH of the water environment.
- + One example we see all over Earth are carbonates, such as limestone. We find some carbonate minerals on Mars, too, in places like Huygens crater and Nili Fossae. Another aqueous mineral is gray hematite, an iron oxide. The Mars Global Surveyor found gray hematite signatures in Meridiani Planum. On Earth, gray hematite only forms in hot springs or standing pools of water. This suggests that Meridiani Planum on Mars may have also had standing water.
- + Signatures of hydrated and aqueous minerals can be seen from spacecraft in orbit around Mars. But the best way to study these minerals is up close, studying many rocks in a particular region. This motivated NASA to

send a series of robotic rovers to Mars. In 2004, twin rovers—Spirit and Opportunity—were sent to opposite sides of the planet, landing 3 weeks apart, and both found evidence of past water. And in 2012, an upgraded rover named Curiosity found water ice in soil samples from Gale crater. This, along with the presence of various minerals, has led scientists to conclude that it was once a freshwater lake that could have supported life.

- + We've also found aqueous minerals in meteorites on Earth that can be traced back to Mars. More than 60 rocks from Mars have been found on Earth, and some of them also contain evidence that they were exposed to liquid water while on the surface of Mars. Having meteorites from Mars makes it possible to do much more detailed chemical studies and, in some cases, even determine the age when the rocks were exposed to water.

A group of meteorites called the Nakhilites were exposed to water while on Mars as recently as about 620 million years ago. Coincidentally, that would mean exposure to Mars water less than 100 million years before the Cambrian explosion of life on Earth.

MARS'S D/H RATIO

- + The third type of evidence for liquid water on early Mars is the ratio of heavy water to ordinary water, also known as the D/H isotopic ratio, where D stands for deuterium and H stands for hydrogen.
- + Deuterium is a heavy isotope of hydrogen that contains a neutron in addition to the regular proton contained in hydrogen, making it about twice as heavy. Because water is made of 2 hydrogen atoms (along with an oxygen atom), some fraction of water molecules have deuterium. These water molecules are heavier than the water molecules with the regular hydrogen.

- + It turns out that Mars has way more deuterium relative to hydrogen than it should have. The only way to explain this high D/H ratio is for the planet to preferentially lose hydrogen while retaining more deuterium. This happens when water molecules are high in the atmosphere.
- + Interactions with solar wind particles can give enough energy for particles to escape a planet. But the lighter isotope will be easier to move and more likely to escape, compared to the heavier isotope. Over time, hydrogen escaped much more readily than deuterium, slowly enhancing the D/H ratio of the whole planet. The ratio today gives us a sense of how much water has been lost through this atmospheric stripping of hydrogen.
- + We can get an estimate of what the D/H ratio was on early Mars by looking at old Martian meteorites. By comparing the D/H ratio in 2 meteorites, scientists have estimated that Mars lost about ½ of its initial water during its first 400 million years. The amount of water lost was around 40 to 100 m (130 to 320 ft) of an equivalent global ocean on Mars.
- + Then, by comparing the D/H ratio of Mars's current atmosphere and polar ice, which is about 7 to 8 times the D/H ratio of Earth's ocean water, scientists estimate that Mars lost an additional 10 to 50 m (32 to 164 ft) of an equivalent global ocean between 4.1 billion years ago and today.
- + If we compare the amount of water we find today on Mars in the form of subsurface ice and the polar caps, we find that around 4.1 billion years ago, Mars had almost 3 times as much water as it does today. And 4.5 billion years ago, Mars had more than 6 times as much water.

SEARCHING FOR WATER AND LIFE ON MARS: THE WAY FORWARD

- + The next big leap in understanding Mars's water, evolution, and possibility for life may occur when humans, rather than robots, analyze rocks from Mars.
- + Sending humans to Mars is a much larger technological challenge, but that hasn't stopped some private companies from working on plans for such missions. But serious hurdles will need to be overcome:
 - 1 Astronauts will need shielding from radiation during the 9-month trip to Mars.
 - 2 Astronauts will need to breathe on Mars.
 - 3 Astronauts will most likely need to grow food.
 - 4 Astronauts will need protection due to Mars's lack of global magnetic field, ozone layer, and other atmospheric protections.

Jezero crater, located at the equator on the western edge of Isidis Planitia, contains an ancient lake delta, and clays and carbonates have been detected from orbit. The Mars 2020 mission to Jezero crater is tasked with collecting secure samples and storing them for eventual pickup by another mission.

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LECTURE 10

Near-Earth Asteroids and the Asteroid Belt



When we think of the solar system, we usually think of the Sun, planets, and maybe moons. But orbiting throughout the solar system, there are also millions of smaller planetoids, also known as asteroids. The largest concentration is located between Mars and Jupiter. But there are also thousands of asteroids in near-Earth orbits very close to us.

WHAT IS AN ASTEROID?

- + Asteroids are small rocky bodies that orbit the Sun. The biggest asteroid, Ceres, is round, but all the rest have irregular shapes, including peanuts and potatoes, dog bones, and even diamonds. Besides having a wide variety of shapes, these small bodies are interesting for at least 3 reasons:
 - 1 Their orbits tend to get perturbed a lot, which sometimes puts them on collision courses with planets, including Earth.
 - 2 These small objects are kind of like leftovers from solar system formation and therefore hold clues to how planets formed.
 - 3 These small bodies have resources, such as precious metals and water, that humans may find useful in the future, especially if we want to travel the solar system.
- + The main difference between an asteroid and a comet is what they are made of. Asteroids tend to be composed mostly of rock and sometimes include iron-rich metal cores while sometimes also having some ice. Comets are much more ice-rich and rarely have intact rocky interiors. But there isn't a clear line that separates these 2 types of objects.
- + Furthermore, asteroids tend to be found, and tend to have formed, in the inner solar system. Icy comets tend to have formed and survive by being mostly in the outer solar system, with occasional trips nearer the Sun. It's only when a comet is nearer the Sun that the ices begin vaporizing from the higher temperatures and we see the glorious tail of a comet.
- + Finally, almost all known near-Earth objects (more than 99%) are asteroids. Comets, being made of ice, don't survive long if they spend a lot of time as close to the Sun as Earth is.

NEAR-EARTH ASTEROIDS

- + We don't have to travel far to find asteroids. The closest ones to Earth are called near-Earth asteroids. These asteroids have orbits that travel partly or fully inside a distance of 1.3 astronomical units (AU) from the Sun.
- + That's already pretty close to Earth's orbit, at 1 AU from the Sun. But there is a subset of near-Earth asteroids known as potentially hazardous asteroids that are even closer. To qualify as potentially hazardous, 2 conditions need to be met:
 - 1 The asteroid's orbit needs to be within ± 0.05 AU from Earth. That's about 7.5 million km (4.6 million mi) from Earth, or about 20 times the Earth-Moon distance.
 - 2 The asteroid must be larger than 120 m (about 400 ft). An asteroid smaller than this size is likely to explode or burn up in Earth's atmosphere, so the ground impact will be indirect.
- + But asteroids smaller than the potentially hazardous asteroid limit can still cause significant destruction on Earth, even if they burn up before hitting the surface.
- + And of course, there have been much bigger impacts. The famous asteroid (or comet) that likely killed the dinosaurs was 10 to 15 km (6 to 9 mi) in size! It made the Chicxulub impact crater in the Yucatán Peninsula of Mexico, a crater that is 150 km (93 mi) wide.

Even though Earth's surface is constantly changing, we have found traces for some 200 impact craters. The largest is a 2-billion-year-old crater in South Africa at Vredefort with a rim-to-rim diameter of 160 km (99 mi) and a damage diameter of 300 km (186 mi).

- + In the 1990s, a “Spaceguard” consortium of programs to search for near-Earth asteroids began in earnest. In 2005, the US Congress even mandated the NASA Near-Earth Object Observations Program (which includes asteroids and comets), which finds targets that are larger than 1 km (0.62 mi). Objects that large are likely to cause global-scale destruction.

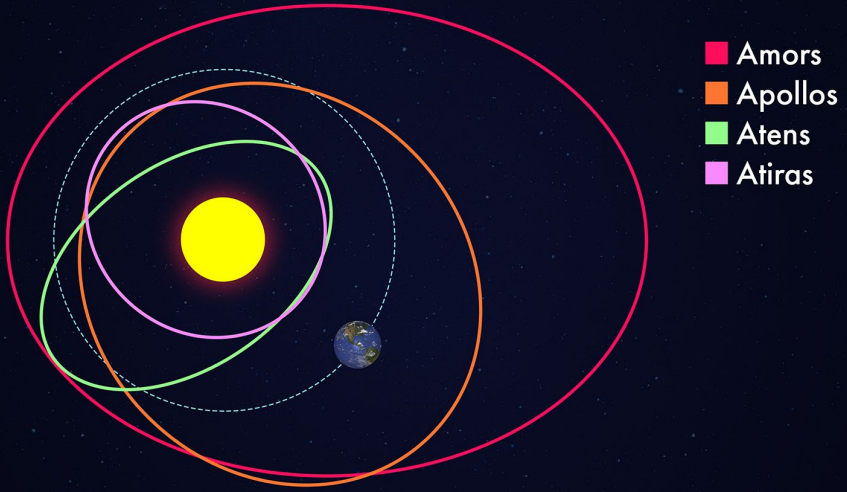
- + The good news is that we now know much more about what’s out there. In 1980, only about 50 near-Earth asteroids were known. That number slowly increased to 500 by 1998. Within just 2 years, the number of known near-Earth objects suddenly doubled to 1000 by the year 2000, and the numbers increased quickly thereafter to around 20,000 by 2019. Of the total, around 1000 of known near-Earth objects are larger than 1 km (0.62 mi). Global efforts continue to search for even smaller objects.

- + Asteroids near Earth are subdivided into 4 groups based on their current orbits.
 - 1 The Amors have orbits that are completely outside of Earth’s orbit but interior to Mars’s orbit.

 - 2 The Apollos have orbits that cross Earth’s orbit but are mostly outside it.

 - 3 The Atens have orbits that cross Earth’s orbit but are mostly inside it.

 - 4 The Atiras have orbits that are entirely inside Earth’s orbit.



- ✦ It's the Apollos and Atens that have the potential to collide with Earth. But the key is having up-to-date information. Asteroid orbits get perturbed by gravitational and thermal forces all the time, so an asteroid can go from not currently crossing Earth's orbit to a more high-risk Apollo or Atens classification. This means they all need to be monitored closely.
- ✦ But near-Earth asteroids aren't just objects to be feared. Studying asteroids helps us learn about the composition and formation of the solar system, and near-Earth asteroids are the easiest asteroids to visit. Near-Earth asteroids may also hold mineral and water resources that we could use in the future.

The first mission to orbit a near-Earth asteroid was the NEAR Shoemaker mission to the asteroid Eros in the year 2000. Eros is the second-largest known near-Earth asteroid and was the first to be discovered, in 1898. Models suggest Eros may eventually be perturbed into an Earth-crossing orbit.

VISITING THE ASTEROID BELT

- + We know from orbital calculations that most near-Earth asteroids are destroyed or ejected from the vicinity of Earth's orbit after a few million years. But we still have tens of thousands of near-Earth asteroids, so they must be replenished from somewhere. Where are they all coming from? Studies of the composition and physical characteristics of near-Earth asteroids indicate that most of these objects originated in the asteroid belt.
- + The asteroid belt is a ring-shaped disk that lies between the orbits of Mars and Jupiter. It's home to millions of asteroids.
- + That sounds like a lot of asteroids, but the total mass in the asteroid belt is only about 4% of the mass of Earth's Moon. And about $\frac{1}{2}$ of that mass is from the 4 largest asteroids: Ceres, Vesta, Pallas, and Hygiea. Only about 200 asteroids in the belt have diameters that are larger than 100 km (62 mi).
- + The densest part of the asteroid belt is known as the main belt, which extends from about 2.2 to 3.5 AU. There are roughly 1 to 2 million asteroids here that have diameters that are greater than 1 km (0.62 mi) spread across the belt. Most have orbital inclinations that are less than 30° above and below the plane of the solar system, so the belt is really more of a donut.

Ceres is about 3.5 times smaller than Earth's Moon, but it is still large enough that its self-gravity makes it a spherical body. This qualifies Ceres as a dwarf planet. Dwarf planets meet 2 of the 3 criteria for planets because they are large enough to be spherical and orbit the Sun, but they haven't met the third criterion: clearing their orbits.

- + Why is the asteroid belt not a planet? In the early 19th century, when multiple asteroids were first being discovered, one theory was that the asteroids used to be part of a planet that suffered some catastrophic impact, breaking it into pieces. But there were problems with this theory because asteroids in different parts of the asteroid belt have different compositions—and because it would require an extreme amount of energy to break up a planet.
- + We now know that Jupiter's gravity makes it nearly impossible to form a planet in the asteroid belt. This is because Jupiter's gravity strongly perturbs objects in this region of space, giving too much energy to these small objects, which prevents them from clinging together in large enough quantities to produce a planet.

Ceres is by far the biggest asteroid. Its diameter is almost 1000 kilometers (621 miles). Ceres alone contains about $\frac{1}{3}$ of the mass of the asteroid belt and was considered a planet for about 50 years after its discovery.
- + Jupiter has also had a lot of influence in shaping the asteroid belt. First, gravitational perturbations from Jupiter tend to keep the orbits of asteroids more eccentric and inclined than we typically see with planets. As the orbits get more eccentric, there is a larger chance of collision between the asteroids. These collisions have resulted in the breakup of many objects in the asteroid belt. Some asteroids become moons of other asteroids, such as Ida, a small, unassuming asteroid that happens to have a tiny moon named Dactyl.
- + Some of the fragments from the collisions recombine through their mutual gravitational attraction into loosely held rubble piles, such as Itokawa. Other fragments are ejected from the asteroid belt entirely, some ending up as near-Earth asteroids.



Itokawa is the smallest asteroid where a spacecraft has landed, and it turns out to be what is referred to as a “rubble pile” asteroid. Evidence suggests that Itokawa is made up of fragments, or previous asteroids, that are loosely held together by gravity.

- ✦ Another possibility for fragments staying in the asteroid belt is for them to orbit the Sun somewhat close together without re-coalescing. These co-orbiting groups of fragments are known as asteroid families. These families are objects that have very similar orbital properties and compositions. Dozens of asteroid families have been reliably identified.

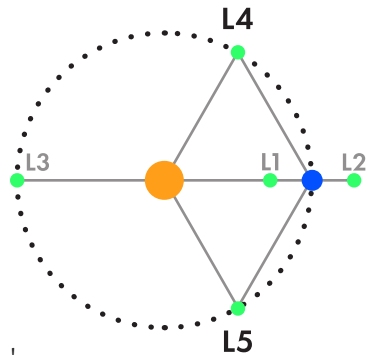
- + **Jupiter is also responsible for gaps in the asteroid belt.** These gaps are known as the Kirkwood gaps, after Daniel Kirkwood, who first noticed them around 1860 and explained their origin. These are places where the gravitational perturbations of Jupiter are always in the same direction and become amplified. This causes larger and larger perturbations of an asteroid's orbit until it gets flung out of this orbital location.
- + There are many forces across the asteroid belt that perturb additional asteroids into one of the Kirkwood gaps, including gravitational perturbations, either from Jupiter or other asteroids, and collisions between asteroids that can affect their orbits. But once there, an asteroid doesn't stay long.
- + **The belt also has a noticeable pattern in the composition of the asteroids.** Approaching the belt from its inner edge, we first see a predominance of silicate-rich asteroids. These are known as stony, or S-type, asteroids. As we move outward through the asteroid belt, the asteroids have more carbon, and the outer belt is predominantly C-type, or carbonaceous, asteroids. In the outer belt, where it's colder, carbon and other icy volatiles were somewhat more likely to be captured and included in asteroids.
- + Throughout the belt, we also see another class of asteroid known as an M-type, or metallic, asteroid. These objects' surfaces appear to be very iron-metal-rich. We think that these asteroids are fractured pieces from a larger asteroid's metallic core. NASA is planning a mission to the metal-rich asteroid Psyche to study what is believed to be the core of a larger object.
- + **Some of these asteroids can even be linked through their composition to meteorites found on Earth!** The metal-rich asteroid Vesta, for example, is thought to be the source of so-called HED meteorites found on Earth.

OTHER ASTEROIDS

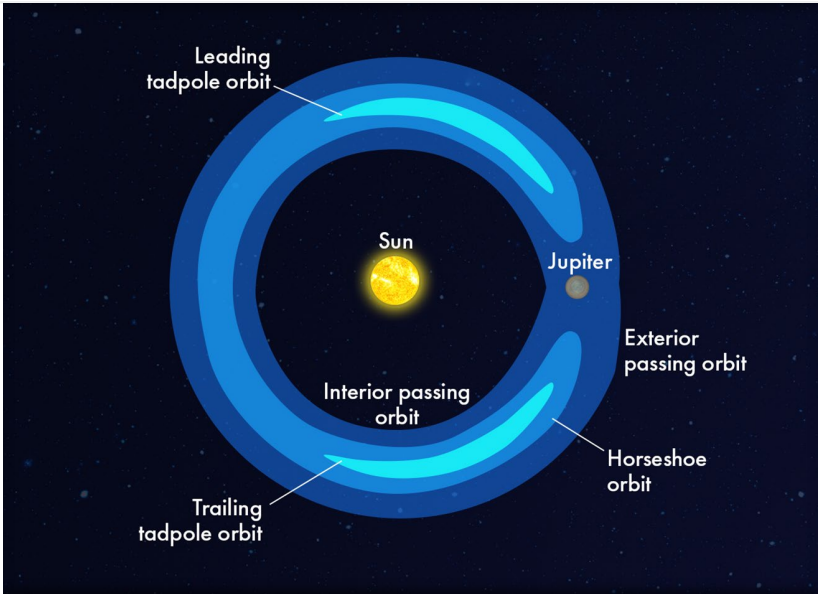
- Although asteroids near Earth and in the main asteroid belt are closer and get more attention, there may be just as many asteroids in the outer solar system.

- The most important locations that asteroids tend to concentrate in the outer solar system are along Jupiter's own orbit: 60° ahead of Jupiter and 60° behind Jupiter. These are the L4 and L5

Lagrange points, which are especially stable locations near the planet's orbit where gravitational forces from the Sun and the planet balance each other. That means asteroids can stay at these locations for long periods of time without being gravitationally perturbed by the planet or Sun.



- And these 2 locations are filled with asteroids! More than 7000 of these so-called Trojan asteroids had been discovered by 2018. Even more amazingly, these 2 locations are estimated as perhaps having about a million asteroids over 1 km (0.62 mi) there in total, all about 5.2 AU from the Sun. That's similar in number to the asteroids in the entire main asteroid belt!
- How do they all fit? A primary reason they can all fit is that the orbital angles of inclination range even more widely than for the main belt, up to 40°. A secondary reason is that the Trojans have small “tadpole orbits” around their respective Lagrange points.



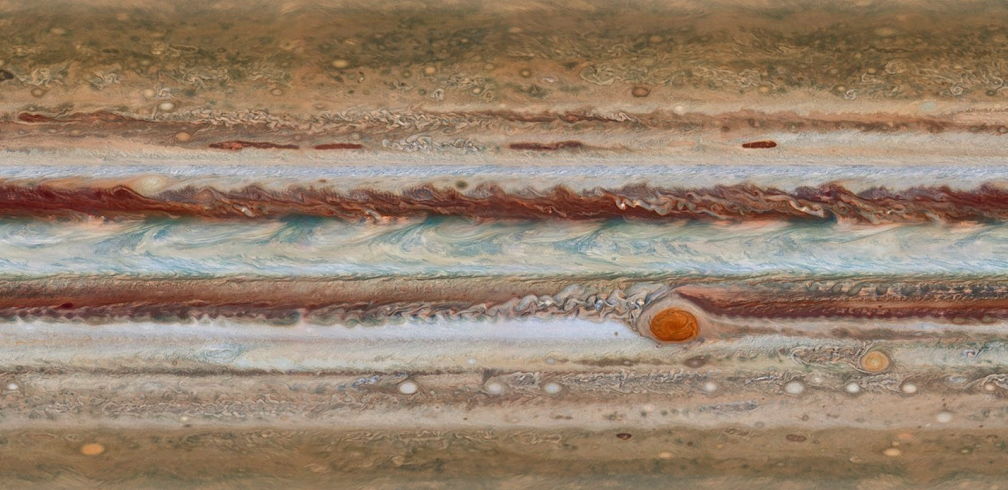
- + Other planets, by contrast, have revealed only a handful of Trojans. In 2011, the first Earth Trojan was found. It's a 300-meter object traveling ahead of Earth at the L4 point and orbiting at an inclination angle of 20° to the plane of the solar system.

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LECTURE 11

Mighty Jupiter, The Ruling Gas Giant



The outer solar system boasts new types of planets unlike the terrestrial worlds in the inner solar system. Starting from Earth, the first planet reached in the outer solar system is Jupiter—the largest of the gas giant planets. Getting to Jupiter means traveling to a distance that is 5.2 times Earth’s distance from the Sun. This far out, the Sun is 5 times smaller in the sky compared to what it looks like from Earth, and it’s about 27 times fainter.

COMPOSITION

- ✦ Jupiter has a diameter that is 11 times the diameter of Earth, making Jupiter 1331 times larger in volume than Earth. That's how many Earths you would need to fill the space occupied by Jupiter.
- ✦ And then there's the mass of Jupiter. All the other planets in the solar system combined still wouldn't reach the mass of Jupiter. In fact, 318 Earths are needed to make up the mass of Jupiter.
- ✦ Jupiter's average density is about 24% of Earth's density. It's only 1330 kg/m^3 (83 lb/ft^3). If Jupiter's density is so low, despite having so much mass to compress everything, Jupiter must be made of much lighter components than the rocky terrestrial planets of the inner solar system.
- ✦ **Jupiter's low density provides an important clue to the planet's composition.** Whereas the terrestrial planets are primarily composed of dense, rocky materials and iron, Jupiter is about $\frac{3}{4}$ hydrogen, $\frac{1}{4}$ helium, and only a tiny smattering of heavier elements. **This is why Jupiter is called a gas planet.**
- ✦ **Jupiter's composition is actually quite similar to the composition of the Sun.** The only reason Jupiter didn't become a star itself is because it didn't grow large enough during its formation. You'd need the mass of 80 Jupiters to reach interior pressures for the onset of hydrogen fusion in a dwarf star—which is a star about $\frac{1}{10}$ the size of our Sun.
- ✦ Another way that Jupiter is similar to a star is that it does not have what we are familiar with as a “surface,” like on the terrestrial planets. Instead, the upper layers of gases we can think of as Jupiter's “atmosphere” simply become more and more compressed and dense with depth due to increasing pressure.

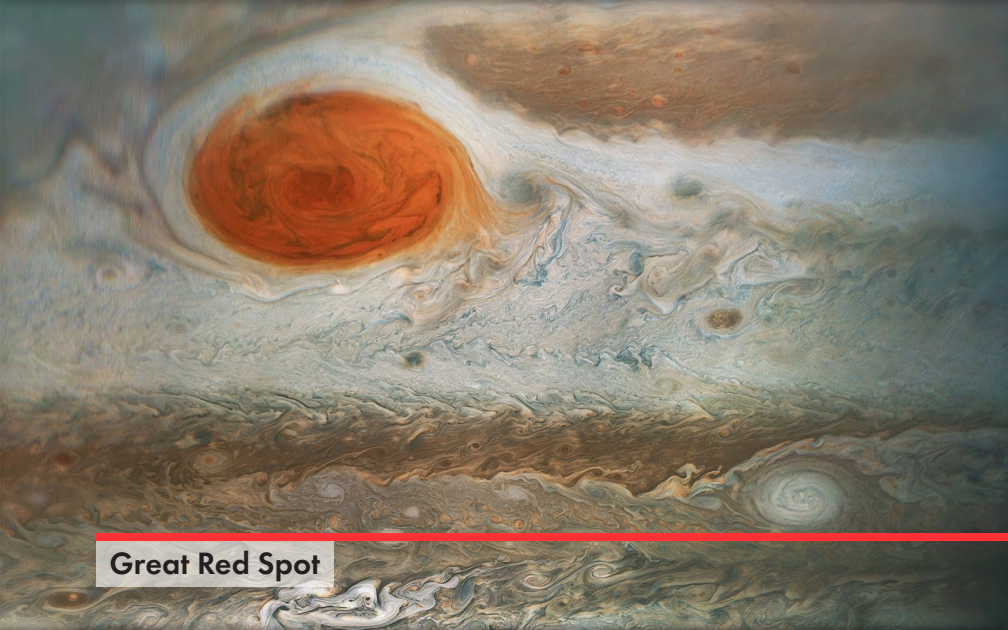
- + Whenever you hear about a “surface” level for Jupiter, that’s merely a level within the gaseous atmosphere that we pick for comparison. And what we usually pick is the region on Jupiter that’s equivalent to 1 bar of pressure, because this is the pressure of the atmosphere at Earth’s surface.
- + On Earth at that pressure, you would experience a gravitational acceleration of 9.8 m/s^2 , while on Jupiter at that same pressure, you would experience a gravitational acceleration of almost 25 m/s^2 , meaning that you would feel about 2.5 times heavier there compared to standing on Earth.

Jupiter orbits the Sun once every 12 Earth years, which means a Jupiter year is 12 Earth years long.

ATMOSPHERE

- + On a planetary scale, the most striking features of Jupiter’s atmosphere are the white and brownish-red bands and giant storms. Sometimes its color looks redder, or browner, indicating that it’s constantly churning around new material.
- + We perceive these colors because of the tiny smattering of heavier elements that are mixed in with the hydrogen and helium. Compounds made from these heavier elements can produce the vibrant colors we see, helping us to distinguish features and motions in Jupiter’s atmosphere.
- + For example, in the horizontal bands, the white regions get their color from ammonia clouds. You might have thought they were water clouds based on your experience with Earth, but that is not the case, although water clouds can be found deeper in Jupiter’s atmosphere. We see the other bands as brownish-red in color because of sulfur-rich compounds.

- + Why do we see these colorful bands of clouds wrapping around the planet?
- + Jupiter, like all planets, is hotter on the inside and cools to space. As hot material rises from the deep regions of the atmosphere, it expands due to the decreasing pressure and cools. Clouds form when a gas present in the atmosphere reaches the temperature of its dew point and condenses.
- + The ammonia- and sulfur-rich cloud bands occur at altitudes in the atmosphere where these compounds reach their dew points. Different cloud bands therefore show us different altitudes in the atmosphere and different temperatures. The white ammonia bands occur at higher altitudes and are cooler; these white clouds are the tops of rising hot plumes from the deeper interior. Warmer and lower in the atmosphere are the sulfur-rich brownish-red bands, which occur where cooler material is sinking back into the interior at lower altitudes. This is all part of the convective cycle that removes heat from Jupiter's interior.
- + But why the horizontal bands? This is a common feature of fluids that are rapidly rotating. The rotation of the planet helps to organize the motion of the atmosphere, resulting in latitudinal bands of winds. It's the same reason Earth has the jet streams in our own atmosphere.
- + One obvious deviation from the banded structure is Jupiter's Great Red Spot: a giant oval storm at a latitude of 22° south. The storm's horizontal extent is so large that it could easily fit the Earth inside it. The storm has an oval shape, with fastest winds on its outer edge swirling about the center at more than 400 kph (250 mph).
- + The Great Red Spot is the size of all of Earth! But data shows that it's currently shrinking. If it were to continue shrinking at the same rate as recently observed, it may disappear in about 70 years.



Great Red Spot

- ✦ Although giant, the Great Red Spot is not the only storm on Jupiter. For example, smaller white oval storms are seen all over Jupiter, and sometimes they are even seen to merge.

Scientists involved in the Juno mission, which arrived at Jupiter in July 2016, determined that the Great Red Spot is about 350 km (217 mi) deep—20 times the depth of a major hurricane on Earth—and that the banded jet streams extend down to 3000 km (1864 mi)—200 times the total depth of Earth's atmosphere.

INTERIOR

- ✦ **The dominant component of Jupiter is hydrogen**—the simplest element, containing a single proton in its nucleus, surrounded by a single electron. In the outer layers of Jupiter, the hydrogen atoms are in a gas phase, where they are very far apart from each other and interact with each other once in a while through collisions. So far, the gas behaves roughly like the gases in the atmosphere of Earth or Venus.

- ✦ As pressure increases with depth in Jupiter, however, the hydrogen atoms are forced closer together.
- ✦ **Pressure and temperature increase very quickly with depth in Jupiter.** And at a pressure of roughly $\frac{1}{2}$ a million bars (that's $\frac{1}{2}$ a million Earth atmospheres!) and a temperature of about 3000°F (1650°C), hydrogen transitions from a gas phase to a liquid phase, where the atoms are more closely packed and feel a moderate force of attraction between them.
- ✦ Even deeper into the planet, the pressure and temperature increase even more, and eventually the hydrogen atoms are forced so close together that their electrons no longer stay bound to a single proton, but instead can move freely. **This is a new phase of hydrogen known as the liquid metal phase, where electrons can move easily and hydrogen becomes a very good electrical conductor.**
- ✦ **It is these electrical currents carried by liquid metal hydrogen that may be responsible for the weaker winds in Jupiter's interior.** That's because the electric currents generate magnetic fields that force the winds to slow down.

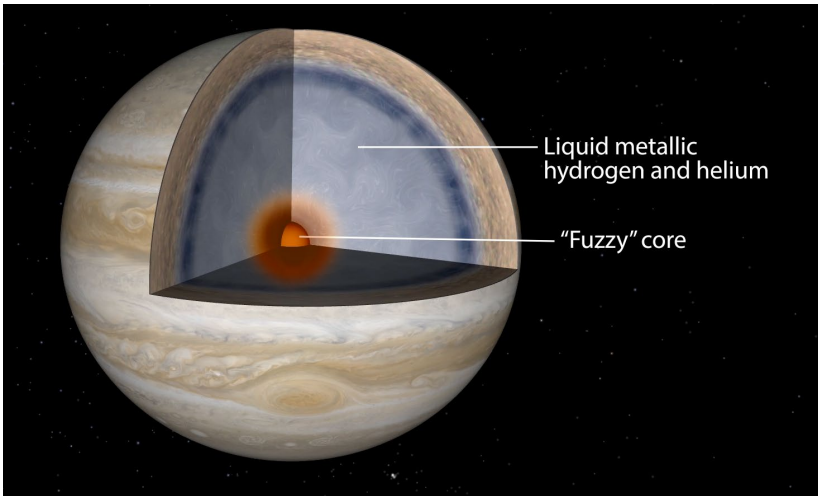
MAGNETIC FIELD

- ✦ We've known about Jupiter's magnetic field since 1955, when radio emissions were detected from Jupiter. These radio emissions are caused by high-energy particles that spiral along Jupiter's magnetic field lines and emit radio waves due to their acceleration.
- ✦ Jupiter's magnetic field has also been studied by spacecraft missions that carry special instruments, known as **magnetometers**, designed to measure magnetic fields. **We now know that Jupiter's magnetic field is**

about 10 times stronger than Earth's magnetic field at its Earth-equivalent "surface." Jupiter's magnetic field looks mostly dipolar, similar to Earth's, with a north and south pole.

- + This strong magnetic field is generated in Jupiter's interior through dynamo action. The metallic hydrogen is a good electrical conductor, so convection in the metallic hydrogen fluid generates electrical currents, which generate magnetic fields.
- If Jupiter's magnetosphere were visible—which it's not—someone on Earth looking at Jupiter would see it in the sky as comparable in size to the full moon.
- + But as the fluid creates magnetic fields, the magnetic field lines push back on the fluid like giant rubber bands frozen into the fluid. This makes it harder for the fluid to move and ends up slowing the winds down.
 - + So, returning to the banded jet streams in Jupiter's atmosphere, as we go deeper into Jupiter, the electrical conductivity is rising and the magnetic fields are more effectively pushing back on those winds, slowing down the motions. And that's why the winds become weaker at greater depth.
 - + An overall effect of Jupiter's strong magnetic field is its giant magnetosphere. The magnetosphere is the bubble in space surrounding a planet that is holding off the solar wind and stopping the high-energy particles and magnetic fields coming from the Sun from reaching the planet.
 - + The size of this protective bubble depends on the strength of the planet's magnetic field and on the distance of the planet from the Sun. Because Jupiter's magnetic field is so strong and because Jupiter is more than 5 times farther from the Sun compared to Earth, Jupiter's magnetosphere is huge.

- ✦ Although the magnetosphere shields the planet from the solar wind, charged particles can be trapped and accelerated along Jupiter's powerful magnetic field lines to create high-energy particles and intense belts of radiation.
- ✦ **Jupiter's strong magnetic field and intense radiation environment also result in brilliant auroras near the planet's poles.** In fact, they are the most powerful auroras in the solar system! Some portions of the aurora are also linked to the large moons surrounding Jupiter.



What's at the center of Jupiter?

The Juno mission found that there does not seem to be a small, dense concentration at the center of Jupiter, but instead a much larger, more diluted mixture of heavy elements and hydrogen and helium. Scientists have dubbed this Jupiter's "fuzzy" core.

JUPITER IN SOLAR SYSTEM CONTEXT

- + The rest of the solar system would be very different if Jupiter had not formed. And this is because of Jupiter's enormous gravitational sphere of influence, known as a Hill sphere.
- + Because Jupiter is so massive, it has a strong gravitational influence on any objects that get close to it. For an object that's orbiting the Sun, we can calculate how close it has to come to Jupiter before Jupiter's gravitational attraction is bigger than the Sun's. This distance is called Jupiter's Hill sphere, and it's 55 million km (34 million mi) surrounding Jupiter.
- + You might think that Jupiter's Hill sphere would be the biggest of any planet in the solar system because Jupiter is the most massive planet. But it turns out that another important factor is the distance from the Sun, because the Sun's gravitational attraction decreases as you get farther from it. Jupiter actually has the smallest Hill sphere of any of the giant planets, while Neptune has the largest, with a radius of 87 million km (54 million mi)!
- + However, being closer to the Sun also means that Jupiter moves faster in its orbit than the other giant planets. So an asteroid or comet is more likely to encounter the fast-moving Hill sphere of Jupiter than it is those of other giant planets.
- + Consider a small rocky or icy body, such as an asteroid or comet, orbiting the Sun, but whose orbit happens to take it near Jupiter. Jupiter's gravity will act to disturb the body's orbit and can result in one of 2 scenarios:
 - 1 If the body's orbit and trajectory are just right, Jupiter can act to slow it down enough that it begins orbiting Jupiter. This is believed to be the origin of many of Jupiter's smaller moons.

- 2 Jupiter may change the body's orbit so much that the body gets kicked to new regions of the solar system that it would never have ventured to otherwise.
- + As far as the inner solar system (and Earth) are concerned, Jupiter is like a gatekeeper between us and the outer solar system: Jupiter attracts away from us many objects that might otherwise come closer to Earth, but many objects from the outer system might not head inward at all if not for the gravity of Jupiter.

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LECTURE 12

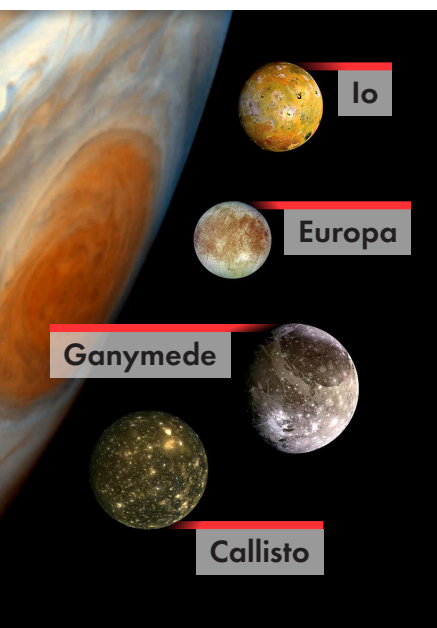
Jupiter's Planetlike System of Moons



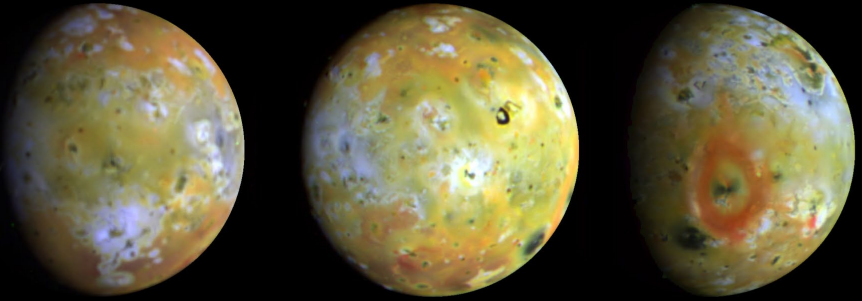
Our Sun sits at the center of a solar system consisting of 8 large bodies we call planets. But planet Jupiter, the fifth and largest of those planets, is itself at the center of another system, featuring 4 large moons: Io, Europa, Ganymede, and Callisto. And the complete Jupiter system as of 2018 also included 75 additional moons! All these bodies are orbiting Jupiter, not the Sun, leading some commentators to describe Jupiter as having a “mini solar system.”

THE GALILEAN SATELLITES

- + In 1610, Galileo was the first to see 4 distinct moons quite clearly using his 30-times-magnification telescope. This led to the moons becoming known as the Galilean satellites. But the names of the individual moons used today—Io, Europa, Ganymede, and Callisto—were given by Simon Marius, who discovered them independently at about the same time as Galileo and got the names we still use from a suggestion by Johannes Kepler.
- + The 3 innermost Galilean moons are Io, Europa, and Ganymede. Io completes 2 whole orbits each time Europa completes 1 orbit; they are therefore said to be in a 2-to-1 orbital resonance. Europa completes 2 whole orbits every time Ganymede completes 1 orbit—which also means that Io completes 4 orbits for every 1 Ganymede orbit. This combined 3-moon resonance is therefore called the 4-to-2-to-1 orbital resonance, and it's an example of what is also known as a Laplace resonance.

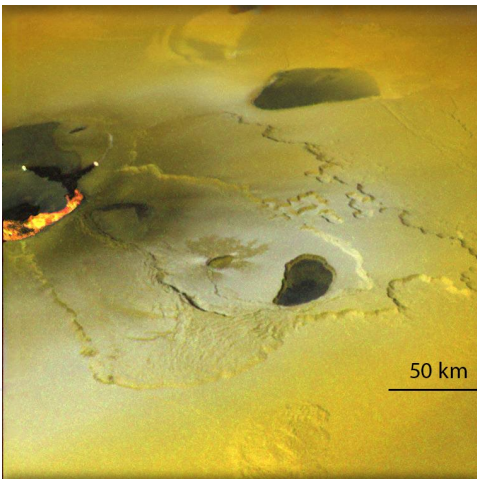


- + The resonance is a result of the gravitational tugs each of the moons exerts on the others as they get near each other in their orbits. It has led the 3 moons to be at specific relative distances and to have particular orbital periods. This orbital resonance is especially important for explaining the appearance and inner workings of Io.



Io

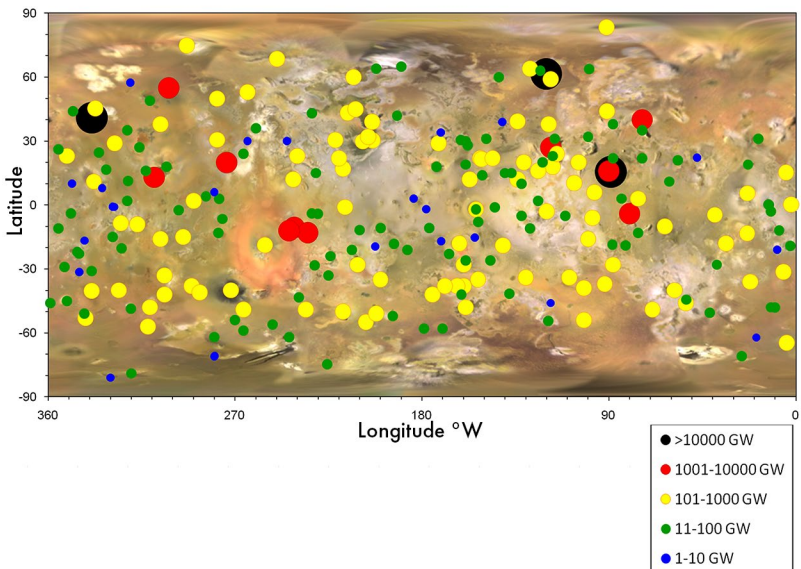
- Io has a splotchy yellowish color with many black specks covering the surface. Each of the black specks is a volcano, and the surrounding material is sulfur-rich magma from volcanic eruptions. Mercury, Venus, Earth, and Mars also have volcanoes, but what's different about Io is that its volcanoes are powered by gravitational tidal forces from Jupiter—and they are still active today.



This volcanic eruption on Io was captured by The Galileo mission, which explored the Jupiter system from the mid-1990s through the early 2000s.

- † These volcanoes erupt sulfur compounds high above Io's surface. Volcanic plumes have been seen reaching 330 km (205 mi) high. Io's radius is 1800 km (1118 mi), so that plume reached a height of almost 20% of the moon's entire radius! As a comparison, Earth's volcanoes emit sulfur usually to heights less than 10 km (6 mi), a mere 0.1% of its radius. Io can get the plumes so much higher because gravity is so much weaker.
- † Some of the volcanic material becomes part of Io's thin atmosphere. Then, through interactions with Jupiter's magnetosphere, these particles sometimes escape Io entirely. In fact, Io loses about 1 metric ton per second of gases and dust! In a sense, Io is a terrible polluter of the Jovian system, spewing sulfur and other material all over the place. The material that escapes Io creates a ring of hot plasma, called a plasma torus, around Io's orbit.

Io's Volcanic Thermal Emissions



Io is the most volcanically active world in the solar system, with about 400 volcanoes that have been mapped.

Why is Io so volcanically active, while the other Galilean moons are not?

Io's interior is constantly flexed and shifted by tidal interactions as it experiences a tug-of-war between massive Jupiter being so close and the other Galilean satellites.

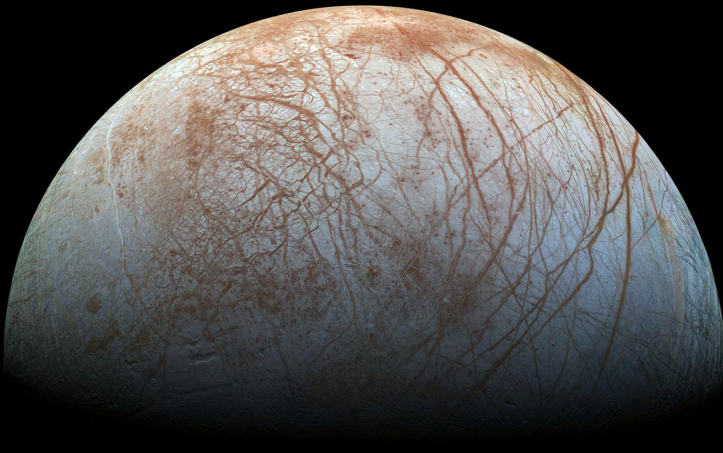
- + It also feeds particles to a magnetic flux tube that connects Io to Jupiter near their poles. It is particles in this flux tube that are responsible for creating a bright auroral footprint on Jupiter.
- + **Io's interior is partially molten.** The volcanoes we see are the surface manifestation of Io's violent cooling to space from all of this heating. Because Io is constantly being resurfaced with new volcanic flows, this also means that we don't see any impact craters on the surface. Any craters that do form are quickly filled in and buried. This means that it's hard to investigate the early evolution of Io because all evidence of any earlier time period is quickly erased.
- + **Io has a typically terrestrial structure, with a rocky silicate crust and mantle, and an iron-rich core.** The difference between Io and other rocky bodies is that Io's mantle is hot enough to be partly melted. There is even evidence that Io has a global molten magma ocean, starting about 50 km (31 mi) below the surface. **Because Io's so hot, we also know that it has no water or other ices—they would just evaporate away.**
- + **This lack of water and other ices makes Io very different from the other Galilean satellites, and indeed different from all the moons in the outer solar system.** And it's all because of that unique orbital resonance.

EUROPA

- + Beyond volcanic Io, the next large moon is the ice moon Europa—one of the most exciting places to look for life anywhere in the solar system.
- + There are no volcanoes here. Instead, the surface is a giant water ice shell full of scars and cracks, due to shifting of the ice shell. This ice shell is as hard as rock and may range from just a few miles thick up to 30 mi thick. The reddish-brown material is a dusting of sulfur-rich compounds dirtying up the ice. We don't see many impact craters on Europa either, telling us that the surface is relatively young.
- + We now know that Europa's ice crust floats on a subsurface ocean and that the ice crust is broken up and moves around from time to time. This makes Europa only the second world in the universe—the other is Earth—with evidence of plate tectonics, albeit in ice.
- + Apart from the ice and water layers, the rest of Europa is more similar to the terrestrial planets, with a rocky mantle and iron core.
- + Europa is a very important world to explore to help our understanding of astrobiology and the search for life in the universe. That's because Europa seems to have many of the key ingredients we think are necessary for life to begin and be maintained:
 - 1 Europa has water, and lots of it. In fact, Europa has 2 to 3 times the volume of water found on Earth! We also know that a significant amount of that water is in liquid form.
 - 2 Essential elements—such as carbon, hydrogen, oxygen, and nitrogen—are all present on Europa. These are important building blocks for biology as we know it.

- 3 There's an **energy source** on Europa that could feed any biological processes going on in its interior. Although no solar energy gets to the subsurface ocean, hydrothermal vents—where nutrients could be supplied to the subsurface ocean and any life there—are likely present at the rock/water interface at the bottom of the ocean.
- 4 Europa's **stable environment** might give chemical reactions and evolution enough time to form life.
- 5 Europa offers **protection**. It's important that the building blocks of life aren't constantly bombarded by high-energy radiation from the Sun. On Earth, we are protected by our magnetic field. Although Europa doesn't have its own magnetic field, the ocean does have a thick ice shell surrounding it. Harmful solar radiation therefore can't penetrate down to the depths where life might be evolving.

**Europa is the smallest of the Galilean satellites.
It's even smaller than Earth's Moon!**



GANYMEDE

- + Ganymede is Jupiter's third and largest Galilean satellite. Ganymede is about 70% bigger in diameter than Europa. In fact, it's the largest moon in the solar system, and it's even bigger than Mercury.
- + Like Europa, Ganymede has many features that may be helpful for life to form. It has an ice shell and global subsurface water ocean. We don't really know how thick the solid and liquid water layers are, but given Ganymede's size, both layers are likely to be much larger than on Europa.
- + A big difference between Europa's and Ganymede's surfaces is that Ganymede's surface is not broken up into rafts or plates, like Europa's is. There are signs of other features caused by the shifting and tidal flexing of the surface on Ganymede, including mountains and grooves. But because Ganymede is farther away from Jupiter, the tidal flexing just isn't as intense on Ganymede as it is on Europa.
- + Ganymede has what we might call "strike-slip" tectonics, where parts of the surface move horizontally relative to each other. But we don't find evidence of plate tectonics, where the surface would be created by upwelling material at ridges and destroyed at subduction zones.
- + Ganymede also has impact craters. Most of the bright spots we see on the surface of Ganymede are from recent impacts that have excavated older ice, bringing fresh ice to the surface. Older regions are darker because they are dusted with carbon and silicon compounds from debris that has showered the surface over millennia. The number of impact craters also tells us that Ganymede's surface is much older than Europa's, with portions of the surface as old as 4 billion years.

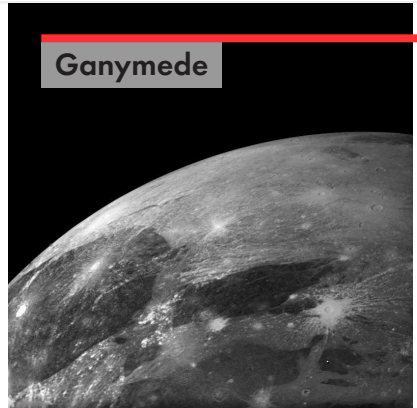
+ **Ganymede's interior is layered.**

Below the ice crust and water ocean seems to be another ice layer and, below that, a rocky mantle and an iron core.

+ **Almost all of the life criteria mentioned for Europa also work for Ganymede, with one possible exception.**

At Ganymede, the bottom of the subsurface ocean is likely another high-pressure ice layer, rather than the rocky layer at Europa. An ice layer would make it harder to get nutrients to Ganymede's ocean, whether through regions like hydrothermal vents or by dissolving minerals directly into the ocean from the rocks.

+ **Ganymede has an iron core**, where, to scientists' amazement, a dynamo operates to produce a global magnetic field at Ganymede. In fact, **Ganymede is the only moon in the solar system known to have an active dynamo today.** The most likely possibility for a heat source to keep the core liquid is tidal heating.



CALLISTO

+ **The final Galilean moon is Callisto**, and at first glance, it appears not so different from Ganymede. It's similar in size, with a radius of 2400 km (1491 mi), making it **the third-largest moon in the solar system and only slightly smaller than Mercury.** **The surface is also a water ice shell like at Ganymede. And there is evidence for a subsurface ocean here, too.**

- + Some differences start appearing as we zoom in. Callisto doesn't have any signs of the "strike-slip" tectonics seen at Ganymede, perhaps because Callisto lacks an orbital resonance that would have heated the interior. There are also more impact craters on Callisto, suggesting that Callisto's surface has changed less and is even older than Ganymede's. Both of these differences suggest that Callisto wasn't heated as much while it formed, or since, compared to Ganymede.
- + **Callisto is one of the most heavily cratered objects in the solar system.** Like Ganymede and other ice moons, Callisto has "ghost craters" that preserve the outline of craters otherwise filled by later movements of ice.



Callisto

- ✦ As we go deeper into Callisto, we find stark differences in structure as compared to Ganymede. Below the subsurface ocean, Callisto appears to be a mixture of rocks and ice. Rather than the separate ice and rock layers at Ganymede, Callisto hasn't fully differentiated. Instead, the ice and rock are mixed together, with the fraction of rock increasing with depth. There is no strong evidence for an iron core at the center, either.

THE SMALLER MOONS

- ✦ Although the Galilean moons are the major satellites around Jupiter, they aren't Jupiter's only moons. But it did take 282 years after the discovery of the Galilean moons to find another moon at Jupiter. That was Amalthea in 1892.
- ✦ All of Jupiter's other moons are much, much smaller than the Galilean satellites—so small that their gravity isn't large enough to make them spherical. Himalia is the most massive of the non-Galilean Jovian moons; Europa, the smallest Galilean moon, is more than 7000 times more massive than Himalia. It was only in 2018 that another 12 of Jupiter's 79 moons were discovered.
- ✦ Jupiter's moons are categorized into families with similar orbital properties. As telescopes become more powerful, we are likely to see an increase in the number of moons detected around Jupiter and a better understanding of the families.

Collisions among Jupiter's tiny inner moons are responsible for supplying the dusty particles that make up Jupiter's rings—which people rarely talk about because rings made of micron-sized dust particles aren't much to look at, especially compared to Saturn's rings of larger ice boulders.

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QUIZ

LECTURES 7–12

- 1** How was the Moon's oldest crust formed? [L7]
 - a** The first minerals to crystallize from the magma ocean, olivine and pyroxene, floated to the top to form the crust.
 - b** After 75% of the magma ocean had crystallized, plagioclase minerals began to solidify and floated to the top to form the crust.
 - c** Volcanic eruptions of basalt solidified on the surface of the Moon.

- 2** The lunar samples collected by the Apollo missions helped in answering which of the following questions? [L7]
 - a** What is the composition of the lunar surface?
 - b** What are the ages of different regions on the lunar surface?
 - c** What are the ages of different regions on the Martian surface?
 - d** All of the above

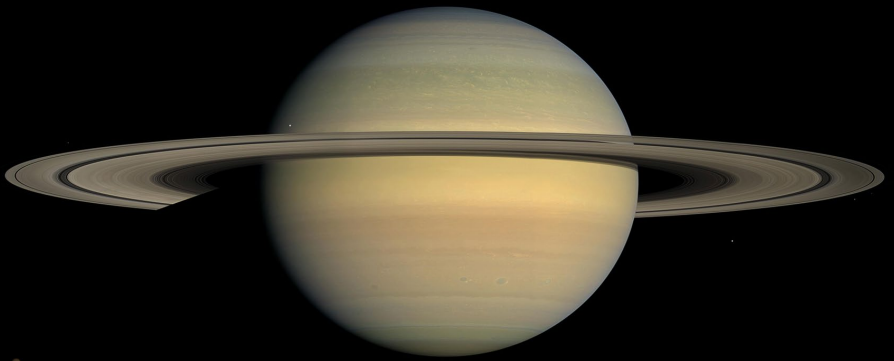
- 3** Why do spacecraft missions take around 6 months to travel to Mars? [L8]
- a** The distance to Mars at our closest approach is 75 million kilometers, and with our fastest rockets, it takes 6 months to travel that distance.
 - b** With the most fuel-efficient trajectory, a Hohmann transfer orbit, it takes about 6 months to get from Earth to Mars.
 - c** We need a gravitational assist from Venus to send spacecraft to Mars.
- 4** Why is Mars's climate more variable than Earth's climate over long time scales? (Choose all that apply.) [L8]
- a** Mars doesn't have a large moon to stabilize its axial tilt.
 - b** Mars has 2 moons that tidally torque Mars's axial tilt.
 - c** Mars's volcanoes expel more greenhouse gasses into its atmosphere than Earth's volcanoes.
 - d** Mars is closer to Jupiter and therefore experiences more gravitational perturbations from Jupiter.

- 5 There is no liquid water on the surface of Mars. [L9]
- a True
 - b False
 - c We don't know.
- 6 How do we know that some of Mars's past water must have escaped to space? [L9]
- a We've accounted for all the water in the Martian interior and it's not enough to fill an ancient northern ocean.
 - b We find water on Mars's moons that must have come from escaped water from Mars's surface.
 - c Mars's D/H ratio tells us that Mars lost water to space.
- 7 Asteroids not labeled as potentially hazardous asteroids are in no danger of causing damage to Earth. [L10]
- a True
 - b False

- 8 Which of the following features are found on asteroid Ceres?
(Choose all that apply.) [L10]
- a impact craters
 - b mountains
 - c plate tectonics
 - d water ice
- 9 Although Jupiter's mean density is 1330 kilograms per cubic meter (83 pounds per cubic foot), we know that it's not composed primarily of water ice, whose density is 1000 kilograms per cubic meter (62 pounds per cubic foot), because: [L11]
- a There were no ices in the region of the solar system in which Jupiter formed.
 - b Jupiter is so massive that ices would be compressed to much higher densities in Jupiter's interior.
 - c The Galileo probe determined that Jupiter has very little water in its interior.

- 10** Why do Jupiter's jet stream winds get weaker as you go deeper in the planet? [L11]
- a** The force driving the winds decreases with depth.
 - b** As hydrogen becomes metallic at depth, its large electrical conductivity means that the winds are influenced by Jupiter's magnetic field.
 - c** Less solar heating penetrates to these depths.
- 11** Based on crater densities, rank the surface ages of the Galilean moons from oldest to youngest. [L12]
- a** Io, Europa, Ganymede, Callisto
 - b** Callisto, Ganymede, Europa, Io
 - c** Callisto, Ganymede, Io, Europa
- 12** Europa, Ganymede, and Callisto all have subsurface oceans. Which subsurface ocean would be easiest to explore? Why? [L12]

Answers can be found on page 298.



LECTURE 13

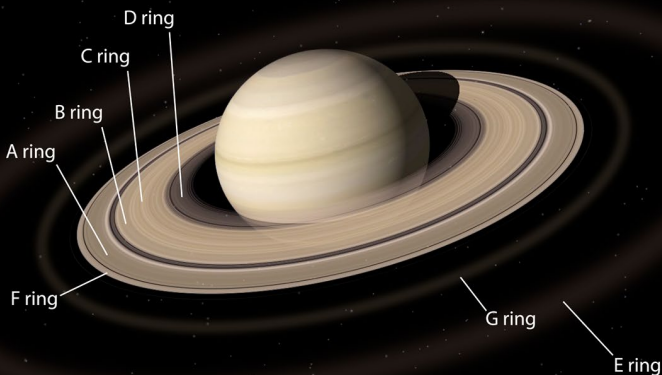
Saturn and the Rings: Gravity's Masterpiece



From Earth, Saturn looks like a bright star in the sky. Its motion has been tracked by astronomers from around the world since ancient times. But it wasn't until the 17th century, when Galileo built a telescope with high enough magnification, that people began realizing something was different about Saturn. And it wasn't until 1655, when Dutch scientist Christiaan Huygens designed a telescope capable of 50 times magnification, that the true nature of Saturn as a planet with a ring system was revealed.

THE RING SYSTEM

- + At times, when Saturn is tilted so that its rings are perfectly aligned with the Earth-Sun line, we see no rings because they are so thin. In fact, the ratio of the thickness of the rings, about a km (0.62 mi), to the width of the rings, about 70,000 km (44,000 mi), makes the rings 20 times thinner than looking at a sheet of paper edge on.
- + The rings all orbit Saturn in its equatorial plane. But the equatorial plane of Saturn's rotation axis is tilted by about 27° from its orbital plane around the Sun, which means that the rings are also tilted with respect to Saturn's orbital plane.
- + We categorize Saturn's ring system by alphabetically naming them in order of discovery. Some of the rings are quite bright and dense. These are easier to observe and were the first to be discovered: Rings A, B, and C make up the 3 main rings, going from outside in.
- + Fainter rings were discovered starting in 1980. They are typically made up of smaller particles and have a lower density. Continuing inward from the 3 main rings is the ring closest to Saturn and next to be discovered: the D ring. The faintest rings are the 3 outer rings: the F, G, and E rings.



- ✦ The particles in the rings can range from micron-sized in the fainter rings to house-sized in the main rings. **The rings are composed of 99.9% water ice.** The relatively large size and icy composition of Saturn's ring particles are what make the rings so bright and visually stunning.
- ✦ **About 97% of the rings' volume is empty space.** Ring particles are about 1 m (3 ft) away from each other, on average. That's close enough that you wouldn't want to try to fly any sort of spacecraft through the rings.
- ✦ A vastly larger ring, the Phoebe ring, was discovered in 2009. It's located much, much farther from Saturn. It lies in the plane of the solar system, so it is tilted 27° away from the plane of the other rings. It's also too faint to see, except in infrared. In fact, it's so tenuous that it only contains about 10 dust particles per km^3 !

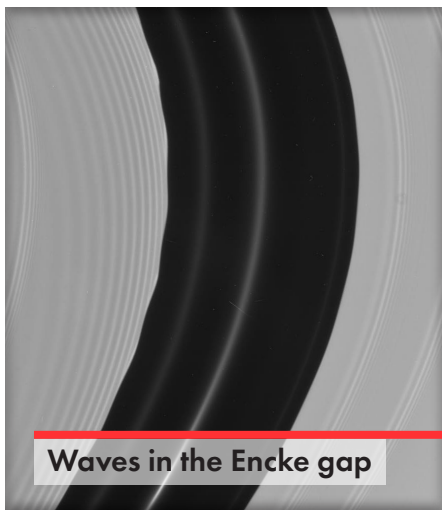
The E and Phoebe rings aren't like all the other rings. The micron-sized ice and dust particles in the E ring come from cryovolcanoes on the moon Enceladus as it moves around the E ring. And the Phoebe ring comes from ejecta from the moon Phoebe.

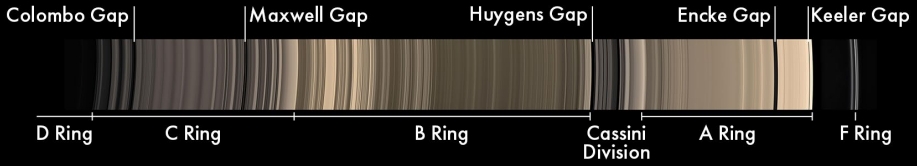


THE CASSINI MISSION

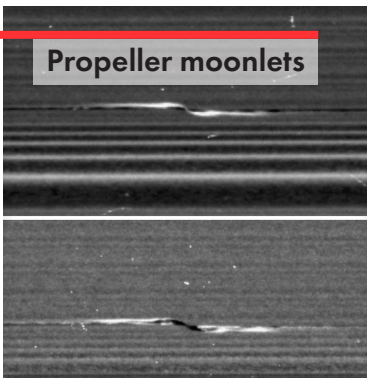
- Named for Giovanni Cassini, the Cassini mission—the most comprehensive mission to Saturn—arrived at Saturn in 2004 and completed its mission in 2017. Over 13 years and 294 orbits of Saturn, the Cassini mission provided us with gloriously detailed resolution of the rings and gaps between the rings. These gaps are carved out by gravitational interactions with small moons.
- The largest gap, the Cassini division, results from an orbital resonance with Saturn's moon Mimas, which is outside the rings. Mimas's orbital period about Saturn is twice the orbital period that particles would have if they entered the Cassini division. This 2:1 resonance of orbital periods results in periodic gravitational tugs that have pushed out material from the Cassini division.
- Other gaps in the rings are caused by small moons that are actually embedded in the gaps. For example, the Encke gap in the A ring is caused by a small moon Pan, which is only 30 km (18 mi) across. Not only does Pan's gravity open a gap in the rings, but it also causes waves on the edges of the ring and that propagate through the ring. Cassini scientists have determined that these waves are about 1.5 km (1 mi) high!

In 1675, Giovanni Cassini first realized that what Christiaan Huygens saw as a solid ring was actually several smaller rings with gaps. Today, the largest of these gaps, the Cassini division, is named for him.





- ✦ Of all the rings, the F ring is uniquely narrow and dynamic. The culprits are 2 small moons, Prometheus and Pandora, which orbit just inside and outside the F ring. In the past, they were called shepherd moons with the idea that they herd the particles in the F ring to create its narrow features.
- ✦ However, in 2014, scientists using data from the Cassini mission figured out that Pandora may not be involved in the shepherding and that the ring's narrowness is due solely to Prometheus. Moreover, both Prometheus and Pandora, and probably other small moons, are responsible for dynamic incursions that change structure in the F ring, giving it many kinks and spirals.
- ✦ The Cassini mission also discovered a new phenomenon in the rings, dubbed propeller moonlets. The first propeller moonlets were discovered in 2006, and it's estimated that the A ring has thousands of them. They are about 10 km (6 mi) across and look like propellers.



- ✦ The dark regions in the propellers are gaps in the rings that are being carved out by tiny moonlets that are less than 500 m (1600 ft) across and too small to see with Cassini instruments. The bright regions are clumps in the rings where ring particles have been forced closer together by the moonlet.

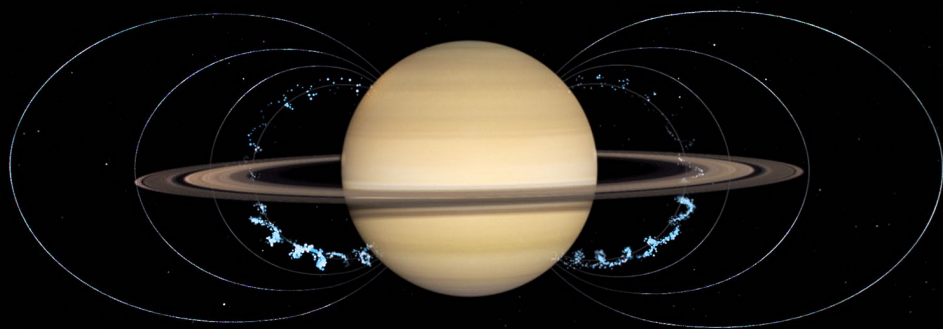
- + These moonlets are believed to have formed from the collision and breakup of larger moons. The moonlets aren't massive enough to create a full gap, like Daphnis and Pan, so they instead just carve out mini gaps in their vicinity.

HOW THE RINGS FORMED

- + Although Jupiter, Uranus, and Neptune also have rings, they are mostly made of smaller-sized particles than Saturn's ring particles. The smaller particles in the rings of all the gas giants are caused by material that gets ejected from nearby moons when they are impacted by meteors. But the larger particles in Saturn's rings can't come from that kind of mechanism. So where do Saturn's ring particles come from?
- + The standard theory is that the ring particles come from the breakup of a moon at least 500 km (300 mi) in diameter—a moon at least the size of Saturn's moon Enceladus or the asteroid Vesta. Such a moon would have been broken up if it got too close to Saturn.
- + The moon would be held together by its self-gravity; that is, particles in the moon are gravitationally attracted to each other, keeping the moon together. However, as the moon gets close to Saturn, it's also influenced by Saturn's tidal forces. That means that different parts of the moon will experience slightly different gravitational forces from Saturn that will act to spread it apart.
- + This is just like the tidal forces that cause Earth's Moon to bulge at the equator. Any of the small moonlets in the inner rings, like Pan and Prometheus, must have enough cohesion to overcome the tidal forces acting on them.

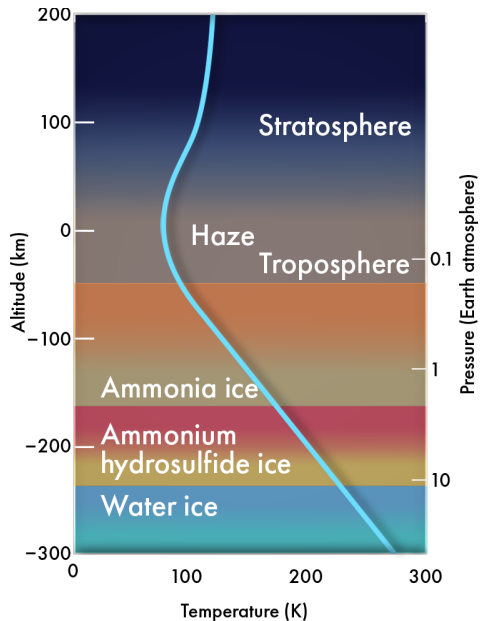
- + But how long ago did a moon break up to create the rings? This is a puzzle, but there is evidence that **the rings are quite young, perhaps only 10 to 100 million years old!** In other words, the rings may be young enough that dinosaurs would have existed in a time when the rings of Saturn did not.
- + **Saturn's rings won't last forever.** Particles from the rings—microscopic water and dust grains—are raining down onto Saturn itself. The Voyager missions determined that ice particles from the rings get trapped along Saturn's magnetic fields, spiraling onto the planet at midlatitudes. In fact, an Olympic-sized swimming pool's worth of water rains down every 30 minutes. Based on the rate at which material is raining out, scientists estimated that the rings would be fully depleted 300 million years from now.

The Cassini mission found that even more ring rain was occurring than was measured by the Voyager missions. By taking this into account, scientists now estimate that the rings may be fully depleted 10 to 100 million years from now!



ATMOSPHERE

- + Saturn is about 9 times bigger than Earth in diameter, and its volume could fit about 764 Earths. It also has a mass of about 95 Earths. **Saturn's volume and mass tell us that Saturn is mostly composed of hydrogen and helium, just like Jupiter.** But Saturn is much larger at the equator than at the poles. Saturn is about 9 Earth diameters at the equator, versus only 8 Earth diameters from pole to pole.
- + **Saturn's atmosphere has bands of zonal winds, like Jupiter's atmosphere,** but more in the yellow-orange shades. The clouds come in layers of ammonia ice, ammonium hydrosulfide ice, and water ice, just like at Jupiter. The difference in appearance between Jupiter and Saturn is due to slight differences in composition between their cloud layers.
- + **The winds in Saturn's atmosphere are extremely fast,** topping out at almost 1770 kph (1100 mph) in the equatorial region—about 5 times faster than the fastest winds ever recorded on Earth. As on Jupiter, the energy for these storms comes from convection as Saturn's interior cools and from solar heating. The rapid rotation of the planet organizes the motion into latitudinal bands.



- + But whereas Jupiter has no axial tilt, Saturn experiences seasons because it has an axial tilt of about 27° , which is quite similar to Earth's 23° tilt. The year on Saturn lasts 29.5 Earth years, which means that each season on Saturn lasts approximately 7.5 Earth years. Between the Voyager missions in the early 1980s and the Cassini mission from 2004 to 2017, this means we've actually been able to study Saturn during its different seasons.
- + Like Jupiter, Saturn has large storms and vortices. But it appears that the giant storms don't last as long at Saturn.

MAGNETIC AND GRAVITY FIELDS

- + Jupiter's metallic liquid hydrogen region has a dynamo that produces Jupiter's magnetic field. The same is true for Saturn, but because the metallic hydrogen region is much deeper in the planet, the dynamo in Saturn is much farther from the surface. This makes the field strength observed for Saturn about 10 times weaker than for Jupiter. Measured from the upper atmosphere, Saturn's magnetic field is about the same strength as Earth's magnetic field!
- + Scientists have been able to determine Saturn's rotation rate by using its gravity field. This is possible because Saturn's rotation causes the planet to bulge at the equator. Basically, the planet's shape is a bit flattened, and the amount of flattening is directly related to how fast the planet is spinning and how the mass is distributed inside the planet. And the mass distribution affects the gravity that a spacecraft feels as it's flying over Saturn's equator.

- + Scientists used models of Saturn's interior density profile to determine what the best rotation rate is to explain the gravity signatures from the observed flattening of the planet. In this way, **Saturn's rotation rate has been determined to be about 10 hours and 33 minutes.**

Saturn is a gas giant that is much less dense than Jupiter. Saturn's average density is just under 700 kg/m^3 (44 lb/ft^3)—which is 30% lower than that of liquid water.

RING SEISMOLOGY

- + **In addition to affecting the gravity that a spacecraft feels, the mass distribution inside Saturn also affects the rings.** The deepest part of Saturn appears to be stratified, meaning that it's not churning and not capable of producing convection. So this stratified region is not participating in the dynamo region above.
- + But waves can still travel through the stratified interior. These waves in Saturn's deep interior move mass around a bit, and these changes in the distribution of the masses slightly change Saturn's gravity field.
- + Amazingly, **the ring particles high above the planet also feel these slight changes in Saturn's gravity field!** This causes the ring particles to oscillate, creating waves that travel through the rings. By watching the frequency and amplitude of these ring waves, we can simultaneously learn about the properties of Saturn's deep interior, such as its density and stratification.
- + Incredibly, this means **scientists have turned Saturn's rings into a giant seismometer!**

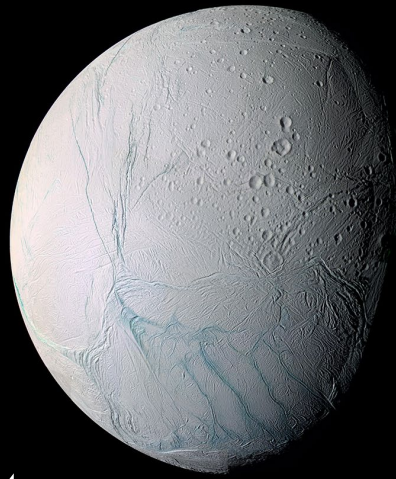
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LECTURE 14

Saturn's Moons: Titan to Enceladus



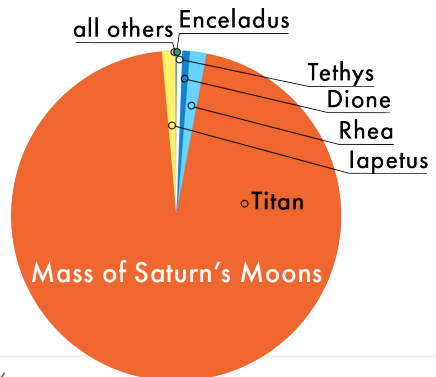
The splendor of Saturn extends far beyond the planet—and the glorious rings are just the start. After all, the gaps and structure of the rings are shaped by moons, beginning with close-in moons like Pan, Prometheus, and Atlas. But in addition to moons in and near the rings, we also encounter moon after moon beyond the rings, located farther and farther from the planet. And each moon is also a unique world worth exploring.

THE SATURNIAN MOONS

- + Titan is by far the largest moon of Saturn, and it was discovered first by Christiaan Huygens in the 17th century. By the end of the 18th century, 6 other moons were found, all named for titans or giants in Greek mythology: Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus. These 7 moons are the largest at Saturn and the only ones big enough for gravity to make them spherical, so they are called the major moons.
- + But Saturn has at least 62 moons. They can be grouped, and even named somewhat, based on their orbital properties and physical characteristics. When the moons started outnumbering the list of titans, additional naming schemes had to be established.
- + We now have a large group of retrograde Saturnian moons named for more than 2 dozen Norse characters. Orbiting in the prograde direction of the main moons, there is also a small Inuit group with highly inclined orbits of more than 40°, and there's a small Gallic group, whose orbits are all inclined at about 35°.
- + Like at Jupiter, an overall distinction between regular and irregular moons is made. The regular ones, which include all 7 of Saturn's major moons, all have roughly circular orbits and move in the same prograde direction as Saturn rotates. This suggests that they formed from a disk around Saturn. The irregular moons instead have orbits that are highly inclined, eccentric, or even retrograde. The irregular moons are likely to have been gravitationally captured objects.
- + It can be helpful to compare the structure of the Saturn system to the Jupiter system. Jupiter has only 4 spherical moons compared to the Saturn 7, which also occupy a wider range of distances than Jupiter's gang of 4. In

the Saturn system, 4 of the round moons—Mimas, Enceladus, Tethys, and Dione—orbit closer to Saturn than Jupiter's closest round moon, Io. All 4 are closer to Saturn than Earth's Moon is to Earth.

- + On the other hand, one of Saturn's round moons, Iapetus, orbits almost twice as far from Saturn as Callisto does from Jupiter. This is more than 9 times the Earth-Moon distance.
- + Only 2 of Saturn's 7 major moons are within the orbit distances of Jupiter's 4 Galilean moons: Rhea is midway between the distance of Jupiter's 2 closest round moons (Io and Europa), and Titan is at a distance that's only slightly farther than Jupiter's third and largest moon, Ganymede.
- + **In terms of size as well as orbit distance, Titan and Ganymede have a lot in common.** Titan is the second-largest moon in the solar system, second only to Ganymede. Both are bigger than the planet Mercury.
- + **But Titan is Saturn's only moon that is similar in size to the Galilean moons.** Titan has a diameter of 5150 km (3200 mi), while the next biggest Saturnian moon is Rhea, with a diameter of only 1528 km (950 mi). That makes Rhea about 3.5 times smaller than Titan and about $\frac{1}{2}$ the size of Jupiter's smallest round moon, Europa. The smallest of Saturn's round moons is Mimas, with a diameter of just under 400 km (248 mi).



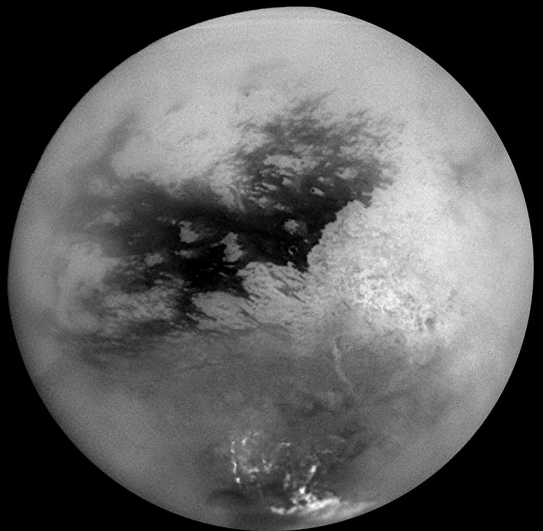
- + All of Saturn's moons are very ice-rich, where ice means they are made not only of water, but also ammonia and methane. Titan has the largest average density at 1880 kg/m^3 (117 lb/ft^3). That's in between the densities for Jupiter's largest moons, Ganymede and Callisto. The rest of Saturn's moons have even lower densities, with a smaller fraction of rock and larger fraction of ice. Some even have densities lower than that of frozen water, which is around 1000 kg/m^3 (62 lb/ft^3). This means that these moons must have some empty pore space in them, like sponges.

TITAN

- + Titan is in a class of its own among the Saturnian moons. Titan alone makes up 96% of the mass of all the moons and rings orbiting Saturn.
- + Not only is Titan the largest moon of Saturn, but it's also the only moon in the solar system with a substantial atmosphere. The atmosphere's composition is about 98% nitrogen and 2% methane. Earth's current atmosphere is about 78% nitrogen and 21% oxygen.
- + Amazingly, the atmospheric pressure at Titan's surface is about 1.5 bars, which is about 50% larger than the atmospheric pressure at Earth's surface. Even though Titan is much smaller than Earth, its atmosphere is about 20% more massive than Earth's and about 4 times as dense!
- + The atmospheric temperature at Titan's surface is about -290°F (-180°C). This is not cold enough for liquid nitrogen, but thanks to higher pressure, it is cold enough for liquid methane.

- ✦ And because of the low gravity on Titan and small impact from the solar wind, this atmosphere can also extend much higher. Titan's mesosphere reaches an altitude that's about 10 times higher than Earth's mesosphere, to about 600 km (373 mi). Titan's thermosphere extends all the way to 1200 km (746 mi).
- ✦ Titan's atmosphere is opaque, and we can't see the surface in visible wavelengths from orbit because of a layer of haze surrounding the planet. But just like at Venus, we can peer through Titan's atmosphere in other wavelengths of the electromagnetic spectrum, such as with radar or infrared.
- ✦ The Cassini mission also sent a probe through Titan's atmosphere to land on the surface. The probe was named Huygens, after Christiaan Huygens, who discovered Titan. Huygens saw low-lying regions that look like dry lake beds and networks of drainage channels, caused by liquid methane flowing on Titan's surface.

Combining the dense atmosphere with the fact that Titan's gravity is only about 14% of Earth's gravity means that it's really easy to fly on Titan.



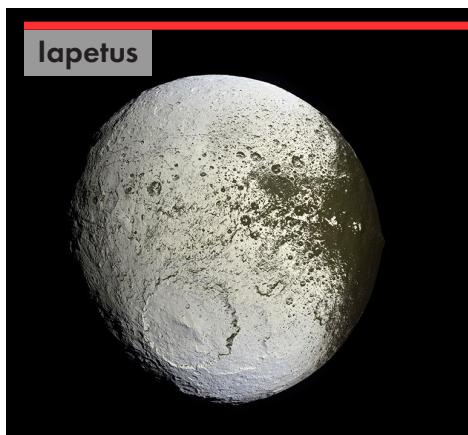
- + Titan's surface is probably the most Earthlike of any world in the solar system. It has rivers, lakes, dunes, mountains, flat plains, and volcanoes (although they are cryovolcanoes). But the liquid flowing on Titan's surface is methane and ethane—not water, like on Earth.
- The Huygens probe marked the first-ever landing of a spacecraft in the outer solar system.
- + Titan's thick atmosphere contains complex hydrocarbons, which we think are important for forming life. Titan is estimated to have hundreds of times more natural gas and liquid hydrocarbons than all the known oil and natural gas reserves on Earth.
 - + The lakes and rivers on Titan's surface aren't the only liquids in this moon. About 100 km (62 mi) below Titan's surface of frozen water ice, there is believed to be a global subsurface ocean of water! All of these liquid layers, together with the complex hydrocarbons in the thick atmosphere, suggest that Titan may be an ideal place to search for the building blocks of life.

RHEA

- + The closest major moon to Titan, both in size and distance, is Rhea, which orbits Saturn about halfway between Titan and Saturn. With a diameter of about 950 mi, it's the second-largest moon of Saturn, and Rhea's density suggests that it's about $\frac{3}{4}$ water ice and $\frac{1}{4}$ rock.
- + Rhea also shares an interesting characteristic with Saturn: It might have rings! We don't see the ring particles directly, but the Cassini mission found evidence for them in how they absorb high-energy electrons in Saturn's magnetosphere.

IAPETUS

- + The farthest of the spherical moons from Saturn is Iapetus. Interestingly, the leading side of this moon is much darker than the trailing side. This bizarre, artificial-looking feature was noticeable even for the astronomer Giovanni Cassini in the 17th century—which is why the dark side is now called Cassini Regio. The dark side is as dark as coal, whereas the bright side looks like shiny water ice. The dark material is only a thin coating, possibly a foot thick, that's covering a cleaner icy layer below.
- + Iapetus also has a giant mountain range around its equator. The mountains can get up to 20 km (12 mi) high—that's more than twice the height of Mount Everest on Earth—and the range runs about 1400 km (870 mi) around the equator.



DIONE

- + We move now to visit 3 moons somewhat closer to Saturn, starting with Dione, a moon of about 1130 km (700 mi) in diameter. Dione is made up of less ice and more rock than Rhea: about $\frac{2}{3}$ ice and $\frac{1}{3}$ rock.
- + Interestingly, Dione is not alone in its orbit around Saturn. There happen to be 2 small moons at Dione's Lagrange points that can stably orbit Saturn without being gravitationally disrupted by Dione. So they are kind of like Jupiter's Trojan asteroids.

TETHYS

- + Moving slightly closer to Saturn we find Tethys, which is of similar size to Dione but is the least dense of all the round moons in the solar system, at only 984 kg/m^3 (59 lb/ft^3). That makes Tethys less dense than water! Because Tethys doesn't have any gas layers to lower the average density below that of water ice, this must mean that Tethys has some porosity. And like Dione, Tethys has Trojan moons.

ENCELADUS

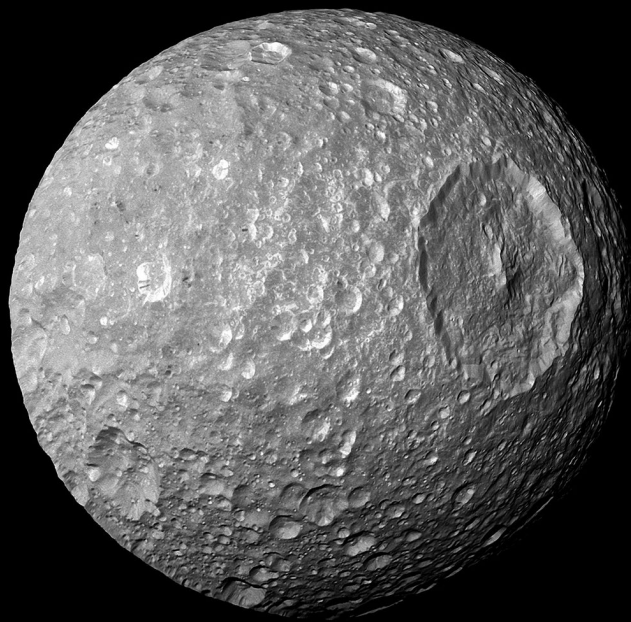
- + At about $\frac{1}{2}$ the size of Tethys—only 504 km (313 mi) in diameter—the sixth largest Saturnian moon is Enceladus. It has the most reflective surface in the solar system. Enceladus is about as wide as Arizona and is found just inward of Tethys. Enceladus is actually embedded in the E ring, which Enceladus helps build.
- + Enceladus is not like some of the other small icy moons. While its surface is ice-rich like the other moons, it has regions with very few craters, meaning those surfaces are very young. But there are also giant fractures, or stripes, surrounding the moon. These all hint of some tectonic activity or heating mechanism that can change the surface and keep it so smooth and shiny.
- + At the southern pole, giant jets are spewing icy water particles, other gasses, and even organic molecules out of the moon into space. These jets are emanating from a series of faults that are warmer than the rest of the surface. These warm faults have been dubbed the tiger stripes, which expel about 250 kg (550 lb) of water vapor every second. The Cassini mission determined that it's these particles from the jets that make up Saturn's E ring.

- + Scientists discovered that there is an ocean below Enceladus's frozen surface. And it's this ocean that is supplying the jets. The ocean is estimated to be about 25 to 30 km (15 to 18 mi) thick and may encircle the entire moon.

Titan and Enceladus are both excellent candidates for future missions to search for signs of life.
- + Below the ocean, Enceladus has a rocky core. Enceladus is about 50% rock and 50% ice by mass. That's a large rock fraction, second only to Titan in the Saturn system. Having that much rock may help explain why Enceladus has a liquid ocean and jets. Rocks contain tiny amounts of radioactive elements, and as those elements naturally decay, they produce heat. So Enceladus's deep interior may be warm enough for there to be liquid water at the depth where the ocean lies.
- + The fact that Enceladus's ocean vents to space makes this moon very attractive for searching for signs of life. The situation is quite similar to that of Jupiter's moon Europa. We know that there's an ocean and that it has nutrients and energy sources. And Enceladus offers particles from the ocean that vent to space, where we could collect them with spacecraft to study.

MIMAS

- + At only about 240 mi in diameter, Mimas is near the lower limit of how small a round moon can be. First imaged closely by Voyager 1 in 1980, Mimas is responsible for the largest gap in Saturn's rings, the Cassini division. Gravitational resonances between Mimas's orbit and certain orbital locations in the rings cause those ring orbits to be unstable and any material there to be ejected.



Mimas would comfortably fit between Boston and Philadelphia.

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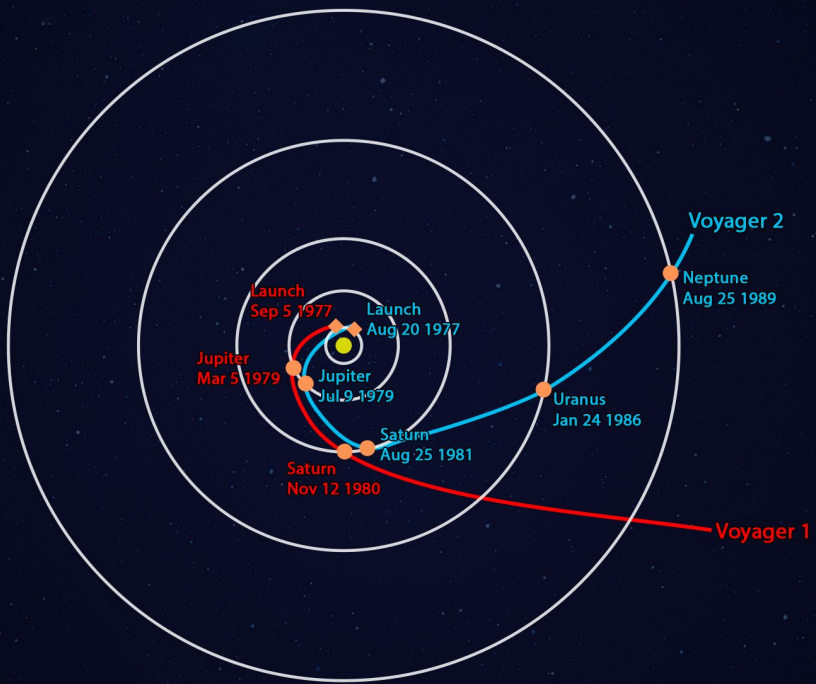


LECTURE 15

Uranus: A Water World on Its Side



In the 1970s, scientists had an opportunity that only comes around once every 176 years. A rare planetary alignment would mean that launching a spacecraft would allow for a mission that could fly by all 4 giant planets, using gravity boosts from each to shorten the total travel. NASA launched Voyager 1 and 2 and decided that Voyager 1 would skip going to Uranus and Neptune in favor of getting close to Saturn's moon Titan. That left Voyager 2 as our only opportunity to visit Uranus and Neptune. Uranus has turned out to be quite different from the other planets we've encountered so far—it's the only planet that orbits on its side.



WHAT IS AN ICE GIANT?

- ✦ A lot was riding on Voyager 2 as it approached Uranus in January 1986.
- ✦ Since the 1940s, scientists knew that Uranus and Neptune had a larger ice fraction than Jupiter and Saturn, but the term *ice giant* seems to have been coined in the late 1970s as a way to describe Uranus and Neptune. So **Voyager 2 would be the first mission to explore a different type of planet: an ice giant.**

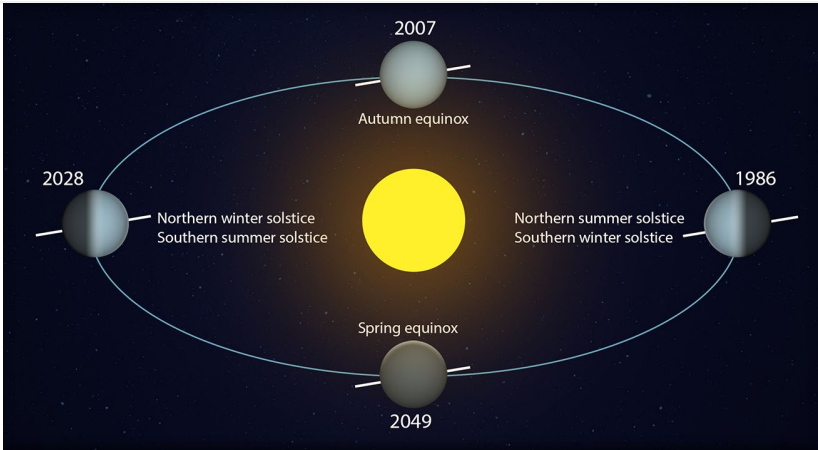
- + For planetary scientists, ice does not mean that Uranus has a frozen-solid surface. Rather, ice is a compositional type that refers to materials made up of combinations of elements that are slightly heavier than hydrogen and helium, such as carbon, oxygen, nitrogen, and sulfur—regardless of how much of those elements are solid, liquid, or gas. These elements, when combined with hydrogen, can form molecules like water, ammonia, methane, and other hydrocarbons. These materials tend to behave in the same way.

 - + The most important difference between the ice moons encountered at Saturn and Jupiter and an ice giant like Uranus is that the planet is big. The diameter of Uranus is 4 times larger than Earth. You would need almost 15 Earth masses to equal the mass of Uranus.
- Uranus and Neptune both sort of look like what we would expect Jupiter and Saturn to look like if we added much less of the surrounding hydrogen and helium layer. So you can think of the ice giants as looking something like the cores of the gas giants.
- + The bulk of an ice giant is icy materials, just like an ice moon. But because it's so much more massive, it was also able to capture some of the hydrogen and helium gas in the protosolar nebula. This gives the ice giant an atmosphere that's similar in composition to that of Jupiter or Saturn, but just not as much atmosphere.

 - + Like gas giants, ice giants also don't have a "surface" the way terrestrial planets do. Instead, the ice giants have atmospheres rich in hydrogen-helium that transition directly to a sort of magma that's a flowing mixture of water, ammonia, and methane. All that is possibly surrounding a core of rock-rich materials deep in the planet.

UNUSUAL ROTATION

- ✦ In 1986, 4.5 years after Voyager 2 flew by Saturn, the spacecraft approached Uranus, which is twice as far from the Sun as Saturn and 20 times farther than Earth.
- ✦ Uranus takes 84 Earth years to complete one orbit, which means Uranus has completed less than 3 orbits since it was discovered in 1781! It also means that only about 2 seasons of a single year have elapsed since Voyager 2 encountered the planet in 1986.
- ✦ And because of how the planet's axis is tilted, seasons on Uranus are quite different than on other planets. Uranus's rotation axis is about 98° away from its orbital axis, which means Uranus kind of looks like it's rotating on its side. But Uranus is not only rotating on its side—it's also traveling along its orbit. This planet doesn't experience normal days and nights, or normal seasons.
- ✦ On planets like Earth that have a smaller axis tilt, the equatorial regions experience the most solar heating when averaged over the year. But on Uranus, if you average over the Uranian year, it's the poles that get the most sunlight. But there are huge chunks of time—decades!—where each pole receives no sunlight. We have to completely rethink how weather patterns and climate are related to seasons for a planet like Uranus.
- ✦ The most common explanation for the tilt of Uranus is that while the planet was forming, it suffered a glancing blow from an Earth-sized protoplanet. Such an impact could have torqued the planet, changing its rotation vector. In some ways, this makes the most sense, considering that the same mechanism is used to explain other planetary tilts. What's a bit unsatisfying is that this means a major property of yet another planet was the result of yet another chance encounter early in the solar system.



- ✦ Because Uranus is so far out in the solar system and moves so slowly in its orbit, people didn't realize it was a planet until 1781! Astronomers using the first telescopes just assumed it was a faint star. But in 1781, amateur astronomer William Herschel recognized that Uranus wasn't a star and that it also did not have the highly elliptical orbit of a comet. It was much more circular and characteristic of planets.

ATMOSPHERE

- ✦ When you look at Uranus, it appears as a featureless blue-tinted orb. It's an atmosphere that is mostly hydrogen and helium, just like the atmospheres of the gas giants Jupiter and Saturn. Uranus's atmosphere is about 83% hydrogen, 15% helium, and 2% methane. It's this 2% of methane that gives the planet its bluish hue.
- ✦ Uranus's atmosphere also has banded zonal winds, like Jupiter and Saturn, but there aren't as many bands, and they are much harder to see. It appears that the atmosphere of Uranus really has only 3 bands:

a westward jet at the equator and an eastward jet in each of the polar regions. The wind speeds in these jets approach 900 kph (559 mph), making them somewhat stronger than Jupiter's winds, but weaker than Saturn's, and almost 2.5 times faster than the fastest wind speeds ever recorded on Earth.

- + We also see storms on Uranus, but many fewer than in the gas giants.

In 2018, scientists using the Gemini telescope in Hawaii confirmed that hydrogen sulfide exists in Uranus's cloud tops. Hydrogen sulfide is what makes rotten eggs smell like they do, so we now have a sense of how Uranus smells!

INTERIOR

- + As we descend through the atmosphere, the fraction of icy compounds begins increasing as the fraction of hydrogen and helium decreases.
- + At about 7000 km (4350 mi) in depth, we are only about 30% of the way into this giant planet and we've reached a location where the volatile ice materials take over as the main components. Here, the water, ammonia, and methane are experiencing pressures around 100,000 bars and temperatures around 3140°F (1725°C). These conditions cause these materials to change into new phases and even break up and form new materials.
- + Uranus is also a place where a lot of water is at high pressures and temperatures. In the atmosphere, Uranus has water in its usual molecular form, with 2 hydrogens bonded to an oxygen. But as the pressures and temperatures increase with depth, water would break up into ions, OH and H, which themselves would have positive and negative ionic charges.

- ✦ As we go even deeper, at about 1.5 million bars of pressure and a temperature of 6740°F (3725°C), a new phase of water, called superionic water, can form. In superionic water, the oxygen ions from water bond together, making a crystal lattice. The hydrogen ions then move freely through the oxygen lattice.

MAGNETIC FIELD

- ✦ The ionic and superionic phases of water turn out to be important for Uranus's magnetic field because they are good electrical conductors. Fluid motions in the ionic ice layer can generate the currents that create a dynamo in the planet. And Voyager 2 discovered that the magnetic field produced from this dynamo is unusual.
- ✦ Before Voyager 2 measured the Uranian magnetic field, all observed planetary magnetic fields had looked like simple dipoles, with a north pole and south pole. But Voyager 2 discovered that Uranus's magnetic field was much more complex, with many poles! This means there are many locations where the magnetic field lines are plunging directly into, or directly out of, the planet. This is called a multipolar magnetic field.
- ✦ Why would Uranus have such a multipolar field? One initial theory was that it might somehow be related to Uranus rotating on its side. That quickly turned out to be an unsatisfactory answer once Voyager visited Neptune and found that Neptune also has a multipolar field. A better answer as to why Uranus and Neptune have multipolar magnetic fields may stem from the fact that both planets have ionic ice layers.

MOONS

- + William Herschel, the same man who discovered Uranus, was also the first to discover moons orbiting the planet. Six years after discovering Uranus, on a single night, he found the 2 largest Uranian moons: Titania and Oberon. Both are less than $\frac{1}{2}$ the diameter of Earth's Moon.
 - + It took another 60 years for astronomers to find the next 2 biggest moons, Ariel and Umbriel, which are only $\frac{1}{3}$ the diameter of Earth's Moon. Then, it took almost 100 years more to find the next one, Miranda, which is only $\frac{1}{7}$ the diameter of our Moon. That was in 1948, and the discoverer was Gerard Kuiper of Kuiper belt fame. These 5 moons are the only moons of Uranus that are large enough to be spherical.
 - + But Uranus has at least 27 moons; the others are all smaller and nonspherical. The Voyager 2 mission found 10 moons during its 1986 flyby, and Earth-based telescopes after the Voyager flyby have found the rest.
- All the Uranian moons are named for magical spirits and characters from the works of William Shakespeare and Alexander Pope.
- + Uranus's moons can be classified as either regular or irregular, but unlike Jupiter or Saturn, most of the moons known for Uranus so far are regular. The 18 regular moons are on very circular orbits and moving in the same direction that Uranus is rotating: 5 round moons and 13 small moons orbiting close to the planet. This suggests that they formed from an accretion disk surrounding Uranus.
 - + But because Uranus is rotating on its side, this also means that these regular moons typically have extreme seasonal cycles, just like Uranus does. One hemisphere of the moons constantly experiences day while the other experiences night in the respective summers and winters.

- ✦ The 9 irregular moons are on more elliptical, inclined, or retrograde orbits, suggesting that they formed elsewhere but were then captured by Uranus's gravity field.

RINGS

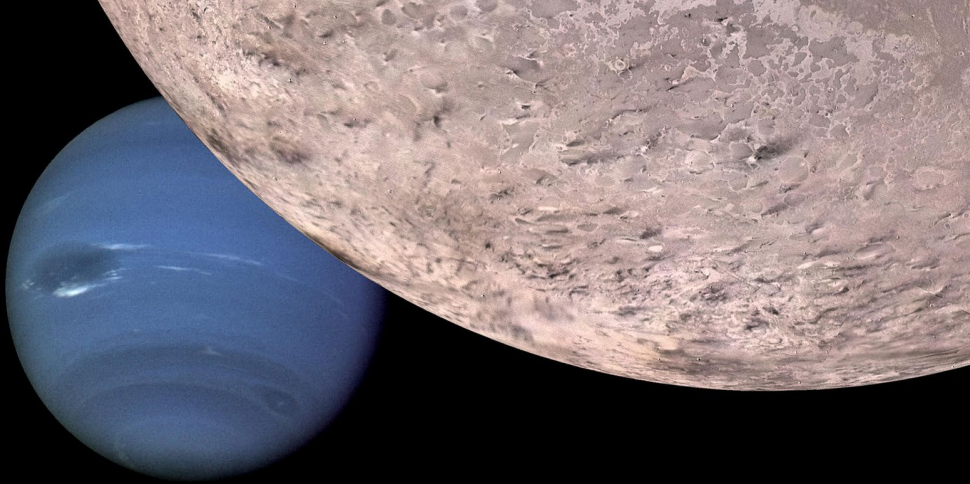
- ✦ In addition to moons, Uranus also has rings—13 of them! This sounds like a lot, but the rings are very thin and dark, with some wide separations. They are dark like Jupiter's rings, but they aren't dusty like Jupiter's rings.
- ✦ The particles in Uranus's rings are actually quite big, typically ranging in size from basketballs to large houses. Saturn has some ring particles that big, but the particles of Saturn's rings are much brighter, thanks to being more ice-rich. We don't really know why Uranus's ring particles are so dark, but it may be because they are richer in organics than Saturn's rings.
- ✦ We didn't know that Uranus had rings until some were accidentally discovered in 1977. This initial discovery found 5 rings, and more soon followed.
- ✦ The rings were eventually imaged by Voyager 2. We don't know what the rings are made of, but they are likely a mixture of rock and ice. They may have formed from collisions of previous moons surrounding the planet.
- ✦ It's also challenging to understand how they stay so narrow. Many of Saturn's rings are quite extended, suggesting that either the rings are extremely young, like 1 million years old, or they must have shepherd moons, like we see at Saturn for some of its thin rings. Some shepherd moons have been discovered for Uranus. In fact, the thinness of rings is inspiring searches for new shepherd moons surrounding the other rings.

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LECTURE 16

Neptune: Windy with the Wildest Moon



The Voyager 2 flyby of Neptune in 1989 drove home the point that even similar planets can harbor big surprises. For example, instead of the weirdly calm atmosphere of Uranus, Neptune has some of the fastest winds in the solar system. Neptune also has our solar system's first and only example of a large spherical moon, Triton, that was captured rather than formed from an accretion disk around the planet. Jupiter and Saturn each have a majority of moons that seem to be captured objects, but Triton is Neptune's largest moon, and spherical, and it's orbiting the planet in a backward, retrograde direction.

FIRST CONTACT

- + Voyager 2 was more than 4 billion km (2.5 billion mi) from Earth for the Neptune flyby in 1989. Any commands the scientists on Earth wanted to send to the spacecraft would take almost 4 hours traveling at the speed of light to reach Voyager.
- + This also meant that any data collected by Voyager would take 4 hours to reach Earth. Voyager was traveling almost 100,000 kph (62,000 mph) as it made its closest approach to Neptune, so the core part of the flyby itself would last only hours. In fact, the flyby itself would be largely over before the first signals had time to get back to Earth!
- + At closest approach, Voyager was flying less than 5000 km (3000 mi) over the clouds near the north pole of Neptune. Getting so close allowed the spacecraft to use a gravity assist from Neptune to change its trajectory, aligning it more with Triton's orbital inclination. That made it possible for Voyager to fly by Neptune's largest moon, Triton, nearly 5 hours after its Neptune encounter.



Voyager 2's first image of Neptune, better than anything seen from Earth, was taken a full year before reaching Neptune.

- ✦ And no one at Earth would know whether the flyby was successful or what any of the data would look like until 4 hours later, when signals from Voyager finally started reaching Earth.

Neptune is the only planet in our solar system that can't be seen with the naked eye. It's too faint because it's so far away.

ATMOSPHERE

- ✦ Neptune's storms brought into focus the striking differences in the ice giants' atmospheres. **Neptune is the coldest planet in terms of light from the Sun, yet it has a very dynamic atmosphere, with storms that come and go.** The largest storms are giant hurricanes that appear as darker spots and typically have accompanying bright-white methane clouds.
- ✦ **Neptune also has zonal jets**—winds that travel eastward or westward in bands around the planet. The directions of these jet streams are very similar to jets on Uranus; that is, there is a large westward jet at the equator and an eastward jet at each pole.
- ✦ **The winds in Neptune's swirling, localized storms are the fastest ever recorded in the solar system.** Neptune also has fast zonal jets, at speeds similar to on Saturn.
- ✦ **The composition of the atmospheres of Uranus and Neptune is very similar.** That's why their colors are similar. Neptune's atmosphere is about 79% hydrogen and 18% helium. The remaining 3% is methane, and this is where Neptune gets its blueish color, just like Uranus. If you compare Uranus's and Neptune's colors, Neptune looks a bit bluer, whereas Uranus is a bit grayer or greener.

- + The planets are about the same size. Their rotation rates are similar. So what's causing such an extreme difference in weather? The most likely culprit is the amount of heating each atmosphere receives from the planet's interior.
- + Voyager 2 measured the heat coming out of Uranus and Neptune. Neptune has a large internal heat source, similar to Saturn and Jupiter. This internal heating can help provide energy to the winds and storms seen in Neptune's atmosphere. The higher internal heat flow at Neptune also means that the temperatures in Neptune's atmosphere are quite similar to the temperatures in Uranus's atmosphere, even though Neptune is about 50% farther from the Sun than Uranus. Neptune only receives about 37.5% as much solar energy as Uranus does.
- + Neptune's axis tilt is similar to Earth's, so the planet experiences seasons. But the year on Neptune is 165 Earth years long. That means that all the data we have about Neptune's atmosphere, whether from Voyager 2 or Earth-based telescopes, is less than $\frac{1}{4}$ of a year. So the only seasonal change we've seen on Neptune so far is a southern hemisphere change from spring to summer.

INTERIOR

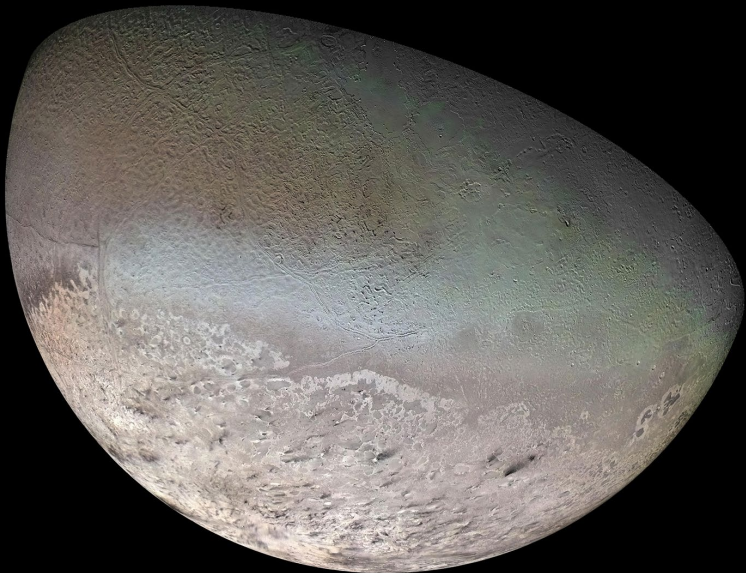
- + Neptune is the densest of all 4 giant planets, denser even than Jupiter.
- + As we go deeper into Neptune, we transition from the atmospheric layer, which is rich in hydrogen and helium, to the ice layer, which is rich in water, ammonia, and methane. Uranus and Neptune are quite similar in size and mass, with Neptune being about 18% more massive yet 2% smaller in diameter. This means that Neptune has a bit higher fraction of ices and rocks—the heavier materials—than at Uranus.

British mathematician John Couch Adams and French mathematician and astronomer Urbain Le Verrier were given credit for Neptune's discovery, along with German astronomer Johann Galle.

- + And this means that similar phase transitions, such as superionic water, occur in Neptune as there are at Uranus. But they may occur at slightly shallower depths in Neptune compared to Uranus.
- + For Neptune, at a depth of about 5000 km (3000 mi) below the clouds, the ices experience pressures of about 250,000 bars and temperatures over 3000°F (2000°C). Here, the ices are a fluid soup of ions. This ionic ice layer is where Neptune's magnetic field is generated by a dynamo.
- + Scientists were particularly eager to see Neptune's magnetic field data from the Voyager flyby. A mere 3 years earlier, Uranus's magnetic field had been discovered to be multipolar, unlike the dipolar fields of the other planets. Explanations for Uranus's magnetic field would be tested by observations at Neptune.
- + As data was returned in 1989, it became obvious that Neptune's magnetic field was multipolar as well. That doesn't mean that the magnetic fields of the 2 planets look the same. In fact, they look quite different, with the multitude of poles sticking out of the planets at different locations. But the key point is that both planets' magnetic fields are not dominated by their dipolar components.
- + The fact that Uranus and Neptune have such similar interior structure and composition suggests that their multipolar magnetic fields may be related to something distinctive about their interiors compared to the other planets. For both Uranus and Neptune, the dynamo is generated in an ionic ice layer, not in an iron core or a metallic hydrogen layer.

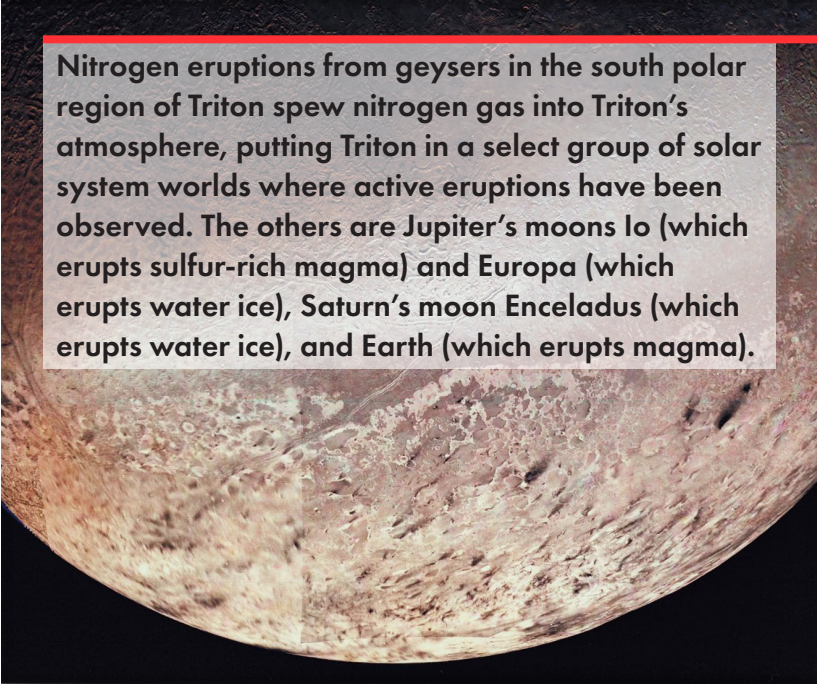
- † One possibility is that the ionic ice layer is a thin outer shell in Uranus and Neptune. Below the ionic layer, there may be a layer of superionic water that is solid. If so, the dynamo may not be able to operate down there because superionic water is a crystalline lattice that would prevent movement. This restriction would confine the dynamo to the thin outer layer that's ionic. Computer simulations have shown that dynamos operating in thin shells can more easily produce multipolar magnetic fields. So this may be the explanation for the multipolar fields of Uranus and Neptune.

Within weeks after the discovery of Neptune, a single moon was found in 1846.



TRITON

- + Although Uranus and Neptune are quite similar in terms of composition and structure, their systems of moons are very different.
- + Neptune is now known to have at least 14 moons, but only one of those moons, Triton, is large enough to be spherical. Compare that to 4 round moons at Jupiter, 7 at Saturn, and 5 at Uranus.
- + In terms of size, Triton is the seventh-largest moon in the solar system: It's close to twice the diameter of Titania (the largest moon of Uranus), but smaller than Earth's Moon, and about 10% smaller in diameter than Europa, the smallest of Jupiter's 4 round moons. Triton is only about $\frac{1}{2}$ the diameter of Jupiter's Ganymede or Saturn's Titan.
- + However, Triton is about 10% denser than Saturn's moon Titan, suggesting a larger rock fraction in Triton and a smaller ice fraction, perhaps $\frac{2}{3}$ rock and $\frac{1}{3}$ ice. The ice is why both Titan and Triton are much less dense than Earth's Moon.
- + What makes Triton truly extraordinary compared to all the other large round moons in the solar system is that it's an irregular satellite. This means that it didn't form from an accretion disk surrounding Neptune. Instead, Triton was captured by Neptune's gravity at some point in the past.
- + We know that Triton is a captured moon because its orbit is retrograde. Triton is orbiting Neptune in the opposite direction that Neptune is spinning. That's a key sign that Triton didn't form from an accretion disk around Neptune. Triton's orbit is also inclined by about 23° with respect to Neptune's equator—another sign that Triton is a captured object.



Nitrogen eruptions from geysers in the south polar region of Triton spew nitrogen gas into Triton's atmosphere, putting Triton in a select group of solar system worlds where active eruptions have been observed. The others are Jupiter's moons Io (which erupts sulfur-rich magma) and Europa (which erupts water ice), Saturn's moon Enceladus (which erupts water ice), and Earth (which erupts magma).

- ✦ Most likely, Triton came from the Kuiper belt. This is the region of the solar system just beyond Neptune's orbit that's home to many other known icy bodies that are similar in size to Triton. The most famous Kuiper belt resident is Pluto. Some Kuiper belt objects, including Pluto, are known to have elliptical orbits that cross the orbit of Neptune. It's therefore not too surprising that one of those objects may have had an encounter with Neptune in the past and been captured by Neptune's gravity.
- ✦ Capturing Triton would have taken its toll on both Triton and the Neptune system. It might not be a coincidence that Neptune doesn't have any spherical regular moons.

- + Since its capture, Neptune's tidal forces have acted to bring Triton's rotation into a spin-orbit resonance. Triton now keeps one face toward Neptune at all times, just like our Moon does with Earth, and travels in a very circular orbit.
- + Triton orbits very close to Neptune—about 10% closer than our Moon orbits Earth! And remember that Neptune is about 4 times larger in diameter than Earth! Considering that Triton is about 20% smaller in diameter than Earth's Moon, this means that Triton appears almost the same size in the sky from Neptune's surface as Earth's Moon does to us.
- + It's very unusual for an irregular moon to orbit so close to its planet host. The tidal forces acting on Triton this close to Neptune have 2 important effects on the moon.
 - 1 The tidal forces are changing Triton's orbit. Triton is slowly spiraling inward toward Neptune, and predictions suggest that in about 3.5 billion years, Triton will begin breaking apart from Neptune's overwhelming tidal forces.
 - 2 These tidal interactions also stretch and flex Triton's interior, causing heating. This heating has resulted in geologic activity on Triton's surface.
- + Our best views of Triton came from the Voyager 2 flyby. The closest approach was at 40,000 km (25,000 mi) from the moon, and Voyager was able to image 40% of Triton's surface. The other 60% has remained a mystery.

Neptune was the last planet visited by the Voyager 2 mission. Voyager 2 was also the last of the Voyager spacecraft.

Both Voyager 1 and 2 are still trekking today and were the farthest spacecraft from Earth, at 21 billion and 18 billion km from Earth, respectively, as of 2019.

- + But that 40% reveals a world that is geologically rich and varied. More than $\frac{1}{2}$ of the surface is covered with frozen nitrogen; the remainder is a combination of water ice and frozen carbon dioxide, or dry ice. The surface has a pinkish hue, thanks to the presence of organic compounds on the surface.

RINGS

- + Neptune's rings are quite dark, similar to the rings of Uranus. But the particles making up Neptune's rings are micrometer-sized dust rather than the basketball- to house-sized ring particles at Uranus. This makes Neptune's rings more similar to those at Jupiter.
- + The accidental discovery of Uranus's rings in 1977 is what motivated scientists to try to find rings around Neptune. But detecting rings at Neptune proved to be more challenging. There were some candidates, and some false positives.
- + In 1989, Voyager 2's flyby conclusively found 5 rings around Neptune. Three of the rings are narrow, and the other 2 are much broader.

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LECTURE 17

Pluto and Charon: The Binary Worlds



In 2015, the New Horizons mission revolutionized our understanding of Pluto. We now know that Pluto is an active world with glacial flows and convective ice, dunes and floating mountains, and maybe volcanoes spewing ice and even a subsurface ocean. And Pluto's not alone. Pluto has the closest thing in our solar system to a binary planet system. The companion, Charon, is about $\frac{1}{2}$ Pluto's diameter, and the 2 bodies orbit a common center of mass in a dance that repeats every 6.4 days.

Although Charon is often referred to as a moon of Pluto, there is no other moon in the solar system that is so similar in size to the body it's orbiting. This similarity in size is what makes it a binary system: **Pluto and Charon orbit each other.**

PLUTO

- + **Pluto is large enough that gravity has made it spherical.** Its diameter is just under 2400 km (1500 mi). That makes Pluto smaller than 7 moons in our solar system. It's about 30% smaller than Earth's Moon. In horizontal extent, Pluto is comparable to about ½ the continental United States.
- + Pluto's average density is about 1900 kg/m^3 (120 lb/ft^3). This tells us that Pluto is a mixture of ice and rock and is much less dense than our Moon.
- + Pluto was discovered in 1930 by Clyde Tombaugh. **And although Pluto was considered a planet for 76 years, it was realized early on that its orbit is not very planetlike.** Instead of a circular orbit, Pluto has an orbit that's very elliptical, which means its distance from the Sun changes dramatically around its orbit.
- + At Pluto's closest approach to the Sun, it's only 30 times Earth's orbital distance. At its farthest point, it's almost 50 times farther from the Sun than Earth.
- + When Pluto is near its closest point to the Sun, it's even closer to the Sun than Neptune. But Pluto and Neptune will never collide because their orbits don't actually cross. This is because Pluto's orbit is also inclined to the plane of the solar system by about 17° . Contrast that with Mercury, which has the largest inclination of any planet in the solar system at about 7° .

- Planets tend to stay in their own lanes, but Pluto's extremely elliptical orbit causes it to cross inside Neptune's orbit for about 8% of every trip around the Sun. That's why Pluto was closer to the Sun than Neptune from 1979 to 1999. Because the year on Pluto is very long, lasting 248 Earth years, the next time Pluto will cross inside Neptune's orbit won't be until 2227!
- Pluto's spin axis echoes unusual features also found at Uranus and Venus. Pluto is inclined by about 120° from its orbital plane, so it sort of rotates on its side similar to how Uranus does, but at a bigger angle.
- The large angle of Pluto's spin axis means that Pluto experiences extreme seasons. Near summer and winter solstices, $\frac{1}{4}$ of the planet's surface experiences total daylight and total night. And, like Venus, the angle of Pluto's spin axis is more than 90° . This means that Pluto technically spins opposite the direction it orbits—so the spin direction is retrograde, like Venus.

Humans have been aware of Pluto for well under $\frac{1}{2}$ a year on Pluto. An entire year on Pluto is longer than the time since the signing of the US Declaration of Independence.

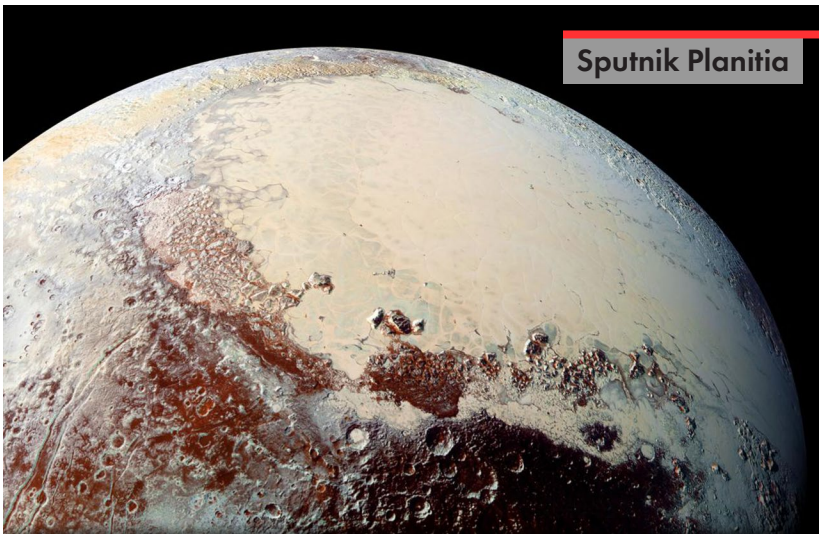
THE NEW HORIZONS MISSION

- NASA decided that it was important to send a mission to Pluto early in the 21st century because Pluto would soon be much farther away from the Sun. Scientists thought that Pluto's atmosphere may condense onto the surface as Pluto moved farther away from the Sun, and they wanted to study Pluto's atmosphere at its most active from solar heating. And so the New Horizons mission was born.

- + The New Horizons spacecraft was launched in January 2006. At the time, its launch speed of 16 km (10 mi) per second—or about 58,000 kph (36,000 mph)—made it the fastest spacecraft ever launched. About 13 months after launch, the spacecraft flew by Jupiter to get a gravity assist, which sped up the spacecraft to around 80,000 kph (50,000 mph). That boost knocked 3 years off New Horizons's flight time to Pluto.
- + New Horizons passed by Pluto at a range of about 12,500 km (7800 mi) above its surface and within the orbit of Charon. After 22 hours of successful flyby, on July 15, 2015, data from the Pluto encounter began to be received at Earth.

New Horizons collected more than 6 gigabytes of data. And because of the extreme distance between New Horizons and Earth, data could only be transmitted at about 1 or 2 kilobits per second, so it took about 15 months after the Pluto encounter to download all 6 gigabytes of data collected.
- + The New Horizons mission revealed Pluto in splendid detail. The surface is covered in frozen nitrogen, with some methane, carbon monoxide, and water ices, too.
- + The surface appears reddish in certain regions. The red material is a dusting of complex organics. Similar reddish material is seen at Saturn's moon Titan and Neptune's moon Triton. Some regions are redder than others. This is thought to be an indicator of the age of the surface, with redder regions having been around longer and therefore having a thicker coating of organics.
- + The youngest and brightest large region on Pluto is also the most dynamic: the Tombaugh Regio (Region), named after Pluto's discoverer. It's also lovingly called the heart of Pluto because of its shape.

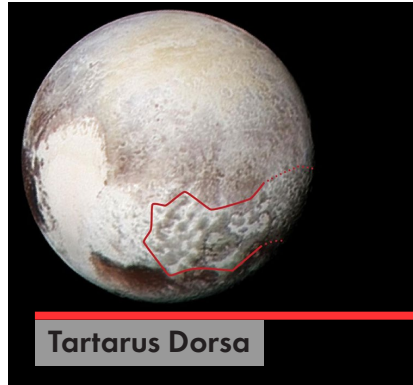
- + The left ½ of the heart is called Sputnik Planitia. Its brightness and lack of craters suggests it may be only 10 million years old. This not-so-old region is about 20% bigger than the state of Texas. The leading hypothesis is that it's an impact basin caused by an impactor that would have been about 150 to 300 km (93 to 186 mi) in size.



Sputnik Planitia

- + The appearance of the region is due to the fact that Pluto's surface is extremely cold. The temperature is about -375°F (-225°C). The nitrogen ice that makes up the surface in this region is denser than water ice at these low temperatures, but it's much less rigid. The whole region appears softer and more flowing than the other regions of Pluto. There are also signs that this region is geologically active.

- ✦ Sputnik Planitia has collections of hills that seem to be floating on the nitrogen ice surface; one possible explanation for these floating hills is that they are eroded pieces of the water ice found in other regions of Pluto. Pits, or hollows, are also seen on parts of Sputnik Planitia.
- ✦ The area immediately surrounding the heart of Pluto at Sputnik Planitia also has some interesting terrain. Near the southern and western edges are water ice mountains that are several kilometers high. There are also signs of cryovolcanoes on the southern boundary.
- ✦ In the northern hemisphere, a region called **Tartarus Dorsa** looks like it's covered in snakeskin. This texture is caused by a series of icy mountains that are about $\frac{1}{2}$ km ($\frac{1}{3}$ mi) high and form a strange bladelike structure. Some scientists have suggested that they are Pluto's version of a feature on Earth called penitentes found in the Atacama Desert in northern Chile.



The features are called penitentes because of their resemblance to a crowd of kneeling religious figures doing penance.



- + Pluto has a very thin atmosphere that is nitrogen-rich with small amounts of methane and carbon dioxide. It's incredibly cold, at about -370°F to -400°F (-220°C to -240°C). The surface pressure is also miniscule: only around 10 microbars, which is about 100,000 times lower in pressure than Earth's surface pressure.
- + Pluto's atmosphere was discovered in 1988, but the New Horizons mission confirmed Pluto's atmosphere and demonstrated that it has a level of unexpected complexity. New Horizons saw about 20 separated layers of haze in Pluto's atmosphere. These haze layers span a height of more than 200 km (124 mi) with about 10 km (6 mi) of distance between the layers. The haze particles are suspended organic particles created when sunlight breaks down methane; it's these haze particles that eventually fall to the surface, creating Pluto's reddish surface areas.
- + Pluto's atmosphere is also escaping—losing about 500 tons of nitrogen atmosphere per hour! That's because the small amount of methane in Pluto's atmosphere heats up the atmosphere. Methane is a greenhouse gas. The heat gives atmospheric particles added energy, and some of them can escape the planet. When the particles are high enough, they can also collide with high-energy particles from the solar wind.

CHARON

- + The New Horizons mission wasn't just a mission to Pluto. It was also tasked to study Charon, Pluto's binary companion.
- + With a diameter of about 1200 km (746 mi), Charon is also big enough for gravity to have made it spherical. Charon has a similar bulk composition to Pluto—ice and rock—but its lower density of 1700 kg/m^3 (106 lb/ft^3) tells us that it's more ice-rich than Pluto.



Charon

- + Data from the New Horizons mission determined that Charon's surface is mostly water ice; this is a big difference from Pluto, whose surface is mainly nitrogen and methane ices.
- + **Why is Charon more of a binary companion than a moon?** We usually think of moons as orbiting an object at the center, similar to how we think of planets as orbiting the Sun at the center. But this isn't exactly right. What really happens is that 2 objects that are gravitationally bound will both orbit their center of mass—the location that represents the average position of the mass in the system. If one of the objects is much bigger than the other, then the center of mass is very close to the center of the large object, and it looks like the small object is orbiting about the center of the large object.

- + This is what happens in the case for all of the moon systems orbiting their planets. But Charon is not much smaller than Pluto. The center of mass of the Pluto-Charon system is actually outside of Pluto. Pluto and Charon both orbit around this point, both with orbital periods of about 6.5 Earth days. Pluto and Charon are also in a mutual gravitational tidal lock so that they both keep the same side facing the other.
- + The binary system of Pluto and Charon is itself orbited by a system of 4 (other) moons, all very small. These small moons are all nonspherical, with longest dimensions of only tens of kilometers across. Nix and Hydra are about twice the radius of Mars's larger moon Phobos, while Styx and Kerberos are closer in size to Mars's smaller moon Deimos.

Despite chaos in the direction of the spin poles, all of Pluto's moons orbit in its equatorial plane in the prograde direction on circular orbits. This suggests that the moons formed around Pluto, rather than being captured.

DWARF PLANET STATUS

- + In 2006, Pluto was demoted from planet status to dwarf planet status.
- + In 2005, astronomers announced finding an object in the Kuiper belt that is more massive than Pluto, although slightly smaller in volume. That object was named Eris. Should Eris be a planet, too? This led the scientific community to take a hard look at what really classified an object as a planet. After much debate, the International Astronomical Union created an official definition of the word *planet*. In order to be a planet in our solar system:
 - 1 the object must be in orbit around the Sun (Pluto was good on this one);

- 2 the object must be massive enough to be rounded by its own gravity (again, Pluto's fine here); and
 - 3 the object must have cleared the neighborhood around its orbit enough to dominate the orbit (here's where Pluto has a problem).
- + If you take Pluto's mass and compare it to the mass of everything else in its orbit, Pluto doesn't dominate. It only makes up 7% of the mass of objects near its orbit. This is in striking contrast to the other planets. For example, Earth makes up more than 99% of the mass in its orbit.
 - + So a new category of solar system object was born: the dwarf planet. Pluto and Eris are dwarf planets.
 - + But that doesn't mean there isn't ongoing discussion about whether Pluto is a planet. Many scientists didn't like the 2005 definition, and some are working on trying to improve on it. One alternative suggestion is to remove the third criterion, which would make Pluto, as well as Eris and other dwarf planets, planets again.

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LECTURE 18

Comets, the Kuiper Belt, and the Oort Cloud



Comets come to us from the outer solar system. Comets are much like asteroids, but their composition includes more ice, and their place of origin is farther from the Sun. Comets are kind of like leftovers of planet formation in the outer solar system. This is very similar to how asteroids are rocky leftovers of planet formation for the inner solar system.

COMETS

- + Comets typically have very elliptical orbits around the Sun. This means that their distances from the Sun vary much more than Pluto's during their orbits. For example, the famous Halley's comet goes closer to the Sun than Venus but also farther from the Sun than Neptune, completing a full orbit about every 76 years.

Halley's comet made its last visit to the inner solar system in 1986. And because it's a periodic comet, we knew when to expect it. Several countries took advantage of the opportunity, and an entire armada of spacecraft missions from the Soviet Union, Europe, and Japan were sent to study the comet.

- + We only get a good look at comets when their orbits bring them to the inner solar system. That means they are closer to us and therefore easier to see. But more importantly, **as comets get closer to the Sun, they heat up, which causes outgassing of their icy components. These gasses spewing from the comets develop into long, bright tails, making them much easier to spot.**
- + **Comets typically have 2 tails: one made of dust and one made of a gas of charged ions.** Interestingly, these tails usually point in different directions.
 - 1 The **dust tail** is made up of the solid material that gets blown off the comet while the ices are evaporating. The dust tail usually points somewhere between the direction behind the comet's orbit and the direction away from the Sun. This dust tail tends to be broad and appears yellow or white in color.
 - 2 The **ion gas tail** is made up of positively charged particles, such as carbon monoxide, molecular nitrogen, and carbon dioxide. Because the ions are charged, they end up trapped by the magnetic fields in the solar wind, so

the ion tail points directly away from the Sun in the direction of the solar wind magnetic field. The ion tail is also usually much narrower and bluer in color than the dust tail.

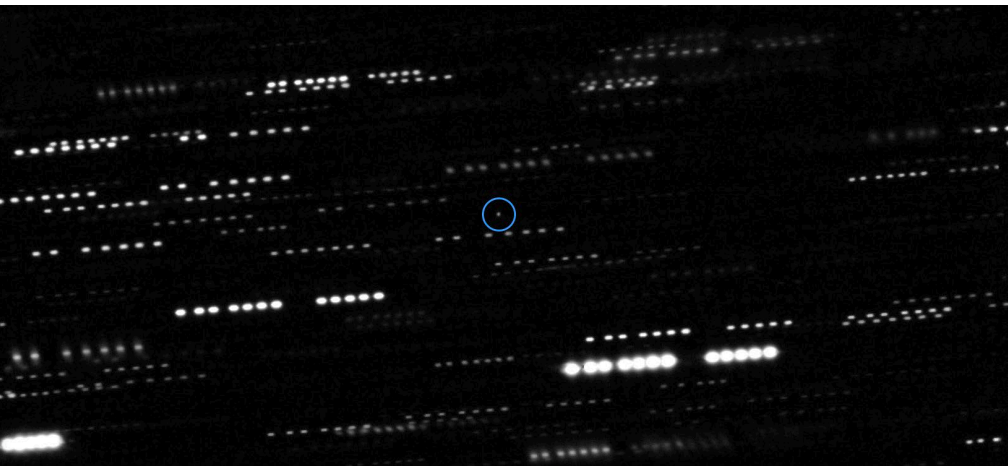
★ Comets are particularly important to planetary scientists for 2 reasons:

1 By studying comets, we learn about the far reaches of the solar system—a place that is much harder to visit than our inner solar system neighbors.

Comets basically bring the outer solar system to us.

2 Comets played an important role in delivering water to the inner solar system, including to Earth! Any water present on Earth's surface while Earth was first forming would have boiled off and escaped Earth's gravity field because Earth was so hot. Instead, the water we have today was most likely delivered to Earth through impacts by small icy bodies: tens of millions of comets, and even asteroids.

In 2017, the first known interstellar object to visit our solar system was discovered: 'Oumuamua. We know it's not from our solar system because it's traveling too fast relative to the Sun—at 26 km (16 mi) per second!



- + Comets are typically divided into 2 categories: short-period comets and long-period comets.
 - 1 Short-period comets have orbital periods of less than 200 years. Such comets are also called periodic, in the sense that we usually see them repeatedly over the centuries and can predict their next return. Short-period comets also tend to have orbits in the same plane and direction as the planets. Most short-period comets originate from a region beyond Neptune's orbit called the Kuiper belt.
 - 2 Long-period comets have orbital periods that are much longer than short-period comets, some even thousands of years. Their orbits are also, on average, much more elliptical and can point in any direction. Long-period comets originate from a region beyond the Kuiper belt, now called the Oort cloud. In fact, long-period comets are the main evidence that such a region exists.
- + When we see a comet in the sky, we are typically seeing the extended sublimating atmosphere, also known as the coma, surrounding the comet. A comet's coma can be extremely large, extending for about 100,000 km (62,000 mi) across—5 to 10 times the diameter of Earth. Material from the coma forms the separate tails of dust and ionized gas.
- + But the real heart of the comet is the small solid portion on the inside of the coma, known as the nucleus. This is the only part of the comet that exists when it's in the outer solar system and not outgassing.

The Soviet Vega 1 spacecraft mission to Halley's comet provided the first-ever images of the nucleus of a comet.

THE KUIPER BELT

- + How many comets are there? It's hard to discover comets until they travel into the inner solar system and develop their bright tails. **Because comets originated in the outer solar system, the small number of comets we know about are likely just a handful from what actually exist in the outer solar system.**
- + **The fact that we see comet tails means that the comets are somewhat fresh.** If they had their current orbits throughout the lifetime of the solar system, they would have lost their icy components long ago and we wouldn't see tails. So **there must be a source region where new comets come from.**
- + **This region of space, called the Kuiper belt, began to be considered more seriously after Pluto's discovery in 1930.** Finding Pluto, this small body beyond the giant planets, led scientists to hypothesize that other small icy bodies are likely to exist in the far reaches of the solar system, too.
- + But it wasn't until 1978 that Charon was discovered. And it wasn't until 1992 that a third object was discovered, now known as Albion. Albion has an elliptical orbit that takes it from its closest distance from the Sun at 41 astronomical units (AU) to its farthest distance at 47 AU. It's around 100 to 170 km (60 to 100 mi) across.
- + **By 2018, more than 2000 Kuiper belt objects (KBOs) had been discovered. Estimates suggest that there are trillions of objects in the Kuiper belt.** Of those, there may be more than 100,000 KBOs with diameters larger than 100 km (60 mi) in the Kuiper belt. If so, each of these will be much larger than both moons of Mars and all but 6 of Jupiter's moons.

- + The Kuiper belt has different components. The whole belt extends from about 30 to 55 AU from the Sun, making it 25 times wider than the asteroid belt. But most discovered KBOs lie between orbital distances of 42 to 48 AU, a region known as the classical belt. These distances mark resonances that KBOs have with Neptune's orbit that keep the KBOs in stable orbits.
- + Neptune's orbit is roughly 30 AU, and a 2-to-3 orbit resonance with Neptune happens at 42 AU. Here, KBOs called plutinos, for their similarity to Pluto's orbit, can maintain stable orbits for long periods of time, and we find a large number of objects at this distance.
- + The outer edge of the classical belt at 48 AU marks a 1-to-2 orbit resonance with Neptune, which again provides stability to KBO orbits. The objects at 48 AU are called twotinos because of this 2-to-1 resonance.
- + There are also scattered disk objects, which have larger ellipticities and inclinations. They can be found anywhere from about 30 AU to more than 100 AU. The KBOs in the scattered disk have likely been strongly perturbed by gravitational interactions with the gas giants, putting them in these scattered orbits. The scattered disk objects are believed to be the source for short-period comets because KBOs in the classical belt have very stable orbits and are unlikely to be perturbed into comet-like orbits.
- + Pluto and Charon are some of the largest known KBOs. But there are other KBOs similar in size to Pluto. There are also 3 KBOs known to be large enough to be spherical and therefore are dwarf planets, like Pluto. All 3—Haumea, Makemake, and Eris—were announced in 2005 and sparked the discussion of what defines a planet and whether Pluto should be considered a planet.

- + Although Haumea, Makemake, Eris, and Pluto have been the only certified dwarf planets in the outer solar system, there are many other known KBOs that are likely to be dwarf planets. We just don't have enough data yet to constrain their masses and confirm that they are indeed spherical.
- + Sometimes we can infer the presence of a large planetary object even if we can't see it. That's how Neptune was discovered, based on Uranus's orbit. It turns out that orbits of objects in the farthest part of the Kuiper belt also hint that there may be another large object out there, although it hasn't been found yet. It is known as Planet 9 and is estimated to be about 10 Earth masses and several Earth diameters. It would therefore be only a bit smaller than the ice giants Uranus and Neptune.
- + This hypothetical planet would help explain the high ellipticity and extreme inclination of the orbits of some extreme objects beyond the Kuiper belt. Planet 9's orbit is also believed to be highly elliptical, taking it from about 200 AU to as far as 1200 AU! And one orbit takes tens of thousands of years. The hunt is on for the hypothetical Planet 9 as scientists further refine what its orbit must be like to explain the perturbed orbits of KBOs.
- + The Kuiper belt contains the farthest solar system objects we've ever discovered, but we know that there must be objects much farther because of long-period comets.

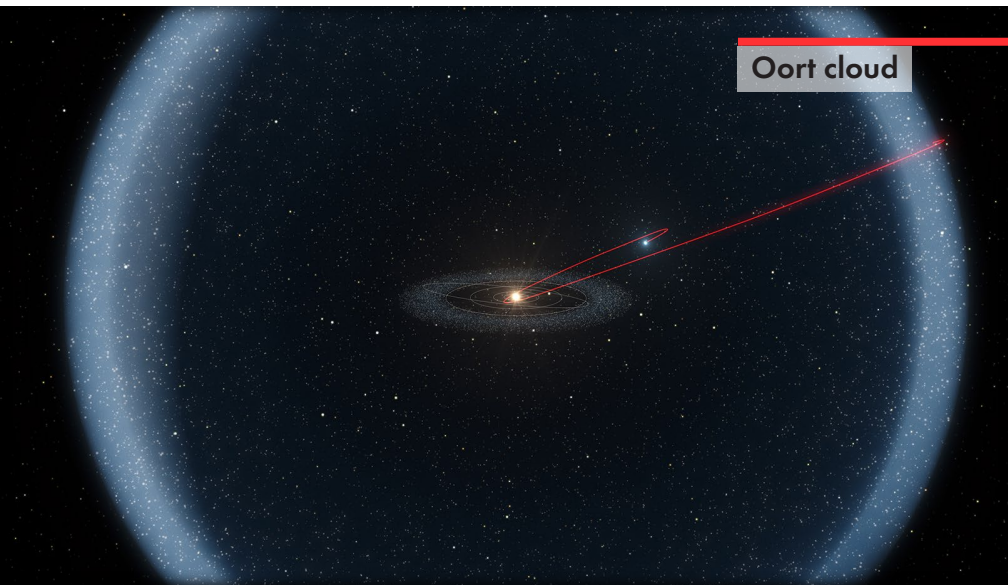
Jupiter-family comets have orbits in the plane of the solar system from out near Jupiter traveling to points inward. Unlike asteroids, Jupiter-family comets are likely to have been Kuiper belt objects that at some point got too close to Jupiter, which gravitationally perturbed their orbits inward. More than 660 Jupiter-family comets have been discovered.

THE OORT CLOUD

- ★ The Oort cloud is a spherical shell of small bodies that is extremely far away. We sometimes treat the Kuiper belt as the outer edge of the known solar system, but the Oort cloud is about 50 to 5000 times farther away from the Sun than the Kuiper belt. The outer edge is about 100,000 times the distance of the Earth from the Sun.

The Oort cloud is so far away, and the objects are so dim and small, that we can't observe any objects there directly.

- ★ The Oort cloud is even beyond the heliopause, the region of space beyond which the solar wind ceases to protect the solar system from the interstellar winds. The Oort cloud is also about 20% of the distance to the nearest star to our solar system, Proxima Centauri!



- + The Oort cloud is believed to contain billions of cometary objects, although we've not been able to see any objects out there. So how do we know where it is if we can't see anything that faint? First, we can track long-period comet orbits to get a sense of how far they travel. And the outer edge of the Oort cloud can be defined in terms of the distance to the Sun's Hill sphere. Any object farther from the Sun's Hill sphere wouldn't be gravitationally bound to it and therefore wouldn't be a part of the solar system. The outer edge of the Oort cloud, then, is the outermost boundary of our solar system.

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QUIZ

LECTURES 13–18

- 1 Which of the following features has not been seen in Saturn's rings? [L13]
 - a spokes
 - b partial ring arcs
 - c waves
 - d gaps
 - e propeller moonlets

- 2 Which of the following statements is true about metallic hydrogen in Saturn? [L13]
 - a Hydrogen transforms to a metallic state at the same depth in Saturn as in Jupiter.
 - b Saturn is not massive enough for pressures to be large enough for metallic hydrogen to form.
 - c Metallic hydrogen is found deeper in Saturn than in Jupiter.

- 3** Which of the following statements is true about Saturn's moons? [L14]
- a** All of Saturn's moons are smaller than any of the Galilean moons around Jupiter.
 - b** All of Saturn's moons orbit beyond the rings.
 - c** Saturn has more round moons than Jupiter.
- 4** Why is Enceladus a promising candidate to search for signs of life? [L14]
- a** It has a liquid water ocean at its surface.
 - b** It has a liquid water ocean in its subsurface.
 - c** It has a liquid methane ocean at its surface.
- 5** Which of the following statements best describes the storms in Uranus's atmosphere? [L15]
- a** We've observed fewer large storms at Uranus than at the other giant planets.
 - b** The storms on Uranus are more intense than at Neptune.
 - c** No storms have been observed at Uranus.

- 6 Which of the following material phases doesn't exist in Uranus's interior? [L15]
- a molecular hydrogen
 - b ionic water
 - c metallic hydrogen
- 7 Which of the following statements is not true about Neptune's discovery? [L16]
- a Neptune was the only planet that required a telescope for discovery.
 - b Neptune was discovered due to predictions based on observations of perturbations to Uranus's orbit.
 - c Neptune was the last planet to be discovered in our solar system.
- 8 Which of the following surface features is only seen on Neptune's moon Triton and nowhere else in the solar system? [L16]
- a coronae
 - b active volcanism
 - c cantaloupe terrain

9 Which statement is not true about Pluto's moon Charon? [L17]

- a Charon is the biggest moon in the solar system.
- b Charon is the biggest moon relative to the size of its planet in the solar system.
- c Charon is the only round moon orbiting Pluto.

10 Which of the following surface geological features are seen on Pluto? [L17]

- a penitentes
- b craters
- c pits/hollows
- d All of the above

11 Which of the following statements is true about the difference between comets and asteroids? [L18]

- a Asteroids don't have water, whereas comets do.
- b There are near-Earth asteroids but not near-Earth comets.
- c Asteroids are more similar to the planetesimals that created the terrestrial planets, whereas comets are more similar to the planetesimals that created the outer planets.

12 Which statement is true about the Kuiper belt? [L18]

- a** All comets originate from the Kuiper belt.
- b** The Kuiper belt contains all of the dwarf planets in the solar system.
- c** The Kuiper belt is more massive than the asteroid belt.

Answers can be found on page 300.



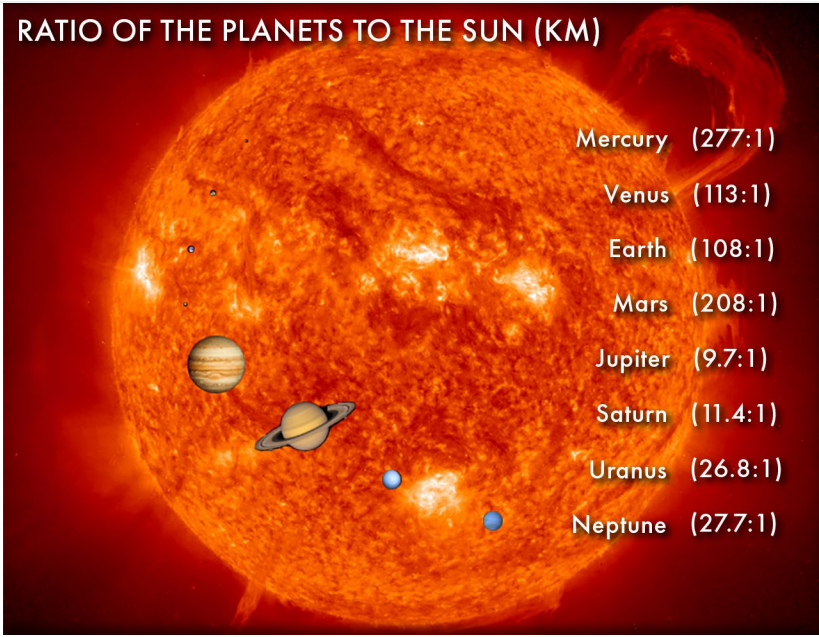
LECTURE 19

How Our Sun Defines Our Solar System



Imagine what would happen if we magically removed the Sun from the solar system. Darkness would reign, temperatures would plummet, and planets would all go flying off in straight lines from wherever they were in their orbits. But the Sun's importance goes even further: Without the Sun, the planets would never have formed. The planet formation process relied on dust and gas being confined to a disk orbiting the proto-Sun. That disk formed because material was collapsing onto the proto-Sun. Thankfully for us, some material had a bit more rotation, making it end up in a disk orbiting around the Sun, rather than onto the Sun itself.

RATIO OF THE PLANETS TO THE SUN (KM)



The Sun is by far the biggest and most massive object in the solar system—making up 99.9% of the total mass of the system.

GRAVITY, LIGHT, AND HEAT

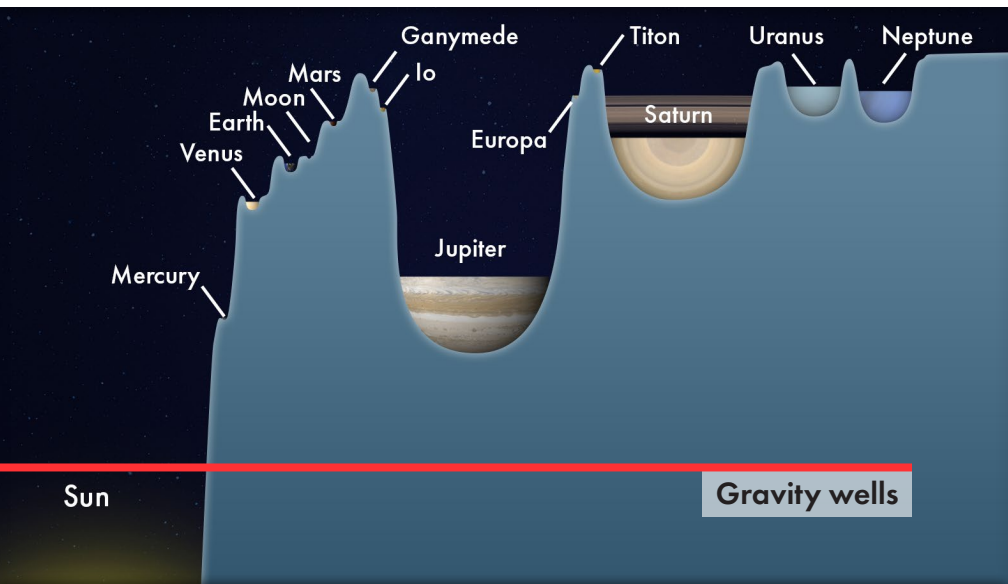
- + Observations of the Sun and its motions in the sky were recorded by ancient astronomers from many cultures, but it wasn't until the 17th century that scientists began to take seriously the idea that the Sun is a star, just like all the stars we see in the night sky. But later in the 17th century, a series of scientific discoveries lent support to the notion that the Sun is a star.

- + Galileo's telescope led him to conclude that stars must be very far away because they still looked like points of light rather than resolved planets through his telescope.

Italian philosopher Giordano Bruno was burned at the stake in 1600 by the Roman Catholic Church for saying that the Sun is a star.

- + Kepler's laws of planetary motion followed Copernicus in putting the Sun at the center of the solar system and determined that the orbits of the planets around the Sun had an elliptical shape, not circular.
- + Then, Newton's theory of gravity explained why planets orbited the Sun and demonstrated that the gravity we feel on Earth was the same as the gravity elsewhere in the solar system.
- + And then people began to try to calculate distances to the stars. Christiaan Huygens calculated the distance to the star Sirius by assuming it had the same brightness as the Sun. And he found that the distance was extremely far.
- + Much later, in 1838, Friedrich Bessel used a new technique called parallax to determine that the distance to a star called 61 Cygni was what we would now call 10 light-years away from Earth. This demonstrated that stars must be extremely bright—as bright as the Sun—in order for us to see them so far away. This ultimately led to the understanding that **the Sun is not a unique entity in the universe**. There are many more suns, or stars, out there.
- + But the Sun is a star that we can study up close. It's *our* star!

- As the most massive body in the solar system, the Sun has the deepest gravity well—which is ultimately defined by how much energy an object needs in order to escape the gravitational pull of that larger body. The more massive the pulling body, the more energy you would need to overcome the attractive gravity force pulling you toward the body.



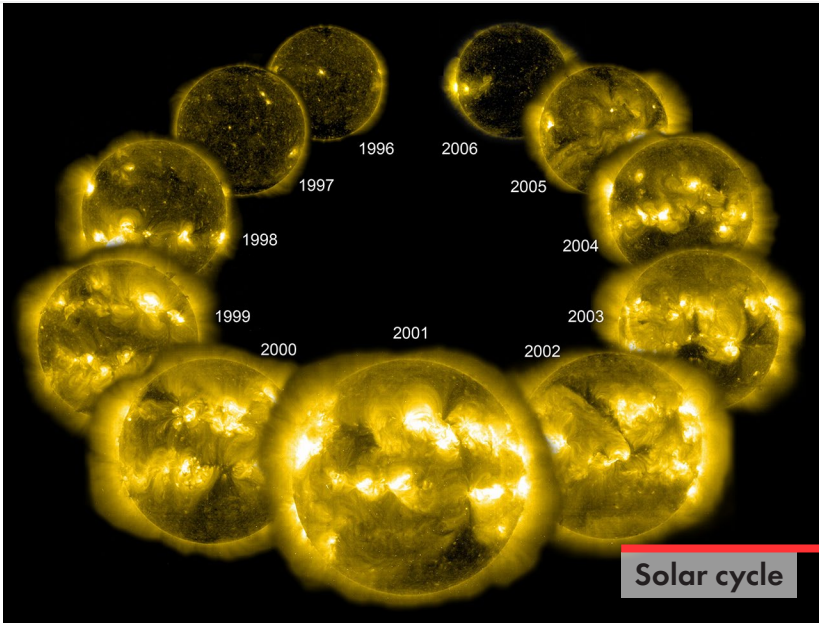
- All of the planets are gravitationally bound to the Sun in the sense that they don't have enough energy to escape the Sun's gravity well. But that doesn't mean we will fall directly into the Sun. Instead, planets orbit the Sun. They essentially are in constant free fall toward the Sun, but their velocity is tangential to their orbit, and that keeps them from ever falling in.

- + But just because the Sun has the largest gravity well in the solar system doesn't mean everything in the solar system orbits the Sun. The strength of gravity is a function of distance. Moons that orbit planets, for example, happen to be close enough to the planet that the planet's gravity at that location dominates the Sun's gravity.
- + **The Sun's gravitational influence extends to far distances, as evidenced by the Oort cloud**, at orbital distances up to 50,000 astronomical units. But at the distance called the Hill sphere—at around 100,000 astronomical units—the gravitational force of nearby stars takes over.
- + But gravity isn't the only way the Sun shapes the solar system. The Sun is also a major source of heat and light for the solar system.
- + The pressures and temperatures are so high in the center of the Sun that hydrogen atoms are squeezed together—fusing—to make helium atoms. **All the energy we are getting from the Sun comes from nuclear fusion occurring in the Sun's core.**
- + This is possible because the 4 hydrogen atoms are slightly more massive than the resulting helium atom. The difference in mass between 1 helium atom and 4 hydrogen atoms is converted to energy, which equals the mass difference times the speed of light squared—Einstein's famous $E = mc^2$ equation.
- + The inner 25% of the Sun converts more than 600 million metric tons of hydrogen into helium every second. Temperatures need to reach about 25,000,000°F (14,000,000°C) in the solar core for fusion to initiate because the hydrogen atoms have to have enough kinetic energy to overcome the repulsive forces between them. **It's this fusion that makes the Sun a star rather than a planet. No planets have fusion going on in their interiors.**

- + The fact that the Sun is composed primarily of hydrogen and helium was first determined in 1925 by Cecilia Payne-Gaposchkin. Before then, the reigning belief was that the Sun's composition was quite similar to Earth's. **The Sun's composition is about 75% hydrogen and 24% helium.** The remainder, a mere 1%, contains all the heavier elements.

SOLAR MAGNETIC FIELD

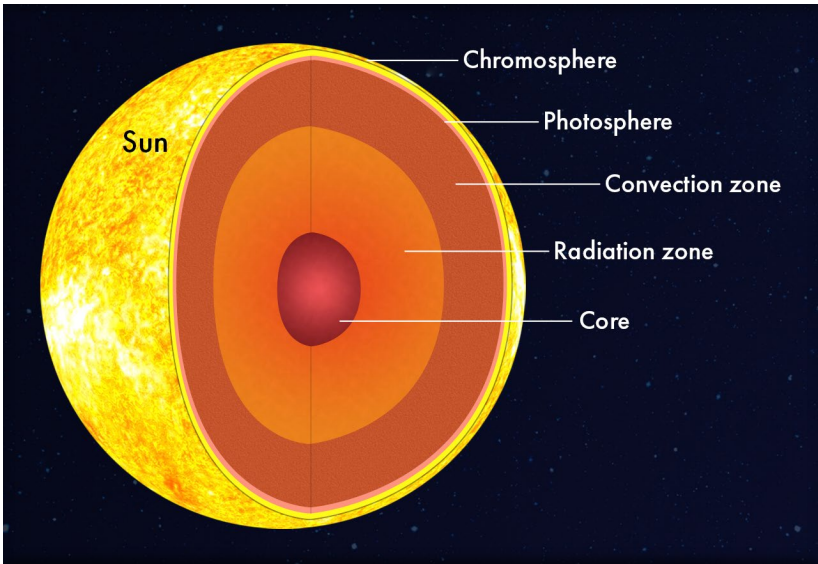
- + **Vigorous motions in the interior of the Sun create a dynamo that produces a magnetic field.** At the surface, the solar magnetic field consists of 2 parts:
 - 1 There is a **global, large-scale, dipolar field**—kind of like the dipolar magnetic field generated by the Earth's dynamo.
 - 2 **Sunspots**, which appear as dark blotches on the surface of the Sun, are caused by intense magnetic fields that let less heat out of the interior and make the Sun look darker there. The magnetic fields in sunspots are about 1000 times more intense than the Sun's global dipole field.
- + **Both the sunspots and the global magnetic field participate in the solar cycle—which lasts about 11 years.** At the beginning of each cycle, the dipole field has a certain polarity, and sunspots begin to form at midlatitudes on the Sun's surface. These sunspots include bundles of magnetic fields that emerge from the interior of the Sun. As time goes on, those sunspots disappear and more and more new spots appear at latitudes closer to the equator. That continues until the sunspots start appearing close to the equator at the 11-year mark. Then, the Sun reverses the polarity of its dipole magnetic field, and the sunspots begin to appear at midlatitudes again.



THE SOLAR WIND

- + The fusion in the Sun's core not only produces light energy that travels up through the interior of the Sun, but it also generates the solar magnetic field. **The character of the planets is fundamentally shaped by their experiences of both the heat and magnetic field from the Sun.**
- + But light and heat aren't the only things that come from the Sun and hit the planets. **There is also ionized mass from the Sun, called the solar wind. The mass in this wind is made of plasma, the fourth state of matter.** Plasma occurs when atoms have so much energy that they separate into protons, electrons, and helium nuclei (which are just proton doublets, also known as alpha particles). This plasma originates in the Sun's atmosphere. When it hits Earth, it's like plasma rain.

- + The Sun's atmosphere is divided into 2 layers:
 - 1 Above the opaque photosphere is the chromosphere layer, which is a few thousand kilometers thick. The temperature increases with height here, reaching about 18,000°F (10,000°C) at the top of the chromosphere. Fibrous jets known as spicules appear and travel through the photosphere in about 10 minutes, carrying plasma to higher altitudes.
 - 2 Above the chromosphere is the corona, which is several million kilometers thick. The corona is where the solar wind originates. The Sun's gravitational force is too weak in the corona to hold onto this energetic hot plasma, so the plasma gets accelerated to high speeds. The temperature spikes to around 3,600,000°F (2,000,000°C). But because the density of the plasma is much lower than at the photosphere, we don't usually see the light from this region.
- The Sun's corona can best be seen during a solar eclipse because it appears as a halo surrounding the blocked-out Sun's disk.
- + The Sun emits about 1.5 million tons of superheated plasma per second out into the solar wind. Speeds can vary a lot based on the Sun's magnetic field and from what region it gets emitted, but it can reach speeds of 2,700,000 kph (1,680,000 mph)! The ionized particles in the solar wind are coupled to the solar magnetic field and take on a spiral structure in space. These high-energy solar wind particles cause aurora at planets with a magnetic field. But they can also be disruptive to planet atmospheres and surfaces.
 - + The solar wind can also be used to define the boundary of the solar system. The wind carries with it solar magnetic field lines, which can act as a bubble, shielding the solar system from the interstellar wind. This is similar to how Earth's magnetic field shields our planet from the solar wind.



SOLAR STORMS

- + The solar wind becomes most dangerous to us on Earth during a solar storm. Much of the plasma in the Sun's corona is typically confined in regions where the Sun has strong magnetic fields, like in sunspots, where the magnetic fields create large arcing loops over the plasma. You can think of it like a net holding a fish in.
- + A coronal mass ejection is a plasma storm that occurs when those magnetic fields experience reconnection events, which realign the magnetic fields. After a reconnection event, it's like there's a big hole in the net, and solar plasma can explode out of it.

- + This explosion causes a much bigger mass of plasma than usual to be hurled through the “hole” and into space. Sometimes that plasma is directed toward the Earth. If so, **the huge flood of ionized particles can disrupt our magnetosphere and cause new currents to flow. This is called a geomagnetic storm.**
- + **Radiation from these events can cause the aurora to appear at lower latitudes than they normally would.** And not only are aurora pretty, but the light signals can also offer us hours of early warning for the mass of plasma to come next.
- + **Electrons (and other charged particles) from geomagnetic storms can also disrupt electronics,** including radio transmissions and satellites. For example, GPS coordinates can stray by several meters during a storm. These geomagnetic storms have also been known to knock out power grids.
- + **So when will the next geomagnetic storm occur?** When the Sun has lots of sunspots, coronal mass ejections occur about **3 times a day.** When there are few sunspots, it’s only about **once every 5 days.**
- + Solar storms also hit other planets, although we don’t have much data or observations of this.

In March 1989, the Sun released a coronal mass ejection whose energy was equivalent to thousands of nuclear bombs. The interaction with Earth’s geomagnetic field caused the province of Quebec in Canada to lose power for 9 hours.

- + There have been several missions designed to observe the Sun and help us begin to forecast so-called space weather.
- ✦ In geosynchronous orbit around Earth is the Solar Dynamics Observatory, which images the Sun's photosphere and atmosphere in many different wavelengths of light to study the magnetic and high-energy features that occur here.
- ✦ Orbiting the Sun from an Earthlike distance, the Solar Terrestrial Relations Observatory, or STEREO, used 2 telescopes at 2 different and changing locations to get stereo images of the Sun. This has allowed for the determination of the 3-dimensional structure of solar features, like the extent of giant coronal mass ejections.

READINGS

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LECTURE 20

A Solar System Time Machine and Meteorites



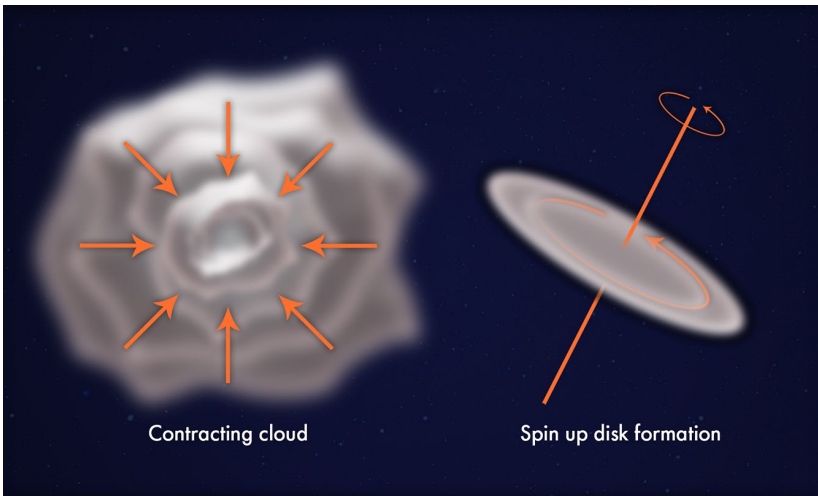
Trying to figure out how the solar system formed is a bit like a crime scene investigation: We weren't there for the formation of the solar system, but the scene we have now provides clues as to what happened. We need to find those clues and piece them together to come up with a scenario that best explains the facts.

The solar system is not just an arrangement in space. It is also an arrangement over time—vast amounts of time—which means that we need to become time travelers. Traveling backward in time allows us to explain key features of the solar system that we have been ignoring or taking for granted.

CLUE 1: ORBITS IN THE SOLAR SYSTEM

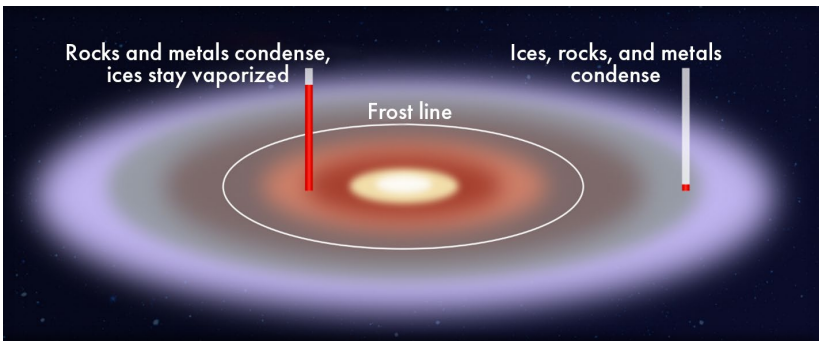
- + All the planets are in the same orbital plane, and they all orbit in the same, prograde direction around that plane. And the direction of their orbits is the same as the direction of the Sun's rotation.
- + The best explanation for this set of observations is that all the planets formed the same way: out of a spinning disk of gas and dust that surrounded the proto-Sun, all rotating in the same direction. Planets formed from the disk by having material clump together through their mutual gravitational attraction to form larger and larger bodies. Eventually, they grew large enough to become planets.

It takes only 1 to 10 million years for an initial cloud about 20,000 astronomical units (AU) in diameter to collapse to the point where there is a functioning star at the center surrounded by a thin disk of about 200 AU in extent.



CLUE 2: PLANET COMPOSITION

- + The rocky terrestrial planets are closer to the Sun than the giant planets, and the gas giants are closer than the ice giants.
- + This can be explained by considering the temperatures in the protoplanetary disk. The Sun at the center would have been sending heat out through the disk, just like the Sun heats the solar system today. Regions closer to the Sun would have been much hotter than regions farther away. This gradient in temperature resulted in different materials condensing out of the gas into solid phases at different distances from the Sun.



- + At the earliest times, only materials with very high solidification temperatures, like metals and silicate rocks, could condense out of the gas in the inner solar system. Farther out, molecules with lower condensation temperatures could condense as well, because temperatures were cooler. These included things like water, ammonia, and methane—what planetary scientists call ices.

+ These differences had 2 consequences:

- 1 **The primordial material that went into making the inner planets was different than the outer planets.** Planets grew from gravitational interactions between smaller objects. If 2 objects were close enough to each other, they could merge into a larger object. This continued until planet-sized objects emerged, and there wasn't much stuff left around the individual planets to keep them growing. But if only metals and rocks were available in the inner solar system, then the planets that formed in this region would be mostly metal and rock, just like we see. In the outer solar system, the planets were forming out of building blocks that had metal, rocks, and ices.
- 2 **Because ices also condensed in the outer solar system, the outer planets had more material available to make the planets. This means that the planets grew faster and larger in the outer solar system.**

+ We know from looking at other protoplanetary disks that it takes about 10 million years for the gas to be blown away or accumulated in the planets.

A STATISTICAL OUTCOME

Gravitational accretion from a protoplanetary disk explains how our planets formed. But if we were to try to build another planetary system by starting with the same ingredients, would we end up with the same distribution of planets in the solar system? Would there be 4 terrestrial planets and 4 giant planets? And would the planets all look basically the same as they do in our solar system?

Although the laws of physics and chemistry would be the same in that solar system, slight differences in the location or motion of the initial planetesimals would likely result in different outcomes for the final planets. That's because solar system formation is, in a technical sense, a very chaotic process.

CLUE 3: FEW AND ISOLATED PLANETS

- + There are only a handful of planets—8 of them. And each planet is relatively isolated in space; that is, the planets are few and far between, with the large planets especially far apart.
- + This can be explained by how planets grow through gravity. Consider a time when the disk was filled with bodies the size of boulders to houses. These are called planetesimals. Gravitational encounters between these bodies sometimes resulted in collisions. A head-on collision that was slow enough might result in the 2 objects merging. A faster collision involving weaker bodies might result in the objects breaking apart. Stronger bodies that hit at an angle might rebound like billiard balls. The specific result would depend on the speed and angle of the collision and the structural properties of the planetesimals.
- + Those planetesimals that experienced more merging collisions would grow. And the bigger they got, the larger their gravitational force would be, so they could attract even more objects and grow even faster.
- + Eventually, the growing planetary embryos accreted all the material in their region of the disk, basically sweeping clear a ringlike portion of the disk. This is why the planets are relatively isolated in space. They each had their own “feeding zone.” Whenever growing planetesimals were especially close together, then it’s likely that they would have gravitationally interacted to either merge or cause one body to get flung far away. When the feeding zone was cleared, the protoplanets stopped significant growth, leaving us with planets.

CLUE 4: WHERE THE TINY THINGS ARE

- ✦ The solar system has many small bodies, like asteroids, comets, Kuiper belt objects, and the Oort cloud. These are planetesimal remnants that didn't end up accreted into the planets. That's why studying these small bodies is so important: They show us unused building blocks of the planets that have remained relatively unchanged.
- ✦ The asteroid belt may offer us the closest thing to examples of the rocky planetesimals that formed the terrestrial planets. The Kuiper belt offers us samples of the icy planetesimals that formed the outer planets and moons. The Oort cloud holds the planetesimals that were flung to the far reaches of the solar system through gravitational encounters with the growing planetary embryos.
- ✦ But keep in mind that the asteroids, Kuiper belt objects, and the Oort cloud have evolved over time, too. These former planetesimals have collided with each other. They've experienced space weathering from interactions with the solar wind. They've had their orbits altered from gravitational interactions with Jupiter and other bodies. And they've experienced different temperatures since they formed.
- ✦ This means that we have to interpret small bodies today as evolved planetesimals, just like the planets today. They are not the same as they were 4.5 billion years ago.

CLUE 5: PLANET STRUCTURE

- + The planets are mostly differentiated into layers, with the densest components found deeper in their interiors.
- + That layered structure is explained by the fact that the collisions that occurred while planets were growing released a lot of energy. This energy heated the interiors of the protoplanets and sometimes melted them.
- + Once molten, denser material would sink to the center of the planet, causing the layered structure we typically see today. For example, the terrestrial planets all have lighter rocky mantles surrounding their denser iron cores, and the giant planets have hydrogen and helium gas envelopes surrounding interiors of heavier elements.

CLUE 6: MOON SYSTEMS

- + Some planets have moon systems! And the largest of those moons tends to orbit its planet in a disk in the same direction as the planet's spin; that is, these moons and planets kind of look like mini solar systems.
- + This suggests that a similar process that created the planets around the Sun created those moons around planets. If a planet were massive enough and were spinning, then gravity would have acted to accrete material into a disk surrounding the planet. Each so-called protolunar disk could create moons the same way the protoplanetary disk created planets.

CLUE 7: PLANETARY CATASTROPHES

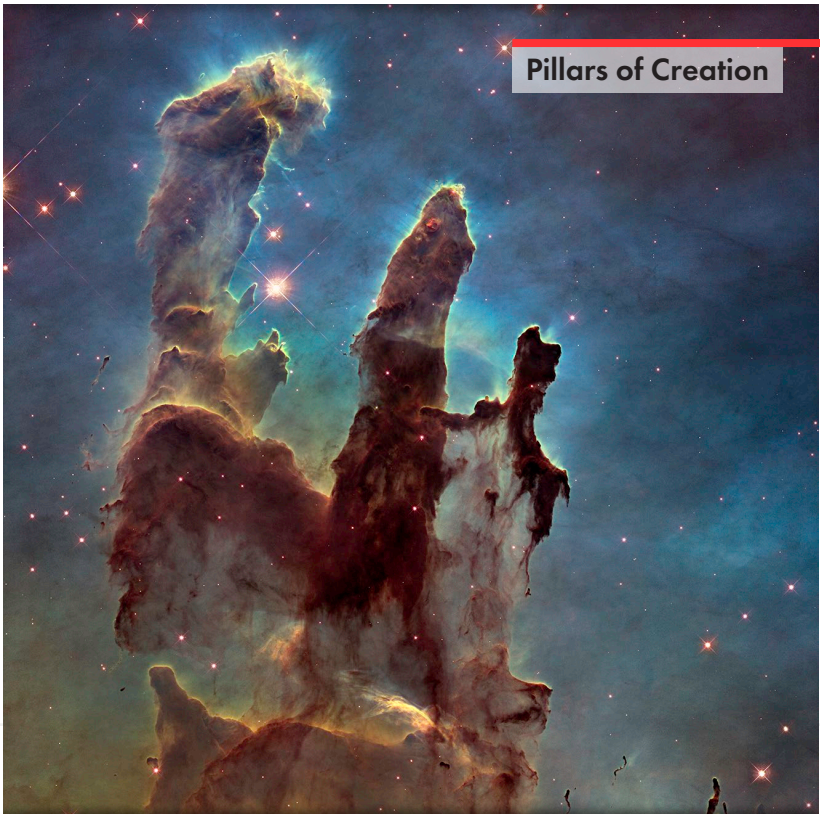
- + Gravitational accretion of the planets from collisions seems a fact. And we see signs of collisions everywhere we look.
- + We see giant impact craters on planets and moons, and these enormous craters suggest that there were collisions between large bodies. We've also used collisions to explain solar system quirks, such as Earth's large Moon, planetary rings, Mercury's large core, and the spin axes of Uranus and perhaps Venus.



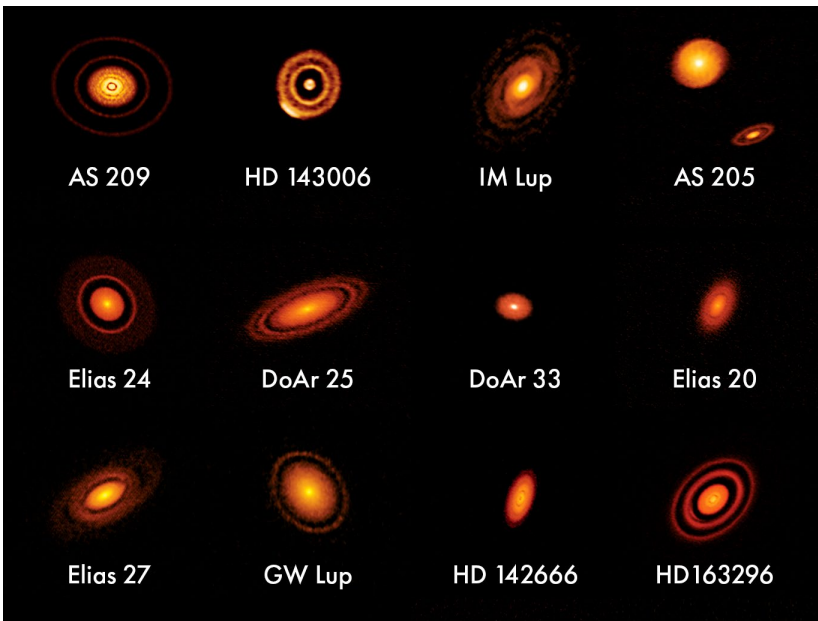
Impact crater

- + Where did the disk come from?
- + So the planets we see today formed from gravitational accretion of smaller bodies that grew from a rotating disk surrounding the forming Sun. But where did the protoplanetary disk come from? We have to go back even further in time to investigate that.

- ✦ Before the disk came the nebula.
- ✦ The nebula that produced our protoplanetary disk came from a molecular cloud. Molecular clouds are seen throughout the galaxy. They are cold, dark, giant regions with condensates of dust and molecular gasses. They can be more than 200,000 astronomical units in size. These molecular clouds serve as nurseries for the creation of new stars.
- ✦ When small perturbations in the motion of the gas and dust in these clouds happen to cause the density to get sufficiently high in a region, then that area begins to collapse under its own mutual gravitational attraction. It's then called a cloud core.



- † The densest regions in a cloud core collapse the fastest, so the cloud keeps fragmenting into smaller and smaller denser regions. Eventually, one of these cloud cores collapses enough to create a central region that's dense enough to form a protostar surrounded by a cloud of gas and dust collapsing in on the star. This spherical cloud is about 10,000 astronomical units in radius and is called a planetary nebula.
- † But the nebula doesn't stay a spherical cloud for long. The gas and dust particles that make up the nebula are randomly moving about. This gives the cloud a tiny bit of net rotation. As the cloud collapses, its angular momentum has to be conserved, so the cloud begins spinning faster and faster.
- † So spinning disks naturally form around a growing star. In fact, we see similar disks orbiting other protostars as well.



TIMING OF SOLAR SYSTEM FORMATION: METEORITES AND ISOTOPES

- + Any great crime scene investigation also has to deal with timing issues. When did events occur? For solar system formation, we have some clues about how long it took the planetary nebula to contract into a disk and how long it took the gas to blow out of the disk. These clues come from looking at other protoplanetary nebulae around other protostars and assuming ours worked much the same way.
- + But when it comes to the formation of the planets, we have another important marker of time: meteorites!
- + Meteorites come from a variety of sources, such as the Moon, Mars, and asteroids. Some of the oldest meteorites we have come from planetesimals like the ones that formed the planets. The fact that we can determine their ages from radioisotope dating means that we can study their features to learn what was happening when they formed. In this way, meteorites help provide us with a timeline for the formation of the planets by constraining various processes.
- + Radioisotope dating of Moon rocks has also told us that the Moon was formed by 4.5 billion years ago. This means that most of the terrestrial planets were formed within 100 million years after the beginning of the solar system.
- + Meteorites also provide us with another important clue that the Sun and the protoplanetary disk formed around the same time: Even the Sun has the same composition as meteorites! Well, technically, if you set aside the hydrogen and helium in the Sun, then the rest of the composition of the Sun is quite similar to the composition of the most pristine meteorites in

the solar system. In other words, it looks like the Sun and oldest meteorites formed from the same stuff at the same time.

- + Meteorites tell us that the solar system is more than 4.5 billion years old. But our solar system is still evolving; currently, it's sort of middle-aged.

Using the Sun's mass and luminosity, we can determine how long it can go on with nuclear fusion in its core. And the answer is about another 5 billion years.

READINGS

Carney, *Planets*.

Elkins-Tanton, *Asteroids, Meteorites, and Comets*.

Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.



LECTURE 21

What the Biggest Exoplanets Reveal



By studying exoplanets—planets around other stars—we’ve found that our solar system seems to be typical because we see analogs to our own planets: giant planets and rocky planets. But we’ve also found exoplanets with no analogs in our solar system, such as rocky worlds 10 times more massive than Earth, called super-Earths; ice giant worlds called mini-Neptunes that are only a few times more massive than Earth; and Jupiter-sized planets orbiting their stars closer than Mercury does the Sun! Clearly, the laws of physics have allowed for more solar system formation scenarios than we could imagine by just examining our own.

PULSAR PLANETS

✦ The first confirmed discovery of exoplanets was an especially unusual case. In 1992, 2 planets, each about 4 times more massive than Earth, were discovered orbiting a pulsar—a tiny, hyper-dense, furiously rotating neutron star that is strongly magnetized.

✦ Then, in 1994, a third planet, with a mass of only 2% of Earth's mass, was discovered in the same system. This particular pulsar is named Lich, after an undead creature that controls others with magic. Lich and its planets are 2300 light-years away from us in the Virgo constellation.

Lich has a mass of about 40% larger than our Sun but a radius of only 10 km (6 mi)! And it is spinning many times each second!

✦ These 3 planets all orbit within $\frac{1}{2}$ an astronomical unit (AU) from their star.

1 The outermost planet is named Phobetor, for the Greek god of nightmares. It orbits the pulsar every 98 days at an orbital distance of 0.46 AU.

2 Then comes Poltergeist, named after the ghostly spirit, which orbits every 67 days at an orbital distance of 0.35 AU.

3 The innermost planet, named Draugr, after an undead creature in Norse mythology, is only about twice as massive as Earth's Moon. It orbits at only 0.2 AU, with an orbital period of 25 days. This would remain the smallest exoplanet discovered for almost 30 years.

✦ Only a handful of other pulsars have been found with planets. In fact, it was surprising to find any planets around a pulsar. That's because of how pulsars form: They form when large stars run out of fuel and

gravitationally collapse in on themselves, resulting in a supernova explosion. What's left behind is just an extremely dense ball of neutrons at the center.

- + We wouldn't expect there to be any planets around a former supernova! It should have blown away everything in orbit, just before becoming a spinning neutron star.

Thousands of exoplanets have been detected so far, and there will be many more to come.

PLANETS AROUND MAIN-SEQUENCE STARS

- + The first confirmed planet around a main-sequence star—a star that is still in the prime of its life—was found in 1995. The planet orbits the star 51 Pegasi, which is some 50 light-years away from Earth. It's actually a star that's quite similar to our Sun, with similar mass and temperature. This means that the environment of this stellar system is also similar to our own.
- + The planet is named Dimidium, which is Latin for “half.” It refers to the fact that Dimidium—which is also known as 51 Pegasi b—is about $\frac{1}{2}$ the mass of Jupiter, which makes it about 150 times more massive than Earth. With such a large mass, Dimidium is assumed to be a gas giant planet.
- + At first glance, Dimidium looks like a planet we would find in our solar system. But its orbital distance is only 5% of an AU! That's almost 8 times closer to its parent star than Mercury is to the Sun! That gives Dimidium an orbital period of only 4 Earth days.
- + It was somewhat baffling that such a giant planet could form so close to its star, but it turns out that this is not an anomalous case.

HOT JUPITERS

- + From 1995 to 2000, 27 planets around main-sequence stars were discovered—ranging from Dimidium, at about $\frac{1}{2}$ a Jupiter mass, to planets more than 10 Jupiter masses in size. And most surprisingly, these Jupiter-like planets are very close to their stars: Their orbital distances range from about 0.04 to 2.5 AU. Compared to the radiation Jupiter gets at 5 AU from the Sun, these large planets are highly irradiated by their stars and have hotter surface temperatures.
- + Because of their high temperatures, large masses, and close orbits, these planets are considered members of a new class of planets, dubbed hot Jupiters. We have no hot Jupiters in our own solar system.
- + In fact, our understanding of how solar systems formed at the time these planets were being discovered implied that hot Jupiters couldn't exist! Gas giants are supposed to form in the outer solar system, where temperatures are low enough so that ices condense, giving lots more material for much larger planet cores to form. Those large cores eventually become large enough to attract the gas in the disk to become gas giant planets.
- + There are 3 theories for how hot Jupiters can form.
 - 1 Their protoplanetary disks were much more massive than in our solar system—massive enough so that giant planet cores could form much closer to the star and fast enough to attract the gas before it blows away.
 - 2 Hot Jupiters could have formed farther away from their stars, much like the gas giants in our solar system, but then they migrated inward because of gravitational drag forces with the remaining disk. They eventually reached a stable orbit much closer to their parent star.

3 The gas giant planets could have formed in the outer regions of the solar system, like how they formed in our solar system, but then they got gravitationally perturbed by a massive object—such as another giant planet or a companion star—even farther out than the planet. The interaction changed the orbit of the giant planet, making it much more elliptical. Finally, the elliptical orbit resulted in strong tidal forces whenever the giant planet got close to the star. These tidal forces damped the ellipticity of the giant planet's orbit, eventually pulling it into a more circular orbit that's also very close to the star.

- + It's possible that all 3 theories are right and that different formation mechanisms work in different planetary systems.

A system of 4 super-Jupiters was discovered orbiting a very new star, HR 8799, which is only 30 million years old. This system is about 130 light-years away from Earth in the Pegasus constellation. All 4 planets are much more massive than Jupiter, with masses ranging from 5 times to 10 times Jupiter's mass.

THE RADIAL VELOCITY METHOD

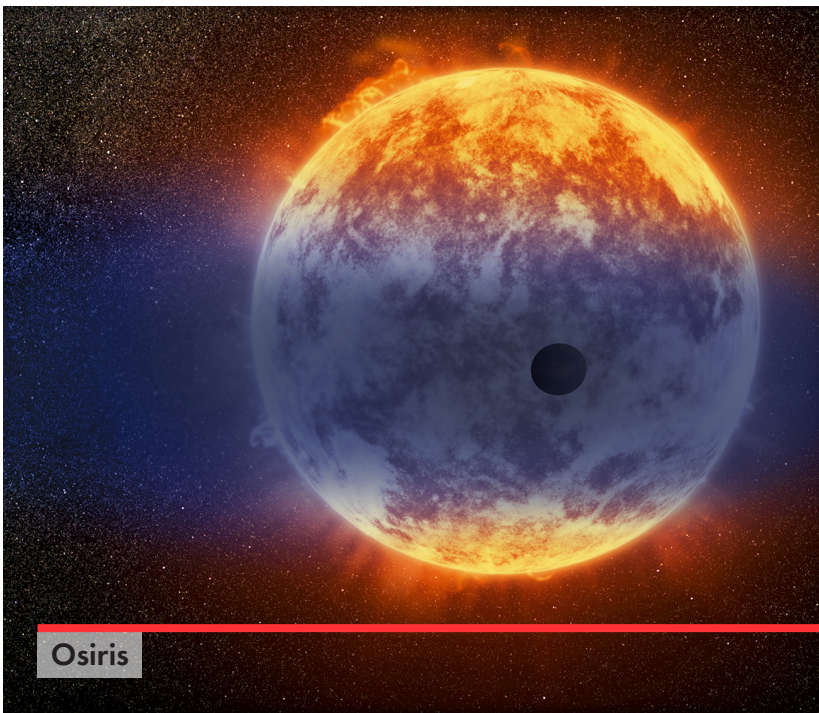
- + As with the pulsar planets, it might seem odd that hot Jupiters were among the first planets to be discovered. But this is due to biases in the methods used to detect planets. It's easier to find very massive planets orbiting very close to their parent stars. Our detection methods made hot Jupiters the most likely to be discovered first.
- + For example, Dimidium was discovered using the radial velocity method, which relies on the fact that planets don't just orbit stars that are fixed at the center of the system. Instead, the planet and the star both orbit the center of mass—the location of the averaged mass—of the system. Because stars are so much more massive than planets, the center of mass is typically located within the star itself, but it isn't exactly at the center of the star.

- + If we focus on the motion of the star as we see it from Earth, it looks like it wobbles about the center of mass. The star heads toward us as the planet heads behind it, and the star moves away from us as the planet moves in front of it.
- + In the radial velocity method, we focus on the light coming from the star. That light gets blue-shifted when the star is moving toward us and red-shifted when it moves away from us. We can use the color shifting of the light to figure out the velocity of the star's wobble. The maximum speed of the wobble is related to the mass of the planet orbiting the star.
- + The period of the wobble also tells us the period of the planet's orbit. Knowing the orbital period leads us to knowing the distance from the star.
- + So by studying the wobbles of the star, we can determine the minimum mass of the planet and its orbital period. It's the *minimum* mass because the radial velocity method doesn't tell us the orientation of the planet's orbit. If it happens to be orbiting directly in our line of sight, then the mass we get from the amplitude of the signal is the full mass of the planet. But most planets have an orbit that is somewhat inclined with respect to our viewing direction because planetary systems are randomly oriented. This means that the actual signal amplitude can be much larger than we observe, which would mean the planet is more massive than we calculate.
- + The radial velocity method also determines the ellipticity of the orbit.
- + By 2019, more than 800 exoplanets had been detected using the radial velocity method; that's about 30% of known planets at that time.

THE TRANSIT METHOD

- ✦ The fact that the radial velocity method only determines the minimum mass of a planet is a disadvantage when we try to characterize the planets. Luckily, another popular method for detecting exoplanets, called the transit method, can measure the inclination of the orbit. It even gives the radius of the planet!
- ✦ In 1999, the first planet was detected using the transit method: a hot Jupiter nicknamed Osiris. Located in the Pegasus constellation, Osiris is about 160 light-years away from Earth. Osiris had already been discovered using the radial velocity method. Combining the radial velocity information with the transit method data meant that the actual mass of Osiris could be calculated rather than just its minimum mass.
- ✦ Osiris has a mass of about 70% of Jupiter's mass.
- ✦ In some ways, this was the first time an exoplanet was actually confirmed to be a planet. That's because the minimum mass from the radial velocity method still left the possibility that the orbiting object was too massive to be a planet. Instead, it might have been a brown dwarf star but orbiting at an extreme angle that minimized the wobble we could detect. The boundary between gas giant planet and brown dwarf star happens around 14 Jupiter masses. By getting the mass pinned down through the transit method, we were guaranteed that Osiris was a planet.
- ✦ The idea for the transit method is simple. We detect the dimming of the light coming from the star whenever a planet passes in front of it. The typical amount of dimming is extremely small, from a few percent to a small fraction of a percent of the total light. The amount of dimming is related to the size of the planet because dimming is determined by what fraction of the star's surface disk is blocked by the planet.

- ✦ The dimming is also periodic, repeating every time the planet passes in front of the star. Looking at when the transit repeats lets us determine the planet's orbital period.
- ✦ The transit method gave the radius of Osiris as 1.35 Jupiter radii. Knowing the mass from the radial velocity method and the radius from the transit method meant that the density of an extrasolar planet could be calculated for the first time.
- ✦ The density of Osiris is 370 kg/m^3 —that's about $\frac{1}{2}$ the density of Saturn, which at 687 kg/m^3 is the planet with the lowest density in our solar system. This means that Osiris is a gas giant.



DIRECT IMAGING

- + **Direct imaging** is the rare but wonderful case when **we can see an exoplanet directly, at least in the infrared**. For this, we use a detection method that is actually biased toward detecting planets that are far from their star, preferably with the whole system tilted toward us.
- + **Here we want the planet and star to be as far from one another as possible—the opposite of what we wanted in the transit method**. It's also best if the planets are young and very massive so that they are radiating more internal heat and hence are brighter in the infrared.
- + The smallest planet detected by direct imaging is less than twice the mass of Jupiter.
- + The biggest problem with directly imaging an exoplanet is that the light from the star is so much brighter than the light from the planet that it's hard to make out the planet if you are staring straight at the star. The trick to observe the planets, then, is to try to block the light from the star. **Close to 20 exoplanets were discovered with this method from 2008 to 2019.**

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Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.

Summers and Trefil, *Exoplanets*.



LECTURE 22

Closing in on Earthlike Exoplanets

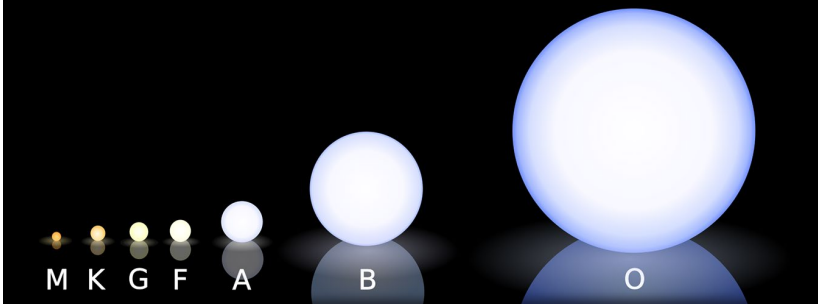


Discoveries of exoplanets have demonstrated that planets around other stars are abundant and varied. There are rocky planets many times bigger than Earth, aptly named super-Earths, some of which may contain a large fraction of water, up to about 50%. But is there another Earthlike planet? And what do we even mean by *Earthlike*? What criteria should we use to determine whether an exoplanet is Earthlike?

We'll want the planet to have a similar environment as Earth—so a similar amount of stellar radiation as well as a similar atmosphere, surface temperature, and climate. This means we'll be looking for planets orbiting main-sequence stars. In addition to environment, we'll want the planet itself to have the same properties as Earth—so mass, size, and composition. Finally, we'll want the planet to have a moon, surface water, plate tectonics, and life.

Main-sequence stars include—from smallest to largest—red dwarfs, which are around $\frac{1}{10}$ to $\frac{1}{2}$ as massive as the Sun, to orange dwarfs and yellow dwarfs (like our Sun), to yellow-white dwarfs. Then come the A-, B-, and O-type stars, which can be up to around 200 times more massive than the Sun.

About 90% of all stars fall into one of these categories of main-sequence stars.



EARTHLIKE CRITERION 1: MASS OR SIZE

- ★ The first somewhat low-mass planet orbiting a main-sequence star was discovered in 2005. The star is Gliese 876, visible in the Aquarius constellation and located about 15 light-years from Earth. The planet is named Gliese 876 d.
- ★ Gliese 876 d is 2.5 times less massive than Neptune but still about 7 times more massive than Earth. Planets in this size range have been dubbed super-Earths, or mini-Neptunes if a thick hydrogen atmosphere has been detected.

- + Gliese 876 d orbits about 20 times closer to its parent star than Mercury orbits our Sun. That's what made it easier to discover. But that also makes its year only 2 Earth days long. And most likely the star has the planet tidally locked, with a permanent day side and a permanent night side.
- + Finding a terrestrial planet that's not "super" but just regular Earth-sized is harder. In principle, we can still use the wobble of a star and the dimming of light from a star as a planet passes in front. It's just that the telescopes need to detect much smaller signals. So, detector technology had to improve, and new methods with capabilities of detecting smaller planets were developed.
- + The year 2014 was a breakthrough year for exoplanets because around 1200 potential exoplanets were discovered by the Kepler Space Telescope. And 68 of them were approximately Earth-sized, defined as having a radius less than 1.25 Earth radii.
- + The Kepler mission was able to do this by having the space telescope stare intensively at a single specific patch of sky for about 4 years straight, starting in 2009. The size of the observing window is about 0.25% of the sky. This patch of sky, located in the northern constellations Cygnus, Lyra, and Draco, contains about 150,000 main-sequence stars. By looking at this one patch, Kepler could detect lots of periodic transits of planets—and that allowed for good data to detect a wide range of planet types, from hot Jupiters to smaller rocky planets.
- + But using only size or only mass is not enough to characterize a planet as Earthlike; we need to know whether the planet has a rocky composition.

Scientists think that about $\frac{1}{3}$ of all exoplanets could be water worlds with oceans that are hundreds of miles deep!

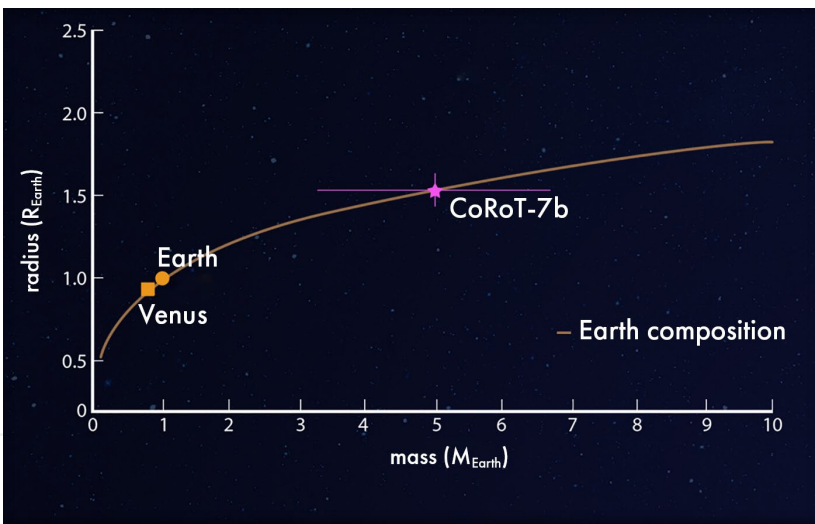
EARTHLIKE CRITERION 2: COMPOSITION

- + The first exoplanet confirmed to have a predominantly rocky composition was CoRoT-7b, discovered in 2009. This system is about 490 light-years away, in the constellation Monoceros. The exoplanet is a super-Earth-sized planet that's very close to its star.

When you come across the term *super-Earth*, think dense, not big.
- + CoRoT-7b's radius is 60% to 80% bigger than Earth, which we know because it transits in front of its star. We estimate mass, using radial velocity, in the range of 3 to 7 Earth masses. The mass and radius allow us to calculate that CoRoT-7b's mean density is between about 3500 and 9500 kg/m³, which is between about 60% and 170% of Earth's density of 5500 kg/m³.
- + So CoRoT-7b is definitely terrestrial. And if the density ends up being near the higher end of the range, then CoRoT-7b may be more like a super-Mercury than a super-Earth and have a large iron core!
- + It takes a bit of work to determine the composition of an exoplanet, given its density. Remember, the bigger the planet, the more it can compress under pressure of its own gravity. If an exoplanet were made of exactly the same material as Earth but was more massive, then the compressed density we observe would be higher. So to determine the composition of exoplanets more accurately, we need to understand how they compress. That is done using a mass-radius diagram.
- + Imagine you had a series of planets, all with exactly the same composition as Earth—so they have the same fraction of iron, silicates, and all the other minerals that Earth's interior has. The only difference between the planets is their masses. They would all have the same uncompressed

density, because that's just a property of the composition. But they would have higher and higher compressed densities as the mass and pressure of the surrounding material in the planet squeezes material into a smaller volume.

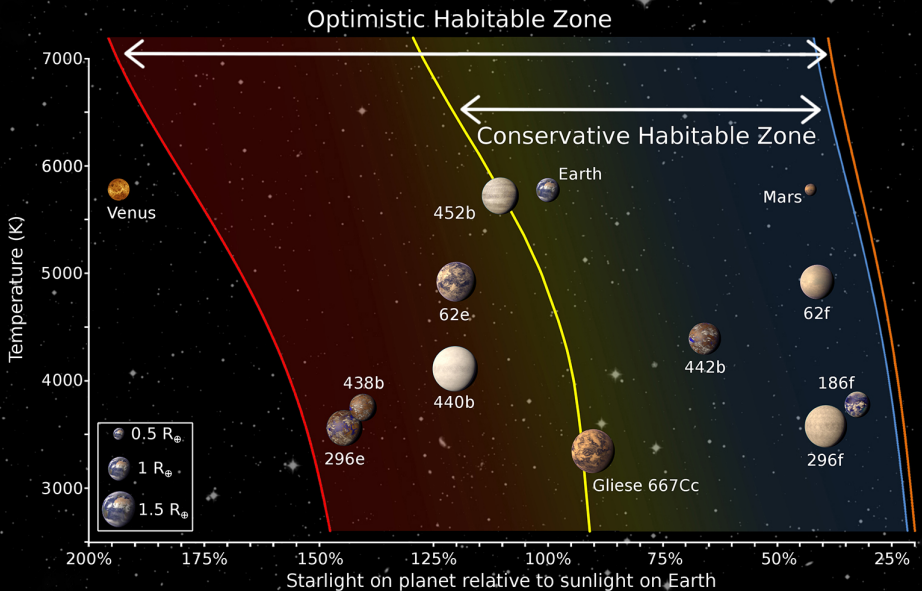
- ✦ For small planets with moderate pressures, we have experiments that are now capable of reaching pressures of tens of millions of atmospheres found inside those planets. But more massive planets can have interior pressures higher than even our best experiments. So we have to rely on computational simulations and theoretical understanding of materials in the quantum realm.
- ✦ Using a combination of experiments, simulations, and theory, we can figure out what a planet's compressed density is for each mass. We can then plot all that information on a mass-radius diagram, where the horizontal axis gives the mass of the planet in units of Earth masses and the vertical axis gives the radius of the planet in units of Earth radii.
- ✦ Even if using a mass-radius relation convinces us that CoRoT-7b is indeed a rocky exoplanet, that's not enough to make it Earthlike.



- ✦ CoRoT-7b orbits very close to its parent star—more than 20 times closer than Mercury orbits our Sun. And its year is only 20 Earth hours long! The parent star is slightly smaller than our Sun, but it's still luminous enough that the temperatures on CoRoT-7b's surface can be as high as 4700°F (2600°C)! That's nothing like Earth, and it might even be a lava planet with a surface that's molten everywhere.

EARTHLIKE CRITERION 3: HABITABILITY

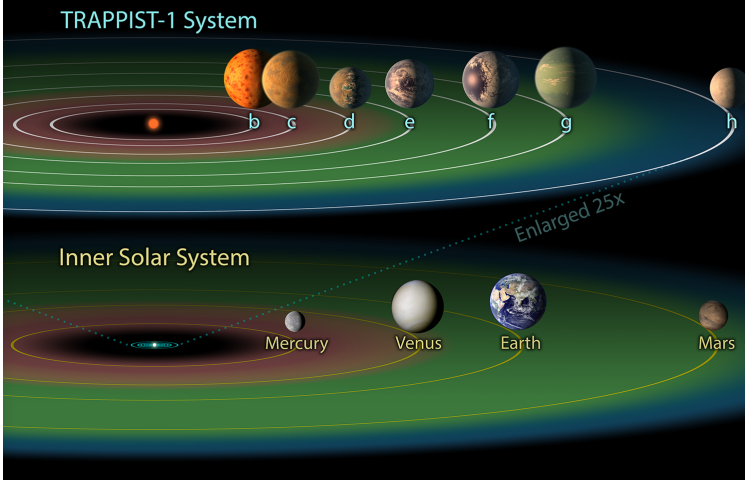
- ✦ So while it's great to have tools to investigate planets with Earth's composition, we need to narrow our search to planets where temperatures are more modest. This leads to our next criterion for an Earthlike planet: Is it habitable?
- ✦ *Habitable* is a loaded term that can have a variety of meanings, but for planetary scientists and astronomers, it has a specific definition: **A habitable planet is one where the temperatures at the surface are in the right range for liquid water to be stable, assuming that the planet has a sufficient atmospheric pressure.** There is also an implied criterion that the planet has a surface to speak of, which means that gas giant planets are not included.
- ✦ **Whether a planet is habitable therefore depends on how much heat it receives from its star. That depends on 2 related factors: the type of star and the distance a planet orbits from that type of star.**
- ✦ **For each type of star, there is a specific distance range of orbits where habitable planets could be found. This range of orbits is called the habitable zone.**



- + In our solar system, the habitable zone goes from about Venus's orbit to the inner asteroid belt. But note that just being located in the habitable zone does not imply that any particular world is habitable; the habitable zone just helps us focus our search for habitable worlds.
- + Kepler-452b was the first near Earth-sized world to be found in the habitable zone of a star similar to our Sun. It's more than 1400 light-years away, in the direction of the Cygnus constellation. It's about 5 times more massive than Earth, with a radius that is only about 50% larger than Earth's. Its mass and radius put its composition on the Earth curve. And the year is 385 Earth days, so that sounds very Earthlike. The equilibrium surface temperature is around 18°F (−8°C), which is also similar to Earth.

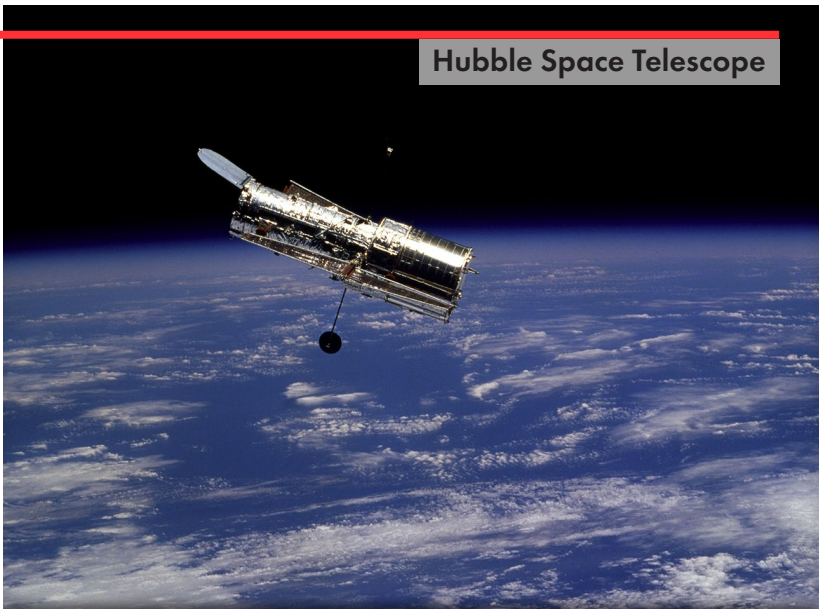
- ✦ If Kepler-452b has an atmosphere, then there might be a mild greenhouse effect, giving the exoplanet Earthlike temperatures. And with an estimated age of 6 billion years, it has a 1.5-billion-year head start on Earth if conditions are indeed promising for life.
- ✦ And there are planets in habitable zones much closer to us. Even our closest neighboring star, Proxima Centauri, has a planet in the habitable zone. And it's only 4 light-years away!

In 2015, 7 Earth-sized and smaller planets were discovered orbiting the star TRAPPIST-1—which is only 40 light-years away in the direction of the Aquarius constellation—and at least 3 of them are in the habitable zone!



EARTHLIKE CRITERION 4: ATMOSPHERE

- ✦ Although there are techniques for probing the atmospheres of hot Jupiters, **it's much harder to detect atmospheres around smaller planets.**
- ✦ But astronomers have used the Hubble Space Telescope to study the atmospheres of planets in the habitable zone. More powerful telescopes, like the James Webb Space Telescope, are designed to resolve atmospheres around Earth-sized exoplanets. That's when we may begin to detect the difference between an uninhabitable atmosphere, like Venus's, and an atmosphere more like Earth's.
- ✦ **The large fraction of oxygen found in Earth's atmosphere is produced by life. So once we are able to study atmospheres of smaller planets, that will also give us more direct ways to search for life!**



Hubble Space Telescope

EARTHLIKE CRITERION 5: A MOON

- + If we really wanted to say that we found an Earthlike planet, we should probably try to find one that has a large moon, like Earth does. **The Moon is important to stabilizing the tilt of the Earth, which has kept our climate somewhat in check.**
- + **There have been some indirect hints of possible exomoons.** One reason to look for exomoons is that there might be Earthlike moons in orbit around a much larger exoplanet. But finding smaller exomoons around smaller planets is going to require better detectors that can detect fainter signals.

EXOPLANET STATISTICS

- + **The more we look, the more exoplanets we find.** Several thousand were discovered by the Kepler mission, which looked at only 0.25% of the sky. **The Kepler mission's objective was to determine the frequency of Earth-sized planets in the habitable zone of Sunlike stars.**
- + Our data so far includes very few examples of exoplanets with orbits longer than a few hundred days. But this is a known bias in the data. And if we make adjustments to work around biases we know are in the data, then we might estimate the number of worlds that are broadly similar to Earth like this:
 - ✦ About 20% of Sunlike stars studied so far have had an Earth-sized planet in their habitable zones.
 - ✦ There are around 200 billion stars in our galaxy.

- ✦ About 10% of those are Sunlike stars, so there are 20 billion stars like our Sun.
- ✦ If 20% of all those stars have Earth-sized planets, that gives us around **4 billion Earth-sized planets in the habitable zones of Sunlike stars.**
- ✦ **But we can also include smaller red dwarf stars**, which are the most common type of star in the galaxy, at 70% of all stars. Kepler data has shown that about **1/3 to 1/2 of red dwarfs have an Earth-sized planet in their habitable zones.**
- ✦ This suggests there are going to be **tens of billions of Earthlike planets to choose from for closer study.**
- ✦ Ultimately, finding Earth 2.0 will mean being able to study even more of the factors that *really* make a planet habitable. For example, is liquid water stable at the surface? What's the composition of the atmosphere—and is it being stripped away?
- ✦ And before we declare a planet *really* habitable, we'll also want to assess radiation levels on the planet's surface. So we're studying the corona and mass ejections of other stars to look at when the parent star supports an atmosphere and magnetosphere on the exoplanet that's welcoming for life.

READINGS

Carney, *Planets*.

Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.

Summers and Trefil, *Exoplanets*.



LECTURE 23

Planets Migrated in Our Early Solar System!

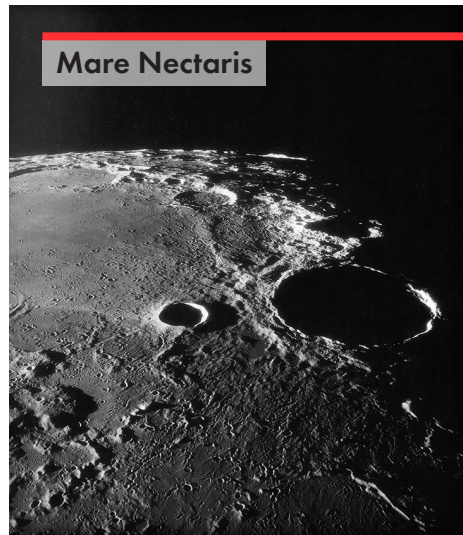


About 4 billion years ago, the inner solar system apparently experienced the late heavy bombardment, during which the inner solar system appears to have been bombarded with an unexpectedly large number of meteor collisions—and big ones, too. It was “late” because it happened hundreds of millions of years after the solar system had completed most of its formation through gravitational accretion.

How could this happen? Exoplanets have taught us that planet migration—after formation—is common. An extreme example is hot Jupiters, which likely formed much farther out in their stellar systems and then migrated inward to their current locations. The existence of hot Jupiters elsewhere suggested that perhaps a large migration event occurred in our own solar system. If so, migration of a large planet could have triggered the late heavy bombardment.

EVIDENCE FOR THE LATE HEAVY BOMBARDMENT

- ✦ The first hints that the late heavy bombardment (LHB) happened were from the Apollo missions bringing back lunar samples for study on Earth. Many of the samples were of rocks that had been deformed or created by melting during large impacts. These crystalline melt rocks required impacts that were tens to hundreds of kilometers in extent.
- ✦ The ages of those melt rocks all cluster between about 3.75 and 3.95 billion years ago. This suggested that several large impacts occurred on the Moon over a concentrated time period of 200 million years—geologically a short amount of time.
- ✦ Other lunar samples provided ages for some of the large impact basins we see on the near side, like the Imbrium, Nectaris, and Serenitatis basins. The ages of such basins were somewhat more spread out, from about 4.2 billion to about 3.7 billion years old. So there's some uncertainty about how to describe the duration of bombardment. But the evidence is compelling that there were a lot more impacts, and much larger impacts, around this time compared to earlier or later times.



- + The evidence for a period of heavy bombardment includes large impacts on the terrestrial planets and our Moon, signs of shock impacts—features that only form when an impact creates a shock wave—in the asteroid belt, and the age distribution of meteors found on Earth. These all suggest that the inner solar system was bombarded with some large meteors around 4 billion years ago.

The late heavy bombardment created the largest impact basins on the Moon, Mars, and Mercury. The mass of impacting material increased by a factor of about 1000 compared to times shortly before.

POTENTIAL CAUSES OF THE LHB

- + There seem to be some possibilities that could work as a source for these impactors:
 - 1 Perhaps some planetesimals were left over from accretion because they got flung into elliptical orbits and therefore missed their chance to get incorporated into planets. Then, they returned later to bombard the inner planets.
 - 2 Something regularly disturbed the asteroid belt, flinging a steady population of asteroids into the inner solar system.
- + But both of these scenarios would predict a steady decline of impactors over time—not a long lull followed by a resurgence of impacts a few hundred million years later.
 - 3 There was a big but more temporary disturbance to the asteroid and Kuiper belts.

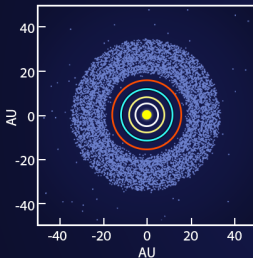
HOW PLANET MIGRATION COULD LEAD TO THE LHB: THE NICE MODEL

- ✦ If we want a big disturbance, we look to the giant planets, going all the way back to their formation. Computer simulations are used to study how the giant planets formed and gravitationally interacted early in the solar system. These simulations demonstrate that **the giant planets can migrate their orbits somewhat during their formation.**
- ✦ This was initially a big surprise. But **we've learned by studying exoplanets that migration can lead to large changes in planetary orbits, sometimes bringing gas giant planets very close to their parent stars.** However, the migration doesn't have to go so close. **In our solar system, the migration was big but didn't go that far.**
- ✦ We don't know what the original configuration of the giant planets was just after they formed, but we can run different simulations and see which ones eventually evolve into the system we see today.
- ✦ One model is called the **Nice model**, after the city of Nice, France, where it was initially developed. The Nice model begins with the 4 giant planets—Jupiter, Saturn, Uranus, and Neptune—situated more closely in space than they are today. Their orbits were more compact, fitting all 4 planets between about 5 and 17 astronomical units (AU). Compare that to today, when Jupiter resides at 5 AU, but Saturn is at 9 AU, Uranus is at 19 AU, and Neptune is all the way out at 30 AU.
- ✦ During this early time, a disk of icy planetesimals with a total mass of tens of Earth masses would have existed beyond 17 AU out to about 30 AU—where the orbital speeds were too slow and the material too sparse to form a giant planet.

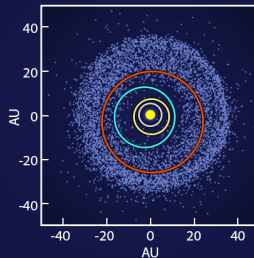
- † Every once in a while, an icy planetesimal from this disk would be perturbed into the region of the giant planets. But when one of these planetesimals is scattered inward by a planet, the planet's orbit is pushed a bit outward. Momentum must be conserved.
- † Admittedly, these outward perturbations of the giant planets would be extremely small, and not every encounter would result in an inward scattering of the planetesimal—other directions are still possible. But on average, the odds are better that the planetesimal gets scattered inward when encountering Neptune, Uranus, and Saturn. And if successive planetesimals are getting scattered inward, over and over again, then the combined effect can be to move the planets' orbits outward.
- † But something different happens when the inward-scattered planetesimal finally reaches Jupiter. Jupiter is so massive that it's more likely, on average, to fling the planetesimal into a highly elliptical orbit, taking the object farther outward in the solar system. But every time a planetesimal is flung outward, then Jupiter migrates inward—a bit.

Nice model

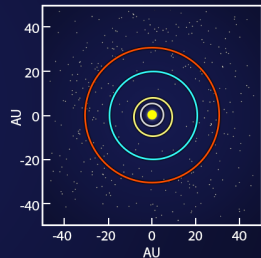
Early configuration



Scattering of planetesimals



After ejection of planetesimals

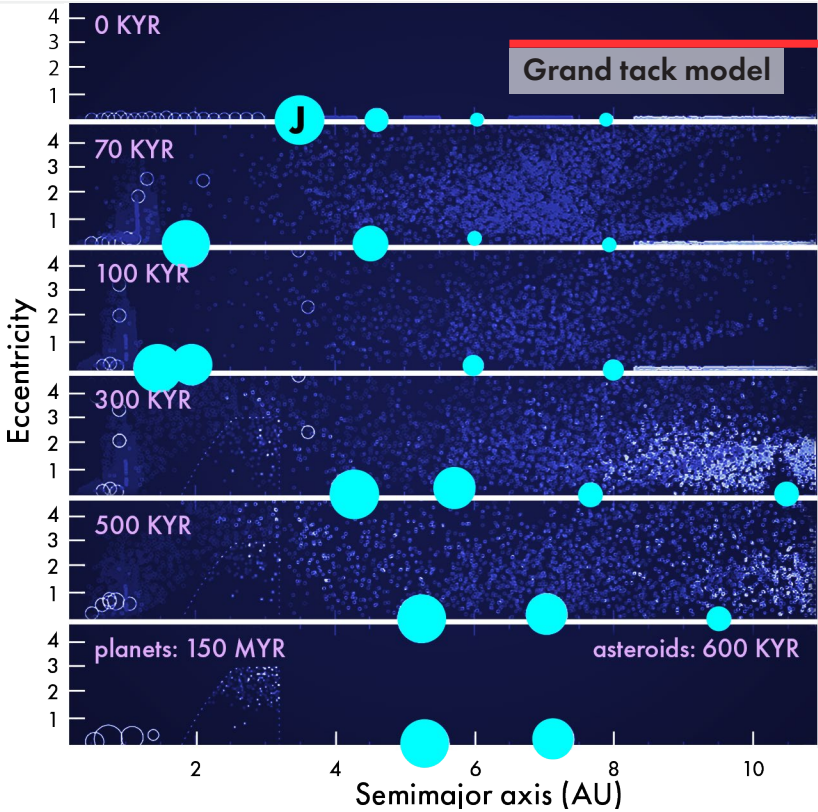


- + So Jupiter moves inward, while Saturn, Uranus, and Neptune each move outward. And all this continues to go on for some time, until Jupiter and Saturn end up in a very special configuration. As Jupiter is moving inward, its orbital period is decreasing; as Saturn's orbit is moving outward, its orbital period is increasing. Eventually, they reach a state where Jupiter completes exactly 2 whole orbits every time Saturn completes 1. They are now in a 2-to-1 orbital resonance.
- + This resonance means that Jupiter and Saturn can gravitationally influence each other more, in a quite regular way. And they perturb each other into more elliptical orbits. This means that Jupiter and Saturn cross through a larger range of orbital distances during their orbits.
- + But taking the 2 biggest planets in the solar system and increasing their ellipticity can cause all hell to break loose among all the remaining planetesimals in the solar system.
- + Saturn quickly moves to a position closer to where we find it today, out at around 10 AU. But this has implications for Uranus and Neptune. Gravitational interactions with Saturn move the ice giants onto more elliptical orbits, pushing them to cross farther out in the solar system.
- + But there were still some icy planetesimals at these far locations, so Uranus's and Neptune's orbital migration destabilized the disk of small bodies out there. Some of those planetesimals would be thrown into the inner solar system, producing a spike in bombardment of the inner planets. But these gravitational interactions between the ice giants and icy planetesimals also change the ice giant orbits, reducing their ellipticities. The ice giant orbits then stabilize close to where we find them today: Uranus near 19 AU and Neptune at 30 AU.

- + So the end scenario is the giant planets where we see them today, along with a period of increased bombardment in the early solar system very early on.
- + The timing for this bombardment isn't well constrained by the Nice model. It depends on the small details in the initial conditions of the models. And we don't know exactly where the giant planets started, but many possibilities lead to this giant destabilization and migration of the giant planets flinging planetesimals into the inner solar system.
- + It turns out that this whole process would have done more than fling icy planetesimals inward from the outer solar system. As Jupiter and Saturn migrate, resonances between orbits in the asteroid belt and Jupiter also cause asteroids to be perturbed into elliptical orbits and flung into the inner solar system. So the bombardment was by icy planetesimals from the outer solar system and by asteroids.
- + The Nice model premiered in 2005 in its original form. But it has been tweaked over the years, with different initial positions for the planets, numbers of icy planetesimals, and the extent of the icy disk. Novel scenarios have been offered, but not all of them have actually happened in our solar system.

THE GRAND TACK MODEL

- + But 4 billion years ago, the era studied by the Nice model, may not have been the first case of migration in the solar system. The giant planets may have been migrating even earlier, while they were forming in the gaseous protoplanetary disk, due to viscous interactions with other material in the early disk. One proposed model of this migration, called the grand tack model, may even explain some features in the inner solar system.



- ✦ Consider what would happen if Jupiter began forming before Saturn. As Jupiter grows by collecting gas from the surrounding disk, it would have migrated inward to about 1.5 AU due to tidal interactions with the gaseous disk.
- ✦ That inward movement might have progressed all the way to a hot Jupiter scenario in our own solar system—if it weren't for Saturn.

- + Although Saturn starts forming a bit later in this scenario, it eventually grows big enough that it, too, starts migrating inward. And Saturn moves inward even faster than Jupiter. Eventually, Jupiter and Saturn end up with the 2 planets at orbital distances where the ratios of their orbital periods enter a resonance of 3 to 2: Jupiter orbits 3 times for every 2 Saturn orbits.
- + And this resonance changes everything. Jupiter and Saturn now interact more with each other rather than tidally influencing the gaseous disk, and they start moving outward together.

CRITICISM OF THE LHB

- + The Nice model opens our eyes to possibilities, but we don't know for sure that the model describes what actually happened. Even the LHB—one of the major consequences that made the Nice model so attractive—may not be real.
- + That's because there is some debate over evidence supporting the claim that there was a spike in large impacts around 4 billion years ago. The debate stems from looking at the locations where we got our lunar samples during the Apollo missions. Remember, it was these samples that were used to determine that a series of large impacts occurred in a relatively short geologic time.
- + But it's possible that all of these samples are actually just from one large impact crater on the Moon: Imbrium. That's not because we collected all the samples from a single location, but because the Imbrium impact would have spread ejecta over large distances surrounding the basin. And because Imbrium is the youngest of the large impact basins, the ejecta would have landed on top.

- + Is it possible that samples we collected from other locations on the Moon all happen to be ejecta from Imbrium? If so, that could explain why all the ages in the samples cluster around the age of Imbrium.
- + This doesn't mean that all those impacts didn't happen; it's just that they may not have happened so close together in time. Instead, it may be that there was a steadier and less dramatic flux of impactors from the beginning of the solar system up to about 3.5 billion years ago, rather than a spike centered at 4 billion years ago.
- + And the fact that we don't see a lot of impact melt crystals older than about 4.2 billion years may be simply because older material was more likely to be pulverized by later impacts. Perhaps virtually all the older evidence has been destroyed.
- + So there's more to learn. Perhaps the most important thing that will help are more samples from the Moon—from a wider variety of locations and different impact basins.
- + If more samples from the Moon resulted in a correction to the ages previously determined for lunar features, it would therefore result in a shift in ages throughout the inner solar system. The timing of events early in the solar system may be fundamentally changed by better knowledge of lunar impact basins.

No samples have been brought back to Earth from the Moon since the mid-1970s.

READINGS

Carney, *Planets*.

Rothery, McBride, and Gilmour, eds., *An Introduction to the Solar System*.



LECTURE 24

Human Futures in the Solar System



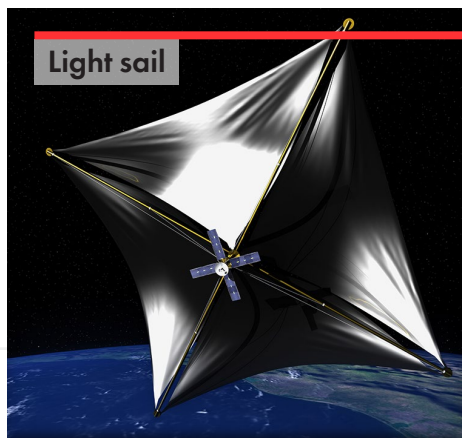
Each successful mission into space rewrites the textbooks, filling in the answers to our previous questions. But each mission also unearths new insights we had not thought to look for and raises new questions we didn't even know to ask. So what are the next big ideas out there to answer the big questions?

GETTING TO THE PLANETS

- ✦ First we have to get to the places we want to explore.
- ✦ **Any mission launch involves the payload**, which is the spacecraft with all its instruments, **plus the rocket** needed to get that spacecraft launched off the Earth. **And then there's the rocket fuel** needed to launch the spacecraft into space—which is usually the largest component. In fact, **the mass of the fuel is usually several times larger than the mass of the payload and rocket combined.**
- ✦ As technologies improve, we are already building larger and more efficient rockets. The NASA Space Launch System is being developed with the goal of being able to send larger payloads, and even astronaut crews, to deep space. It may be the vehicle that first sends astronauts to Mars.
- ✦ There are also methods that don't need fuel to speed up and slow down or change the direction of our trajectory after being launched from Earth. For example, we can slow down spacecraft to land on Mars or other bodies with atmospheres by using aerobraking. That's where the drag from the atmosphere helps the spacecraft land.
- ✦ We can also use a planet's gravity to gain, or reduce, velocity. That's known as a gravity assist, or gravity slingshot. The gravitational encounter between the spaceship and planet transfers some of the energy associated with the planet's orbit to the motion of the spaceship. Gravity assists are used a lot in planetary missions because much less fuel can be used, but the trade-off is that sometimes it takes a lot longer for a mission to reach its destination.

Voyager 1 and 2 used gravity assists from Jupiter and Saturn. New Horizons used a gravity assist from Jupiter to get to Pluto. Spacecraft use gravity assists to slow down when traveling to Venus or Mercury.

- + If we could use less massive bodies as our base to build and launch spacecraft, then we would need much less fuel. **What about building spacecraft on the Moon?** With an escape velocity that's almost a factor of 5 times smaller than Earth's escape velocity, spacecraft would need much less fuel to escape the Moon's gravity.
- + **Could we use resources on the Moon to build spacecraft and generate fuel?** Elements like silicon, titanium, iron, and oxygen have been found in the lunar regolith. Perhaps we could mine these to build rockets and create rocket fuel.
- + We also know that the Moon has water ice in permanently shadowed polar regions. In principle, water could be broken down into its hydrogen and oxygen components using an energy source like electricity from solar panels. Then, the components could be used as fuel, because the hydrogen and oxygen, when they recombine, ignite and burn.
- + **What about technologies for reaching faster speeds during space travel?** One interesting idea involves using a light sail. The concept is similar to a sailboat, but instead of using the momentum inside an atmosphere, a light sail would propel a spacecraft using the momentum of little parcels of light called photons. Typically, light sail concepts—such as the LightSail project, funded through public donations to The Planetary Society—have considered using solar photons for the propulsion.



- + A very different approach to using photons for travel is getting photons from lasers. The Breakthrough Starshot project is researching laser-powered travel, but there are several technical challenges, including the amount of laser power needed—close to a gigawatt, which is similar to the power produced by a large nuclear power plant.

NEW WAYS TO EXPLORE PLANETS

- + **How can we collect more and better data at any worlds we visit? What are the next big ideas for how to design a spacecraft?**
- + Ideally, we want spacecraft that can take instruments as close to a planet as possible but also get data over large distances to give us a global perspective. Our current missions can usually only meet one of these criteria at a time. For example, orbiters get a global perspective but stay high above the surface, while landers and rovers get close to the surface but aren't mobile enough to get data on a large scale.
- + One big idea is to develop low-flying airplanes or copters or balloons to explore planets, such as the Mars helicopter technology demonstration on the Mars 2020 rover or the dual-quadcopter Dragonfly mission proposal for Saturn's moon Titan.
- + Another big idea is to go with lots of small spacecraft. They don't even have to move—just land many really small spacecraft all over the surface to take measurements. The first technology demonstration that such small spacecraft could fly to far locations and have their instruments work properly were the MarCO CubeSats that flew to Mars alongside the Mars InSight spacecraft.

- + But what about places we want to explore that are not on the surface of planets, like the subsurface oceans on outer solar system icy moons, such as Europa and Enceladus?
- + So far, we've been able to detect the oceans from orbit using information from magnetics, rotation, and gravity. And for Enceladus and Europa, plumes from subsurface oceans erupt into space, where we can sample them without even landing on the surface.
- + But what about in situ exploration? What are the next big ideas here?
- + How about a submarine on Europa? The first hurdle to overcome would be getting the submarine down to the subsurface ocean. That means somehow getting through around 10 to 25 km (6 to 16 mi) of solid ice. Prototypes of heat-powered drills have been proposed that could melt down through the ice, slowly descending the submarine to the subsurface ocean.
- + One futuristic idea for what to do once a drill gets through is being tested on Earth now. It's a buoyant rover. NASA/JPL (Jet Propulsion Laboratory) scientists have traveled to the Arctic to test a rover that drives on the underside of the solid ice in the frozen ocean.
- + Another way to explore other planets is to bring samples from them to Earth. The Apollo mission samples changed our understanding of the Moon, Earth, and the rest of the solar system. Being able to use lunar samples to figure out chronologies in the solar system has been crucial to understanding solar system evolution. And the ability to analyze samples of planetary bodies in laboratories on Earth allows a level of science that's not possible by sending spacecraft to other planets to do analysis in the field.

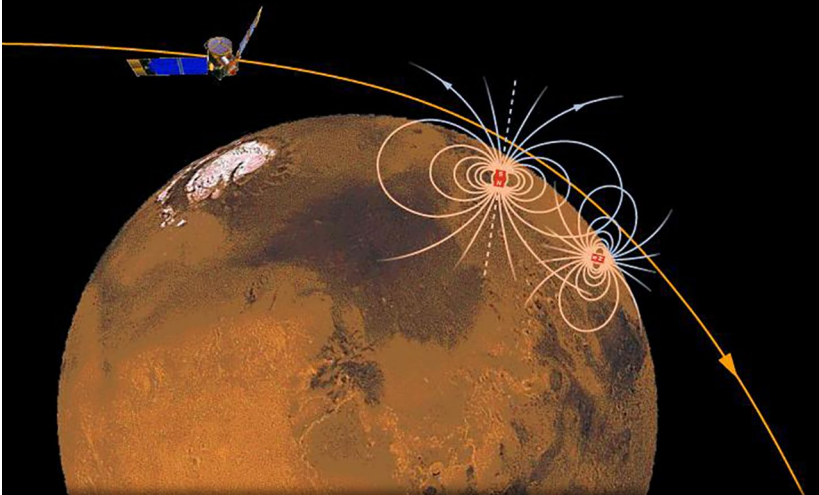
- + So what are the next big ideas for sample return? Some missions are already underway.
- + For example, the OSIRIS-REx mission will return a sample from the near-Earth asteroid Bennu to Earth in 2023. There are also several mission concepts for a Mars sample return, perhaps in the 2030s. And we want to get more samples from the Moon—to understand the large number of impacts during the early solar system and provide absolute ages for different crater densities. We can then use all that for more accurate chronology on the other terrestrial bodies across the solar system.

MAGNETIC SHIELDING

- + The dream of a future in which humans wander the solar system confronts a significant hurdle: how to protect ourselves from high-energy particles and radiation launched by the Sun in solar storms as well as high-energy cosmic rays that come from outside the solar system.
- + Cosmic rays are another mix of photons and ionized particles, but they reach us traveling much faster than particle storms from our Sun. Some cosmic rays are from distant supernova explosions, so cosmic rays are even harder to protect against.
- + Here on Earth, we are protected by Earth's magnetic field. But human-crewed spacecraft or a base on the Moon or Mars doesn't have this protection. Is there a way to engineer a magnetic shield that's similar to Earth's magnetosphere?

- + One idea is to create a mini-magnetosphere that can be used when there is a giant solar storm. But you would need to somehow transport very strong magnets into orbit. But the stronger you want your magnet to be, the more magnet mass it's going to need. And that increases the amount of rocket fuel you need to launch off the Earth.
- + But there are some ideas that it might be possible to exploit a turbulent plasma's ability to shield against high-energy particles. But the technology needs a lot of work before it seems feasible.

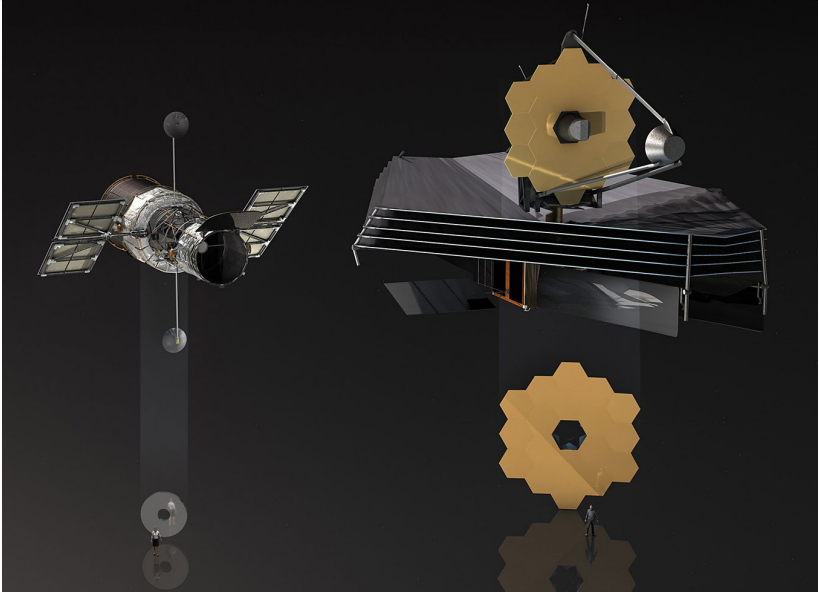
At the Planetary Science Vision 2050 Workshop held in 2017, NASA scientists and collaborators proposed creating a magnetic shield to protect the entire planet of Mars. In essence, a magnetic shield might be able to turn the clock back 3 or 4 billion years and allow for the terraforming of the planet!



GIANT TELESCOPES

- + Another area where technological advances will be important is telescopes!
- + Our study of the solar system, and the universe, changed when Hubble was launched in 1990 and successfully repaired and upgraded in 1993. Hubble's large mirror is 2.4 m (about 8 ft) in diameter. That combined with the fact that the telescope operates in space, where the Earth's atmosphere can't cause any problems, are the important factors in the science revolution that Hubble brought forth.
- + With Hubble, we've been able to monitor the planets in our solar system, especially at times when spacecraft aren't visiting them for even closer views. Hubble can also be used to study the atmospheres of extrasolar planets.
- + The successor space telescope to Hubble, with an even bigger mirror, is the James Webb Space Telescope, which is scheduled for launch in 2021. This telescope's mirror is 6.5 m (about 21 ft) in diameter, producing a light-collecting area that's more than 6 times larger than Hubble's mirror. This means it will be able to see things that are much fainter. A larger space telescope will also be able to study the atmospheres of exoplanets in much finer detail than is possible today—perhaps even finding biosignatures in the atmospheres of habitable planets.

In our solar system, the James Webb Space Telescope, which is scheduled to launch in 2021, should be able to determine the composition of surface ices on objects as far away as the Kuiper belt. It could also study the variability of water in Mars's atmosphere over time.



Hubble (above left) versus James Webb Space Telescope (above right)

- ✦ Telescopes from Earth are also getting much better, including the Giant Magellan Telescope, which should be able to see oxygen molecules in the atmospheres of exoplanets. And there's the Extremely Large Telescope, whose 39-m (128-ft) mirror should let us image rocky exoplanets.



- + But beyond all that, **what might be the next big thing in telescopes?**
- + One possibility is the Large UV/Optical/IR Surveyor (LUVUOIR), a space telescope concept that's being considered for launch in the 2030s. It might be twice as big as the James Webb Space Telescope, or more, with a mirror diameter possibly as big as 15 m (about 50 ft).
- + Another strategy for getting a big telescope in space is to put a telescope on the Moon!
- + One idea involves a liquid mirror telescope. We have liquid mirror telescopes on Earth, and they're relatively inexpensive to construct. They're made with mercury that stays molten at room temperature and reflects light very efficiently.
- + On the Moon, we'd need liquids that stay liquid at cold lunar temperatures and are also stable against evaporation, even in the lunar vacuum. Scientists are experimenting with different possibilities, such as liquid metal films covering ionic liquids. The mirror could sit at the bottom of a lunar crater and perhaps be as large as 100 m (330 ft) in diameter.
- + Another appealing possibility for Moon telescopes would be to put a radio telescope on the far side of the Moon—so that the telescope would be shielded from all the radio emissions from Earth. You could build the radio telescope from millions of small radio antennas scattered over a region of about 100 km² (40 mi²).
- + Such a radio telescope could be used to study radio emissions from aurora around other planets—perhaps even exoplanets! This could therefore be a way to detect magnetic fields from exoplanets and give us a better idea

which planets are truly habitable! And if any such planet harbors an alien civilization, a Moon-based radio telescope would be a way to detect any radio wave signals they might be emitting.

ASTROBIOLOGY

- + What are the next big ideas in trying to figure out how life starts? What are the necessary ingredients for life to start on another planet?
- + Finding signs of life, present or past, on another planet will revolutionize our understanding of life on Earth; in many ways, it's the underpinning of much of solar system exploration. But it would also be really great if we could actually figure out how to create life. In other words, how do you go from chemistry to biology?
- + Putting a bunch of organic molecules together in a room and giving them some energy has been proven capable of creating more complex molecules—even some proteins. But what do we have to do to create DNA, the basis of life as we know it? Future experiments on Earth to understand how DNA started will also hone the search for life-friendly planets elsewhere.

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QUIZ

LECTURES 19–24

- 1** How was it determined that the Sun is primarily composed of hydrogen and helium? [L19]
 - a** The yellow color of the Sun was determined to be due to hydrogen and helium.
 - b** The high-energy particles in the solar wind are primarily hydrogen and helium.
 - c** Features in the Sun's spectrum were realized to be due to hydrogen and helium.

- 2** Which statement is true about the solar magnetic field compared to planetary magnetic fields? [L19]
 - a** The Sun's magnetic field reverses periodically, whereas no periodic reversals of planetary magnetic fields have been observed.
 - b** The Sun's magnetic field is not generated by a dynamo, whereas planetary magnetic fields are.
 - c** The Sun's magnetic field is strongest in its polar regions, whereas planetary magnetic fields are strongest in equatorial regions.

- 3** Which of the following solar system observations is not a direct consequence of processes occurring during the formation of the solar system? [L20]
- a** The planets all orbit in the same plane.
 - b** The rocky planets form in the inner solar system, while giant planets form in the outer solar system.
 - c** planetary rings
- 4** If a planet's mantle has excess tungsten, then what does that tell you about its core? [L20]
- a** The core differentiated earlier in solar system history.
 - b** The core differentiated later in solar system history.
 - c** No core differentiated.
- 5** Why were hot Jupiters the first exoplanet type to be discovered around main-sequence stars? [L21]
- a** Hot Jupiters are the most common type of planet in the galaxy.
 - b** Hot Jupiters are more easily detected because they produce larger signals in transit and radial velocity detection methods.
 - c** The stars closest to our Sun contained hot Jupiters.

- 6 Which property of a planet can the radial velocity method not detect? [L21]
- a mass
 - b orbital distance
 - c presence of an atmosphere
- 7 Which statement is true about habitable zones? [L22]
- a Habitable zones occur at different orbital distances for different types of stars.
 - b Habitable zones only exist around red dwarf stars.
 - c Habitable zones take into account greenhouse effects occurring on planets.
- 8 The most likely way we will detect life on extrasolar planets with near-future telescopes is through which of the following? [L22]
- a imaging the surface of an exoplanet
 - b detecting global-scale chemical signatures in a planet's atmosphere due to life
 - c detecting changes to a planet's orbit due to life

- 9 The only evidence we have for the late heavy bombardment comes from the Moon. [L23]
- a True
 - b False
- 10 The Moon-forming impact occurred during the late heavy bombardment. [L23]
- a True
 - b False
 - c We don't have enough data to know for sure.
- 11 What is the main reason we use gravity assists during spacecraft mission trajectories? [L24]
- a Gravity assists are the fastest way to get to a solar system destination.
 - b Gravity assists are a fuel-efficient way to change a spacecraft's speed or direction.
 - c Gravity assists ensure that a spacecraft doesn't crash into a planet.

12 Which of the following is not an advantage for doing science from the Moon? [L24]

- a** Radio telescopes on the far side of the Moon would be shielded from radio signals from Earth.
- b** Launching spacecraft missions from the Moon would be more fuel efficient than from Earth.
- c** The far side of the Moon never receives sunlight, so the night sky would always be dark there.

Answers can be found on page 301.

Answers

LECTURES 1–6

- 1** **b.** Ices would have remained in gaseous form in the inner solar system and therefore couldn't be incorporated into growing planets. [L1]
- 2** **b** and **e.** Although we see volcanoes on some of the other bodies, such as Venus and Mars, we see no evidence for active eruptions in modern times. [L1]
- 3** **c.** Due to the lack of an atmosphere, temperatures in permanently shadowed regions can stay cold enough for ice to remain stable on the surface. [L2]
- 4** No! The Sun changes direction when Mercury approaches perihelion and speeds up in its orbit to a point where its orbital speed is faster than its rotation speed. If Mercury's orbit were circular, its orbital speed would be constant, so the Sun would always move in the same direction. [L2]
- 5** **a.** A dynamo needs vigorous motions in an electrically conducting region like an iron core. Because Venus doesn't have plate tectonics, it can't cool fast enough to generate these motions. It's a common misconception that you will even find in textbooks that the reason has to do with Venus's slow rotation. This is absolutely not true. A planet does not need to have fast rotation to generate a dynamo. [L3]
- 6** The hot surface temperature means that any water on the surface or released from the interior from volcanoes quickly evaporates into the atmosphere. There, water is dissociated into hydrogen and oxygen. But the hydrogen escapes to space, thereby not allowing water to re-form and recycle back into the planet. [L3]

- 7 c. Surface material is constantly created at ridges, where the plates spread apart, and is destroyed at subduction zones, where it descends back into the Earth. [L4]
- 8 (1) Plate tectonics lets the Earth cool fast enough for the core to generate a magnetic field that shields the surface from harmful solar radiation. (2) Mountain building from plate tectonics can increase erosion rates, bringing new nutrients to the ocean. (3) Plate tectonics changes sea level, creating shallow water regions where life may flourish. [L4]
- 9 (1) Space debris from other nonfunctioning satellites and (2) high-energy particles and radiation from the solar wind. [L5]
- 10 This height is above the troposphere, so the airplane avoids turbulence associated with storms. But importantly, this height is still low enough that air pressure is high enough to get good lift without having to fly too fast. [L5]
- 11 a. The Moon must be between Earth and the Sun for the Moon to block the Sun's disk. [L6]
- 12 c. The Moon formed from the debris placed in orbit after the collision. [L6]

[Click here to go back to the quiz.](#)

LECTURES 7–12

- 1 b. Olivine and pyroxene sank to the bottom of the magma ocean because they were denser. And basalt on the Moon formed later than the plagioclase crust. [L7]
- 2 d. Because lunar samples provided absolute ages for surfaces with different crater densities, the lunar samples were able to provide ages for the Martian surface as well! [L7]

- 3 **b.** By being as fuel efficient as possible, we can carry a heavier payload of scientific instruments on a mission. [L8]
- 4 **a** and **d.** Without a large moon, Mars can be more perturbed from gravitational tugs by Jupiter that affect its axial tilt. [L8]
- 5 **b.** False. Although not stable for long time periods, liquid water is seen in recurring slope lineae on some crater walls. [L9]
- 6 **c.** The only way to explain the D/H ratio is by loss of hydrogen (from the water molecule) to space. [L9]
- 7 **b.** False. As the Chelyabinsk and Tunguska events demonstrated, even bodies that are so small that they burn up in the atmosphere before reaching the surface can cause destruction. [L10]
- 8 **a, b,** and **d.** There are no signs of plate tectonics on Ceres. [L10]
- 9 **b.** To determine what Jupiter is made of, we need to figure out its uncompressed density to compare with the density of various compositions. [L11]
- 10 **b.** Magnetic fields act to brake the winds when hydrogen develops a strong electrical conductivity. [L11]
- 11 **b.** Callisto has the most craters, followed by Ganymede and then Europa. Io has no observed craters. [L12]
- 12 Europa's subsurface ocean would be the easiest to explore because the cracks in the solid ice shell make the subsurface ocean more accessible to exploration. The solid ice shell may also be much thinner than those of Ganymede and Callisto. [L12]

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LECTURES 13–18

- 1 **b.** No partial ring arcs have been seen at Saturn. They were once thought to be seen at Neptune, but Voyager 2 demonstrated they were also full rings. [L13]
- 2 **c.** Because Saturn is less massive, the pressures needed to attain metallic transformation occur deeper in Saturn than in Jupiter, at a depth of about $\frac{1}{2}$ Saturn's radius. [L13]
- 3 **c.** Saturn has 7 round moons, whereas Jupiter only has 4. Titan is bigger than Io, Europa, and Callisto, but smaller than Ganymede. Saturn also has several moons embedded in the rings. [L14]
- 4 **b.** Having the ocean buried at depth may also shield any life from harmful radiation. [L14]
- 5 **a.** Although no storms were observed at Uranus during the Voyager 2 flyby, they have been observed by the Hubble Space Telescope. [L15]
- 6 **c.** Pressures are not high enough in Uranus for metallic hydrogen to form. [L15]
- 7 **a.** Although Neptune is the only planet that can't be seen with the unaided eye, Uranus required telescope observations to confirm that it was a planet rather than a star. [L16]
- 8 **c.** Coronae are not found on Triton, only on Miranda (a moon of Uranus) and Venus. Active volcanism is seen on Triton, but also on Io and Earth. [L16]
- 9 **a.** There are many moons larger than Charon, including Titan and Earth's Moon. [L17]

- 10 d. Pluto is a geologically active world with many processes altering the surface. [L17]
- 11 c. The source region of comets is the Kuiper belt and the Oort cloud, which are home to icy planetesimal remnants from the outer solar system. Some asteroids contain water, and there are comets that get perturbed into near-Earth orbits. [L18]
- 12 c. The Kuiper belt is much wider and contains many more objects than the asteroid belt. [L18]

[Click here to go back to the quiz.](#)

LECTURES 19–24

- 1 c. These spectral features demonstrated that the Sun is 75% hydrogen, 24% helium, and a tiny smattering of heavier elements. The Sun's yellow color is due to its temperature. The solar wind is predominantly composed of high-energy electrons and ions. [L19]
- 2 a. Although we know that Earth's magnetic field does reverse, it does not do so periodically; it's much more random. [L19]
- 3 c. Planetary rings are typically created by the breakup of a moon inside of a planet's Roche limit or by impacts of meteors with moons that kick dust off of small moons. [L20]
- 4 a. When core differentiation happens earlier, then hafnium remains in the mantle and later decays to tungsten in the mantle. [L20]

- 5 **b.** Hot Jupiters were the easiest to find and therefore the first to be found. They are not the most common type of planet in the galaxy; there are more super-Earths and other types of planets. [L21]
- 6 **c.** Atmospheres can be detected by the transit method, but not by the radial velocity method, which measures the Doppler shift of light from the star. [L21]
- 7 **a.** The habitable zone is determined by equilibrium temperatures at different orbits, and those depend on the type of star. [L22]
- 8 **b.** Global-scale atmospheric chemical signatures, such as a large amount of oxygen, will be the easiest to detect. We can't yet image an exoplanet's surface, and life is unlikely to change the orbit of a planet. [L22]
- 9 **b.** False. We also have evidence from giant impacts on other terrestrial bodies, such as Mars and Mercury, as well as evidence from disruptions of the asteroid belt. [L23]
- 10 **b.** False. The fact that the Moon has craters from the late heavy bombardment means that it must have formed earlier. We also have lunar rocks that date back to 4.51 billion years ago—much earlier than the late heavy bombardment. [L23]
- 11 **b.** Gravity assists allow a spacecraft to conserve fuel by using a planet's gravity to speed up or slow down or change direction. It would be faster to take a more direct path to some planets, but that would require much more fuel. [L24]
- 12 **c.** Although we can't see the far side, it does receive sunlight as much as the near side; that means it's not actually the "dark side" of the Moon. [L24]

[Click here to go back to the quiz.](#)

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The Planetary Society. *The Planetary Report*. <http://www.planetary.org/explore/the-planetary-report/>. This quarterly magazine features amazing articles on current research in planetary science.

WEBSITES

There are many excellent websites with accessible information about planetary science and relevant spacecraft missions. The best (and free!) way to get the most up-to-date research in planetary science is through the following websites, which typically contain articles as well as multimedia.

Cassini at Saturn. NASA. https://www.nasa.gov/mission_pages/cassini/main/index.html.

Exoplanet Exploration: Planets beyond Our Solar System. NASA. <https://exoplanets.nasa.gov/>. Great resources for learning about exoplanet detection techniques as well as the latest research in exoplanets. There is also a link to NASA's Eyes on Exoplanets, an app that allows you to visit and learn about exoplanets in our galaxy.

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