Lecture 2 - Ocean Origins

Lecture 2: Ocean Origins

In this lecture, we will explore:

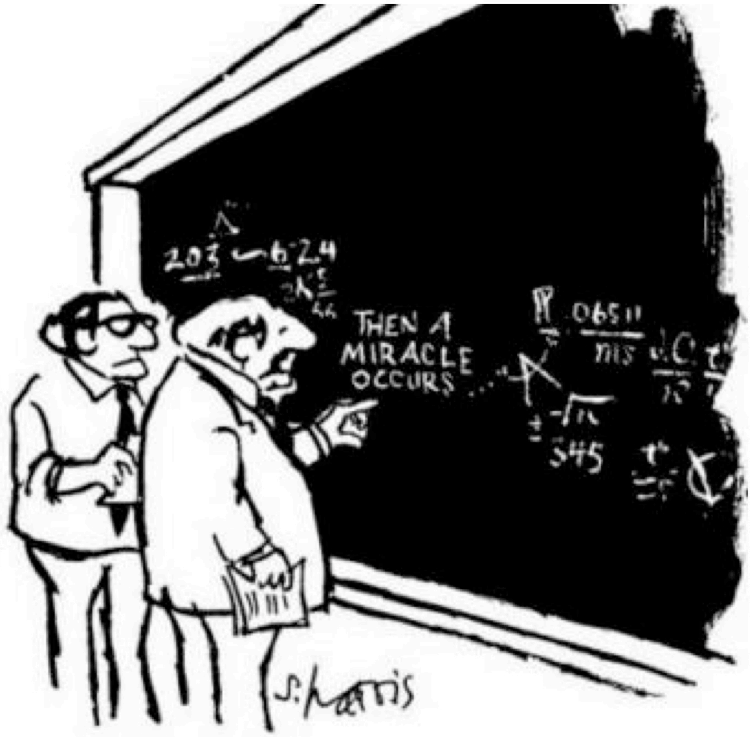
How was Earth formed?

How and when did the ocean arise?

How did life come to be in the ocean?

But first, let's remind ourselves about the scientific process. This class will look at the ocean through a scientific lens. This is after all, a science course, and we are science nerds. So before we dive into the formation of the Earth's ocean, lets review the scientific process (a bit of a repeat, but this is important stuff). If you all walk away from this class with science and ocean literacy, even if you move into business, law, politics, social work, having you being informed will be a great asset for society, as more and more, politics-ideology are being confused with science.

So how does science work?



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Scientific Method: The goals of science are to discover and understand patterns in the natural world and to develop the ability to make predictions. Then, through unbiased measurements and analysis, we can test how well our understanding works to explain and predict reality. Often the mis-matches between our predictions and observations are the most informative to scientists, as they can result in adjusting their physical/chemical/biological explanations. The process of drawing conclusions and revising those conclusions is essential to the development of scientific knowledge. This leads to lots of debates between scientists, which is often used by non-scientists to suggest that there is not a consensus among scientists. However, this is often not the case, as the science debates tend to focus on the nuances and not the general ideas surrounding them. We will touch on this later in the term when we talk about climate change, the oceans, and policy debates.

The scientific method has several components, all of which are equally important. Much of the approach is sometimes called the Popperian view of the science, based on the great philosopher of science Sir Karl Popper who advocated empirical falsification. The key parts of the scientific method include:

Observation: Collection of scientific facts through observation and measurement. These can be quantitative (measurements, counting, etc.) or qualitative (color, shape, condition, etc.), and the type of observations determines what kind of conclusions you can make. For example with quantitative observations you may be able to perform statistical analyses, whereas with qualitative observations your analysis may be mostly descriptive. Observations also require us to have the appropriate tools to document these occurrences. Since our tools are always improving, we have new ways of making better more detailed observations. If an observation is repeatedly confirmed, and results in a consensus among scientists, it might transition from an observation to a **scientific fact (Links to an external site.) (http://en.wikipedia.org/wiki/Scientific_fact#Fact_in_science)** .

Hypothesis: A tentative and TESTABLE statement about the natural world that can be used to build more complex inferences and explanations. This often is a process that can be slow and results from lots of professional "discussion" (aka debate). The mark of a great scientist is the ability to organize the existing facts and then construct a unique hypothesis that can be tested. It sounds simple, but here lies the art of science. Hypothesis (hypo = under, thesis = an arranging) sometimes looks like an informed and educated guess, the key difference is that a hypothesis is a testable guess.

There can be many hypotheses from a single observation, and the difficulty is sorting out which is the right explanation. However, often in nature the real explanation might represent a complex combination of several hypotheses. This is where much debate comes. For example there has been a lot discussion about ***intelligent design (Links to an external site.)*** **(http://en.wikipedia.org/wiki/Intelligent_design)** over the last few decades as a counter-argument to ***Darwinian (Links to an external site.)*** **(https://en.wikipedia.org/wiki/Darwinism)** evolution. Can you think of a test for intelligent design? One test is referred to as **irreducible complexity (Links to an external site.) (https://en.wikipedia.org/wiki/Irreducible_complexity)** , which states that certain biological systems are too complex to be formed by evolution. Much of the work by evolutionary scientists fighting this idea involves discovering and explaining the development and evolutionary process of different species and biological functions (e.g. **the evolution of the eye (Links to an external site.) (https://en.wikipedia.org/wiki/Evolution_of_the_eye)**). One of the most challenging aspects of the intelligent design debate is that, as a theory, it is predominantly faith-based, and is therefore very difficult to fully disprove. Science deals with testable (i.e. refutable or disprovable) hypotheses, and religions do not necessarily have that requirement, which can cause disconnects and potentially unending debates. Even though there is much debate in the present, just a few centuries ago some of the most influential scientists came from religious orders, take for example it was the friar **Gregor Mendel (Links to an external site.) (http://en.wikipedia.org/wiki/Gregor_Mendel)** who gave us the basis of heritable traits which was a major advance for evolutionary theory.

Examples of observation, h*ypotheses to explain the observation*, and test of that hypothesis.
My computer isn't working *because I need a new battery.* Replace the battery, and see if it works.

My aquarium fish keep dying *because the temperature is too high.* Decrease the temperature and see if they live longer.

Clams grow larger in northern estuaries *because the temperature there is cooler in summer.* Bring clams into the lab from northern and southern estuaries and grow them both in warm and cool conditions to see if they grow larger.

Examples of UN-testable questions and hypotheses

Purple squirrels exist. You would have to find every squirrel in the world and check its color. Even then, you might have missed one.

Chocolate is the best ice cream flavor. This is just an opinion, and there is no way to prove it is objectively true.

Dogs are better pets than cats. The wording of "better" makes this too vague to test, and depends on whom you are requesting the opinion from.

Here is a great video by Rutgers Department of Marine and Coastal Sciences on testable questions

https://youtu.be/Np1T7VNnfBk **(https://youtu.be/Np1T7VNnfBk)**

(https://youtu.be/Np1T7VNnfBk)

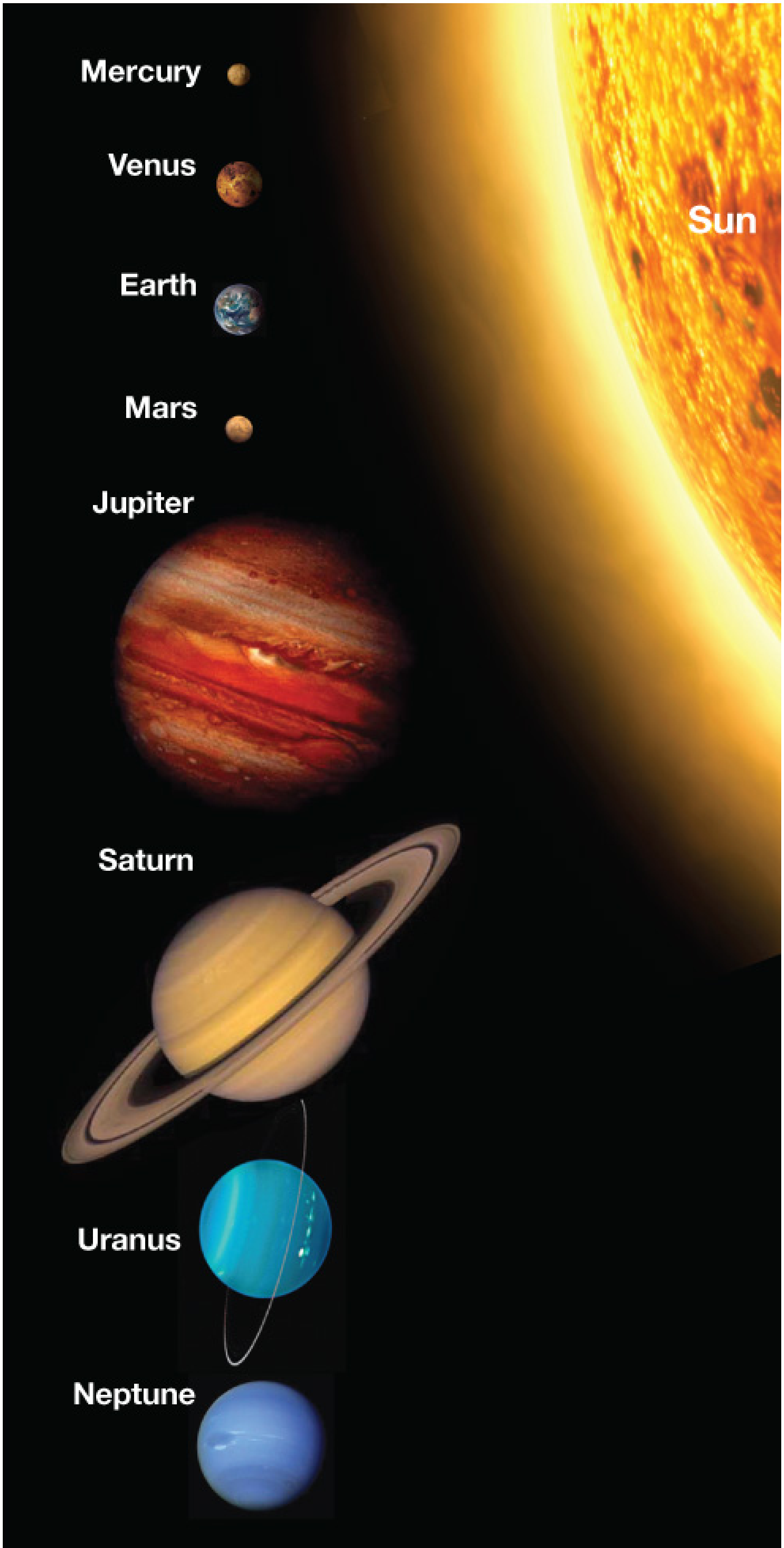
Testing: Gathering the observations, performing experiments, and creating models that then can be used to test the hypotheses. This is often the key in discriminating between science and pseudo-science. Here the scientist's goal is to disprove a hypothesis. If you disprove a hypothesis, it can make generate advances in understanding and can open up new testable explanations. Imagine how revolutionary it would be for a major theory to be proven wrong (as opposed to be confirmed correct). This process can lead to large debates and will go back and forth over and over. For instance, in 2011 scientists thought that they clocked a neutrino (a subatomic particle) traveling faster than the speed of light. After much debate, checking, and rechecking the results, it was determined that a mistake was made in the measurement. This is an excellent example of how rigorous the scientific community can be and what amount of evidence is required to refute existing theories. If a new hypothesis is discovered to be true and other related hypotheses are also confirmed, it may generate a new scientific theory.

Theory: In science, a well-substantiated explanation becomes a **scientific theory (Links to an external site.)** **(https://en.wikipedia.org/wiki/Scientific_theory)** after repeated iterations of observation/hypothesis/testing. You often transition to a theory when your explanation has the ability to make accurate predictions. This process can take years to decades. It's also important to note that a scientific theory is not the same as what is generally referred to in common English as a "theory." The popular use of "theory" is more closely related to a hypothesis. For example, the Theory of Gravity or Einstein's Theory of Special/General Relativity are much more closely related to facts than someone's "theory" on how to best organize **your closet (Links to an external site.)** **(https://www.modularclosets.com/blogs/themodule/closet-organization)**.

Theory versus Truth? With the process of developing theories can we ever reach truth? It can sometimes be useful to think of a theory as the combination of the best available knowledge for a problem. Science never reaches the final absolute truth, but it is a process that is always working to refine our understanding and predictions. New observations can always change our understanding. However, if you think of the truth as a peak of a mountain, science is the process that slowly defines the path up the mountain but will never reach the top.

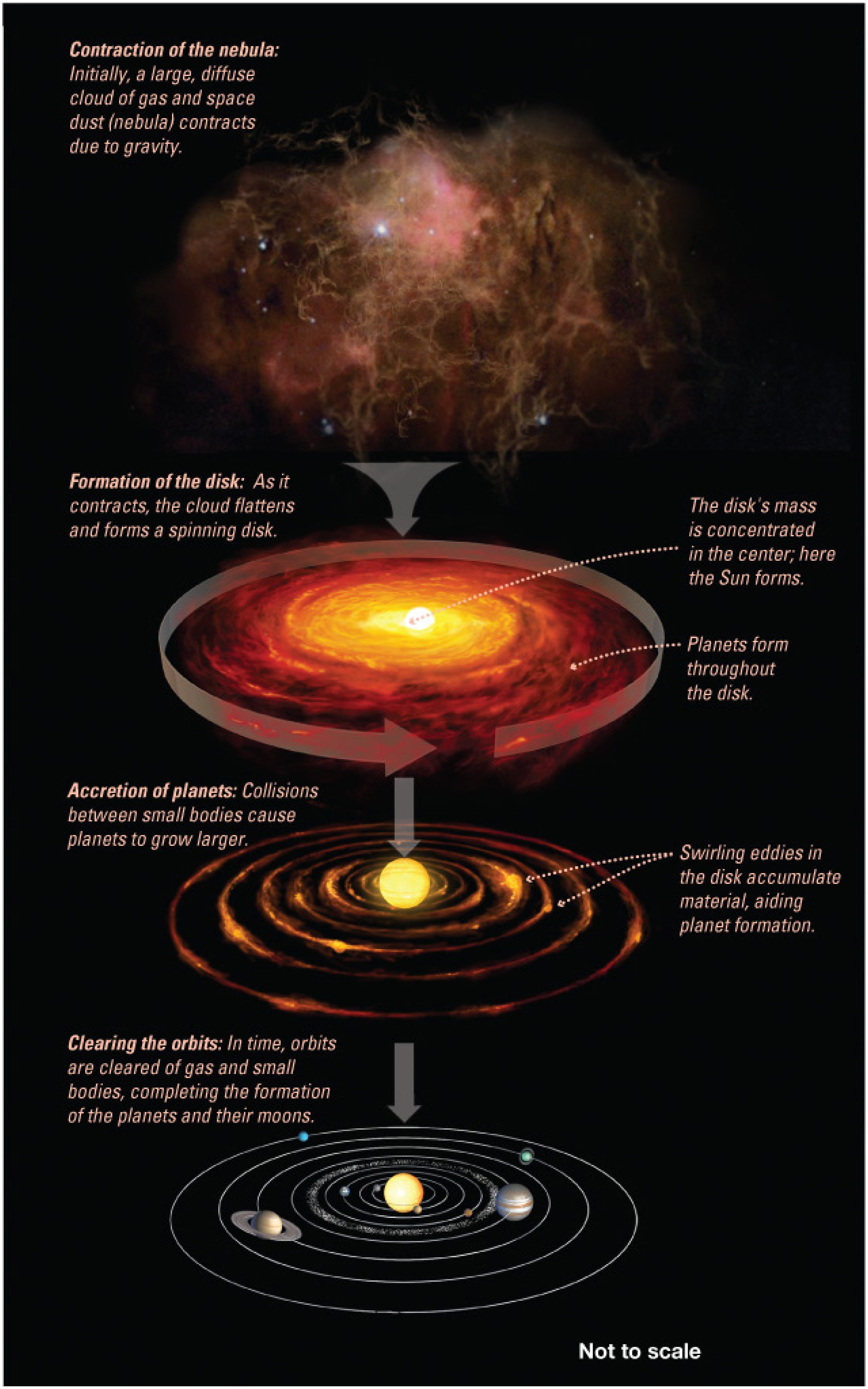
ORIGINS - FORMATION OF THE EARTH AND THE SOLAR SYSTEM

Earth is the third of eight minor planets in our solar system (look up those eight planets if you don't know the names off the top of your head – and sidenote that Pluto used to be part of the planetary gang, but was redefined as a ‘dwarf planet’ so is no longer part of the gang). These planets revolve around the Sun. Evidence from our solar system suggests that it formed about 5 billion years ago from gas and space dust (known as ***nebula (Links to an external site.)*** **(http://en.wikipedia.org/wiki/Nebula)**). This hypothesis is based on the structure of the solar system and composition of meteorites.



(a) Features and relative sizes of the Sun and the eight major planets of the solar system.

The nebular hypothesis, states that all planets in the solar system formed from an enormous cloud (made up by Hydrogen and Helium which are relatively light elements – only a tiny bit of heavy elements were in the cloud). The dust cloud revolved around the center, and the Sun began to form as magnetic fields and turbulence continued to concentrate accelerated by gravity. As the attraction grew, the coalescence of material formed the sun. Over time the sun was compressed (it used to be bigger than our solar system!!). As the Sun formed, pieces of it broke off, and formed what are called **protoplanets (Links to an external site.) (http://en.wikipedia.org/wiki/Protoplanets)** . The protoplanets became the planets and moons in our solar system today. Because different materials condense at different temperatures, each proto-planet composition depended on their proximity to the very hot protosun. Those planets that formed closest to the sun tend to be smaller and more 'terrestrial' or 'rocky' planets like Earth and Mars, while those further away from the sun are bigger and more gaseous like Saturn and Jupiter.



Contraction of the nebula: Initially, a large, diffuse cloud of gas and space dust (nebula) contracts due to gravity.
Formation of the disk: As it contracts, the cloud flattens and forms a spinning disk.
The disk's mass is concentrated in the center; here the Sun forms.
Planets form throughout the disk.
Accretion of planets: Collisions between small bodies cause planets to grow larger.
Swirling eddies in the disk accumulate material, aiding planet formation.
Clearing the orbits: In time, orbits are cleared of gas and small bodies, completing the formation of the planets and their moons.
Not to scale

Proto-earth was different than our planet is today. It was larger than today's planet earth, and did not have an ocean, atmosphere, or any life. It began as relatively homogeneous (which means it is pretty uniform in composition), but over time heavier elements migrated toward the center of the protoplanet. This early time on earth was violent. There were MANY meteorite/comet impacts, which is the basis of the theory that Moon was formed after some of massive impact between a Mars-size planet (***Theia (Links to an external site.)*** **(http://en.wikipedia.org/wiki/Giant_impact_hypothesis)**) and proto-earth. While much of Theia was absorbed into the proto-earth, it threw debris up into space, which concentrated into the Moon that circles the Earth today. On a clear night, you can see the impact craters on the Moon's surface of that early violent period. Here's a video

https://youtu.be/wflmQOZp3hE (https://youtu.be/wflmQOZp3hE)

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showing a simulation of what that Theia:proto-earth impact might have looked like. Sidenote - for those of you who are interested in this idea, the moon formation continues to **undergo debate (Links to an external site.) (https://astronomy.com/news/2019/05/giant-impact-hypothesis-an-evolving-legacy-of-apollo)** and we may have a new theory soon, or not, depending on data and observations that are produced.

During this period, the Sun continued to form, and over time the Sun condensed into a hot mass with energy released from the interior via the process of **nuclear fusion (Links to an external site.) (http://en.wikipedia.org/wiki/Nuclear_fusion)**. In the sun, the fusion results from the Hydrogen atoms that combine to form Helium. This reaction releases A LOT of energy. The Sun releases energy and it releases ionized (electrically charged) particles that make up **solar wind (Links to an external site.) (http://en.wikipedia.org/wiki/Solar_wind)**. Solar wind blew away the remaining nebular gas. The fusion process occurs at the center of the sun, and the energy cascades out the Sun's edge. This takes time. The Sun you see today walking around is the result of a fusion reaction in the center of the sun that occurred when the pyramids were being built. How cool is that!

The protoplanets closest to the sun got cooked by the intense solar radiation, and this intense heating boiled away their atmospheres. The heat was so intense, that as the planets cooled, they shrank. As the protoplanets continued to contract, heat was produced within the planet core from the disintegration of atoms, a thing that we now call radioactivity.

We have hit upon a fun and important concept that will come up throughout the class. The concept is density. Density is mass per unit volume (how heavy is something for its size). Density has nothing to do with thickness, it reflects the molecular structure, or how densely electrons are packed together in a molecule. As the Earth formed, the intense heat made Earth a molten ball, and the chemical elements separated inside that gell-like ball based on the density of the elements. The high density elements (iron and nickel) concentrated in the planets core. The density segregated the core, Earth crusts, with the low-density elements at the surface and heaviest elements in the core. Check out this video for a cool simulation of solar system formation.

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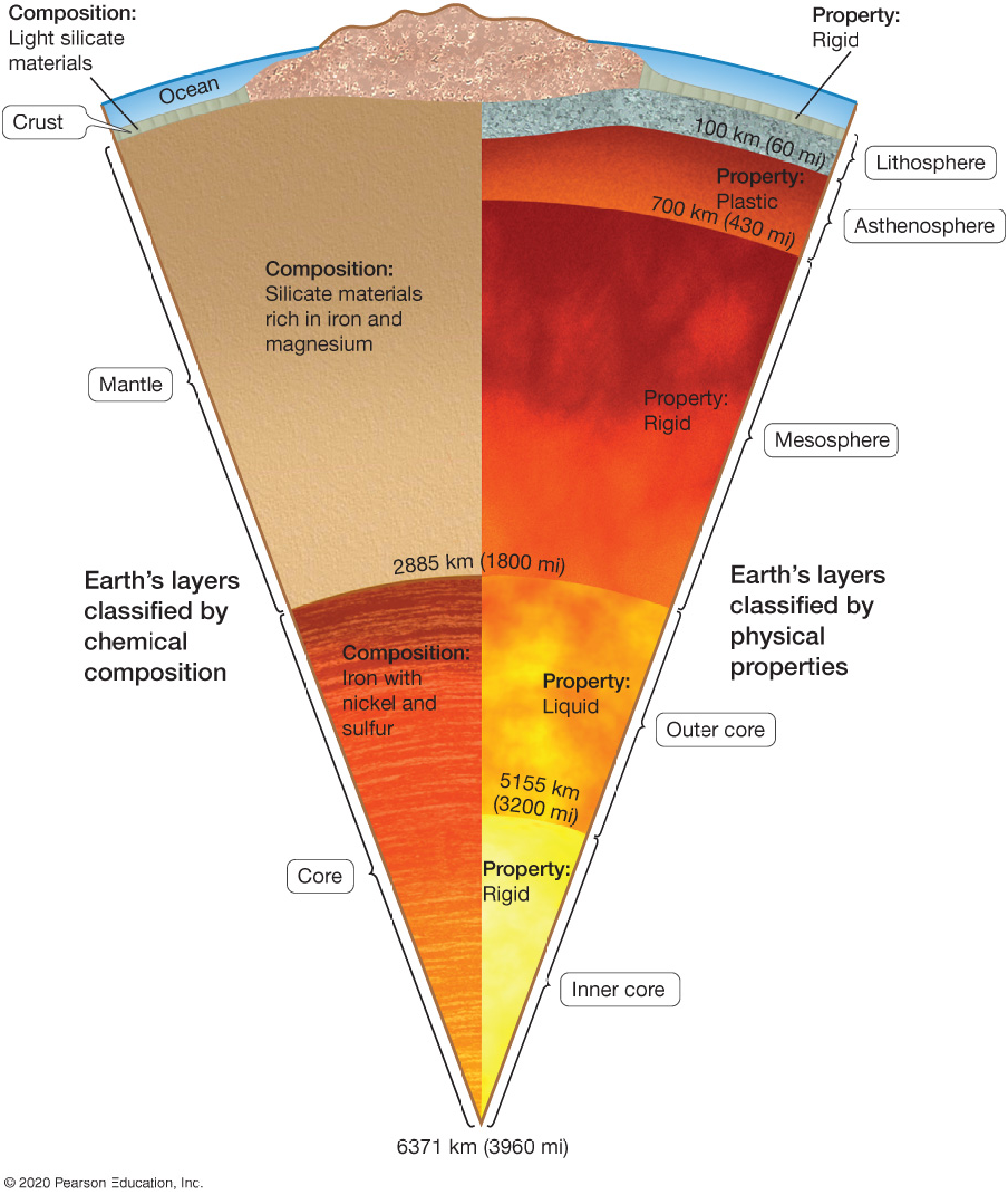
EARTH STRUCTURE

The density stratification resulted in a layered sphere. The result was an internal structure of the planet today. This is often described based on both the chemical and physical structure. Based on the chemistry, the Earth consists of three layers, the crust, the mantle, and the core. The crust is composed of a range of silicate minerals. The mantle is the largest volume (a depth of 2885 kilometers!!) and consists of iron and magnesium silicate rock. Beneath that is the core, which consists of high-density elements (Iron and Nickel). Based on the physical properties, the Earth is composed of five layers. Based on the physical properties, the Earth consists of the inner core, the outer core, the mesosphere, the asthenosphere, and the lithosphere.



The lithosphere is Earth's cool rigid layer, and as it turns out, is a brittle layer. Below the lithosphere is the asthenoshere which is a more flexible plastic-like fluid region. Below that region is the mesosphere, is relatively another relatively rigid layer. The core is at the bottom and especially at the inner core is a non-fluid medium.

Another critical concept that helps us understand how the Earth's structure works is isostatic adjustment, which describes the vertical movement of the crust. It is the result of buoyancy of the Earth's lithosphere as it floats on the plastic-like asthenosphere below. Think about a cargo ship in the ocean – when it is unloaded and light, it floats higher in the water, but when it is loaded down and heavy it sits lower in the water and displaces more water. The key idea with isotactic adjustment is that the continental and oceanic crust float on the denser mantle beneath. Crust thickness (or density) varies; mountains are very thick crust and the oceans represent a more dense but thin crust The thick crust floats higher, because of isostatic adjustment (the mountain displaces the mantle but it very tall so floats high), and dense thin crust (the ocean) floats lower creating basins for the ocean.

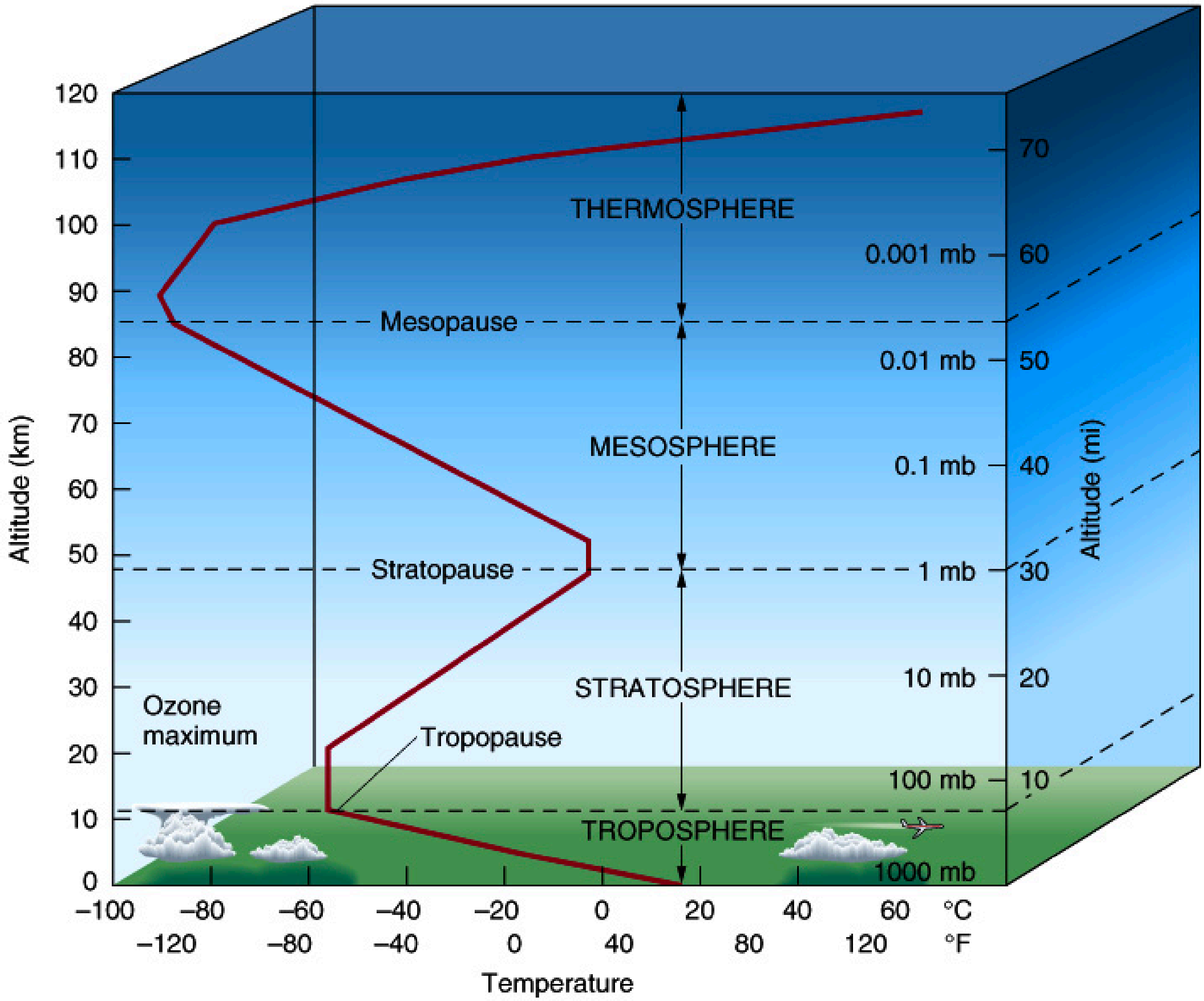
Formation of Earth's Atmosphere:

The atmosphere is the envelop of gases that surrounds the Earth. The atmosphere has no outer boundary, it just fades into space. The denser part of the atmosphere (97% mass) lies within the 30 kilometers of the Earth surface. The chemical composition of the current atmosphere is dominated by nitrogen gas (78%), oxygen (O_2) (21%), carbon dioxide (CO_2) (0.03%), and other trace gases.

The Earth's first atmosphere probably consisted of Hydrogen gas (H_2) and Helium (He). These gases are rare on Earth today compared to other places in the universe and were probably lost to space relatively quickly. Earth's gravity was not strong enough to hold onto the lighter gases and the Earth's core had not formed yet. The formation of the core created the Earth's magnetic field which deflected the solar winds that blew away the first atmosphere.

The Earth's second atmosphere was produced by volcanic out gassing. Gases produced were probably similar to modern volcanos (H_20, CO_2, SO_2, S_2, Cl_2, N_2, H_2), ammonia (NH_3), and methane (CH_4). There was no oxygen gas (O2) at this time on Earth.

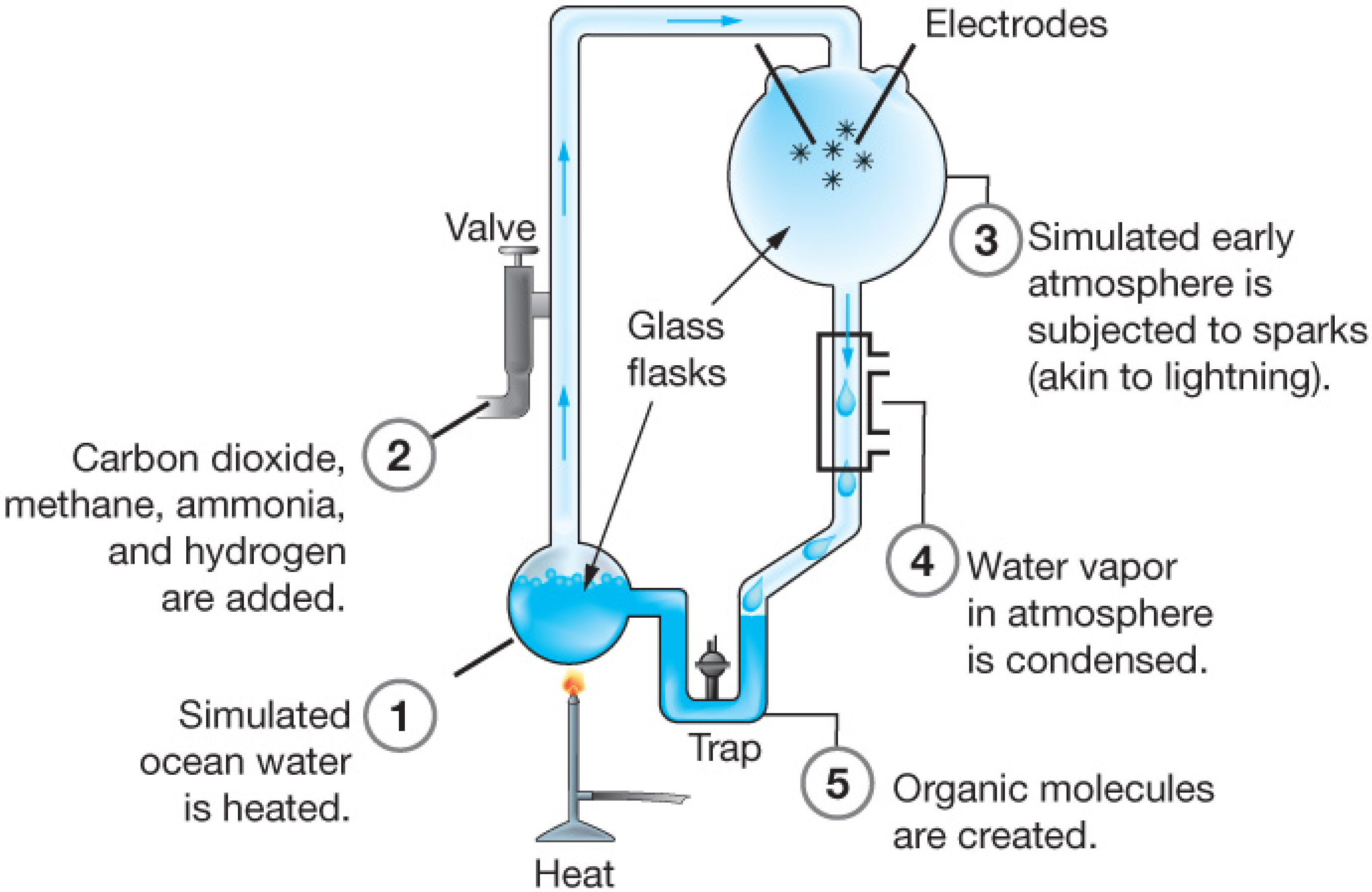
The Earth's third atmosphere was formed after life had formed on the planet. Oxygen - a key element created by life - was formed by several different mechanisms. The first process was photochemical dissociation (the break-up of water molecules by ultraviolet light, this produced around 1-2% of the current oxygen in the atmosphere). This helped form the Earth's ozone layer, which shielded the Earth from UV radiation. The big engine of the oxygen production was the biological innovation of photosynthesis. A totally amazing innovation that changed the profile of Earth, and among the most important chemical reactions to life as we know it. We will review this later - but it really is one of the most important chemical reactions out there! Much of the evidence for atmospheric changes is based on the geologic record, where geologists often look at the form of iron (Fe) in the rock record. Different concentrations of oxygen result in different forms of iron in ancient rocks. Like the modern ocean, the modern atmosphere has many layers.



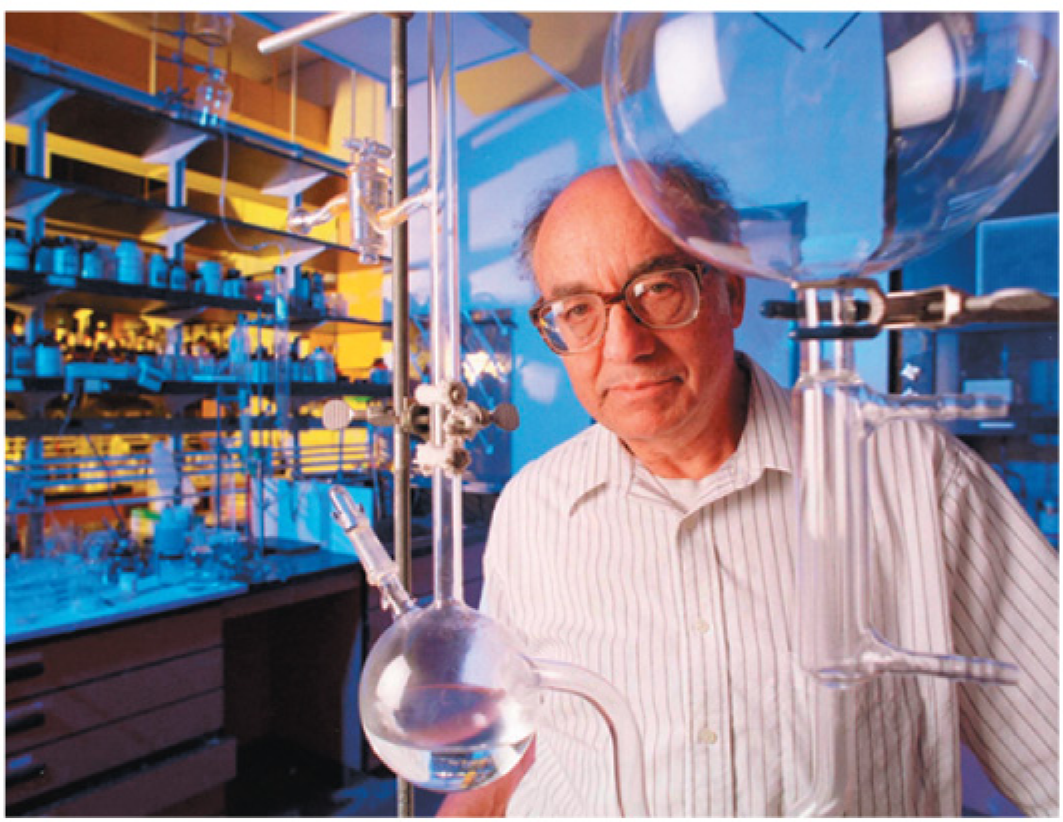
Formation of Earth's Ocean: The origin of the Earth's ocean is linked to the origin of the atmosphere. As the earth cooled, the water vapor in the atmosphere condensed and rained out. By about the 4 billion year mark, much of the water vapor had rained out into the ocean. You might ask then "why is the ocean salty then, isn't the rain fresh?" That is a great question. The relentless rain from the early atmosphere washed down on the Earth surface and it dissolved many elements and compounds into the newly forming ocean. The chemical composition of the ocean has changed over time. This reflects the changing chemistry of the atmosphere and thus the rain. The early atmosphere was very acidic, which dissolved lots of the Earth's surface. Eventually as many compounds in the Earth's atmosphere, and the acidity decreased and the Earth system settled into a relatively stable state.

Life on Earth

How did life start on Earth? Wow – heavy ideas there! Luckily, science has some answers for you. An hypothesis (first suggested 1920) was that inorganic molecules would spontaneously form organic molecules and the building blocks of life (called the 'Primordial soup'). It wasn't until the 1950's when a clever young man named Stanley Miller devised an experiment to see if he could recreate the conditions of early Earth's ocean and whether organic molecules would form in that 'primordial soup'. He added compounds that were commonplace in the early Earth atmosphere (ammonia, methane, etc.) and exposed them to energy (spark to simulate lightning), and guess what?! The basic elements that make up you and I (amino acids and other organics) were created.



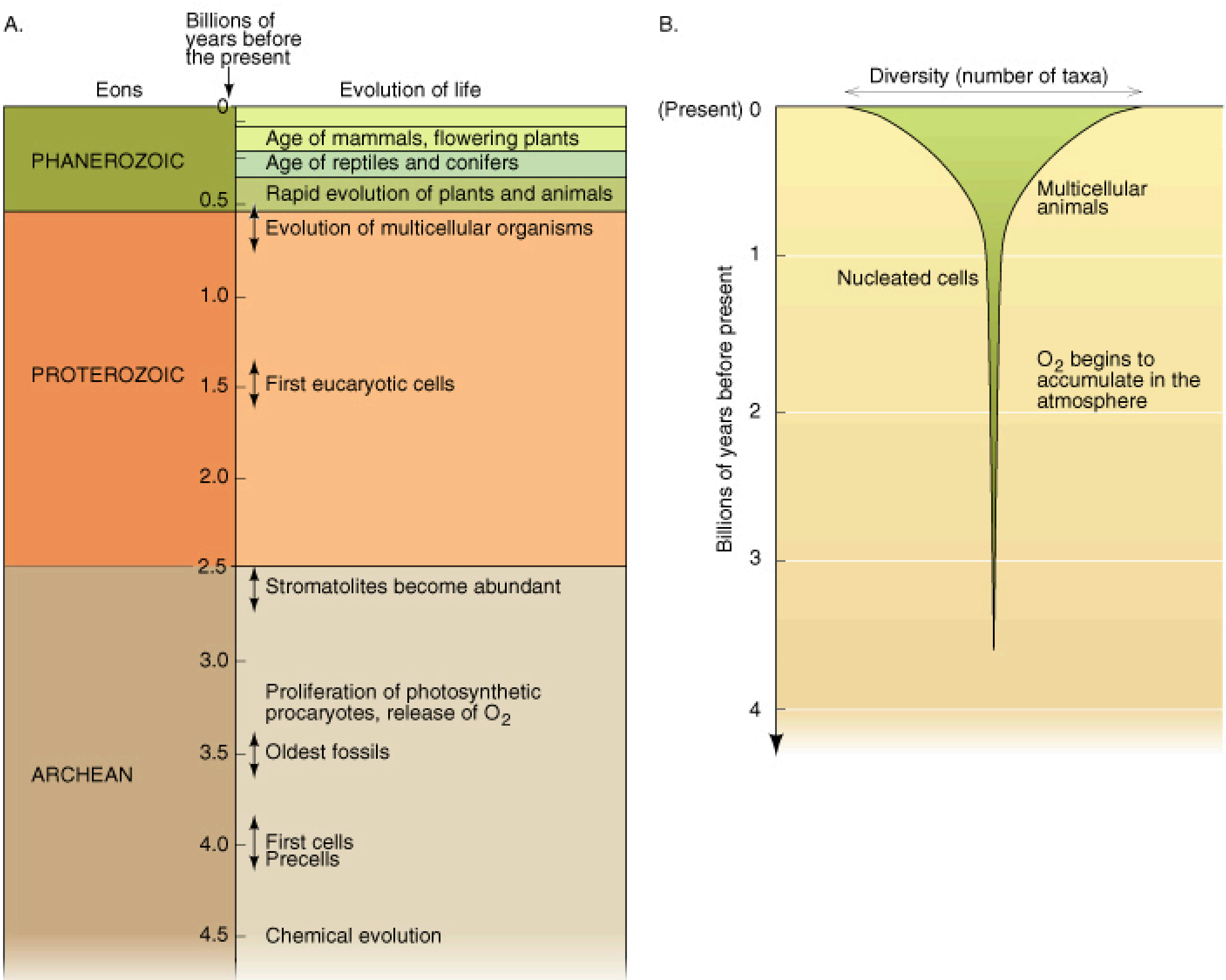
(a) Laboratory apparatus used by Stanley Miller to simulate the conditions of the early atmosphere and the oceans. The experiment produced various organic molecules and suggests that the basic components of life were created in a "prebiotic soup" in the oceans.



(b) Stanley Miller in 1999, with his famous apparatus in the foreground.

There is an alternate hypothesis for how life started on Earth, called the Panspermia hypothesis. This idea has the organic molecules that for life's building blocks, or even microscopic organisms themselves, arriving on Earth from other planets in the solar system. The biggest problem with this idea is that it would be very unlikely for organisms or organic molecules to survive long journeys in the harsh cosmic radiation of space. Although the Panspermia idea has some possibility, the experiments by Miller, and many subsequent similar experiments confirm that the Primordial Soup hypothesis is much more likely.

The first evidence we have of life on early Earth dates back to 3.5 billion years ago. This first evidence is fossils of procaryotic cells preserved in in rocks. In fact, there is a lot of evidence of life on early Earth, and these bits of evidence can be morphological in nature – things like fossils which are petrified remains of organisms, trace fossils which are fossils of things like footprints, or biogenic structures like stromatolites (more about that in a minute). Other forms of evidence of life on early Earth are geochemical in nature – direct things like molecular fossils, biomarkers, genomic traces, or indirect things like metabolic byproducts like oxygen, or tracers like trace metals or isotopes that would not exist if it were not for a living process that helps to concentrate or create them.

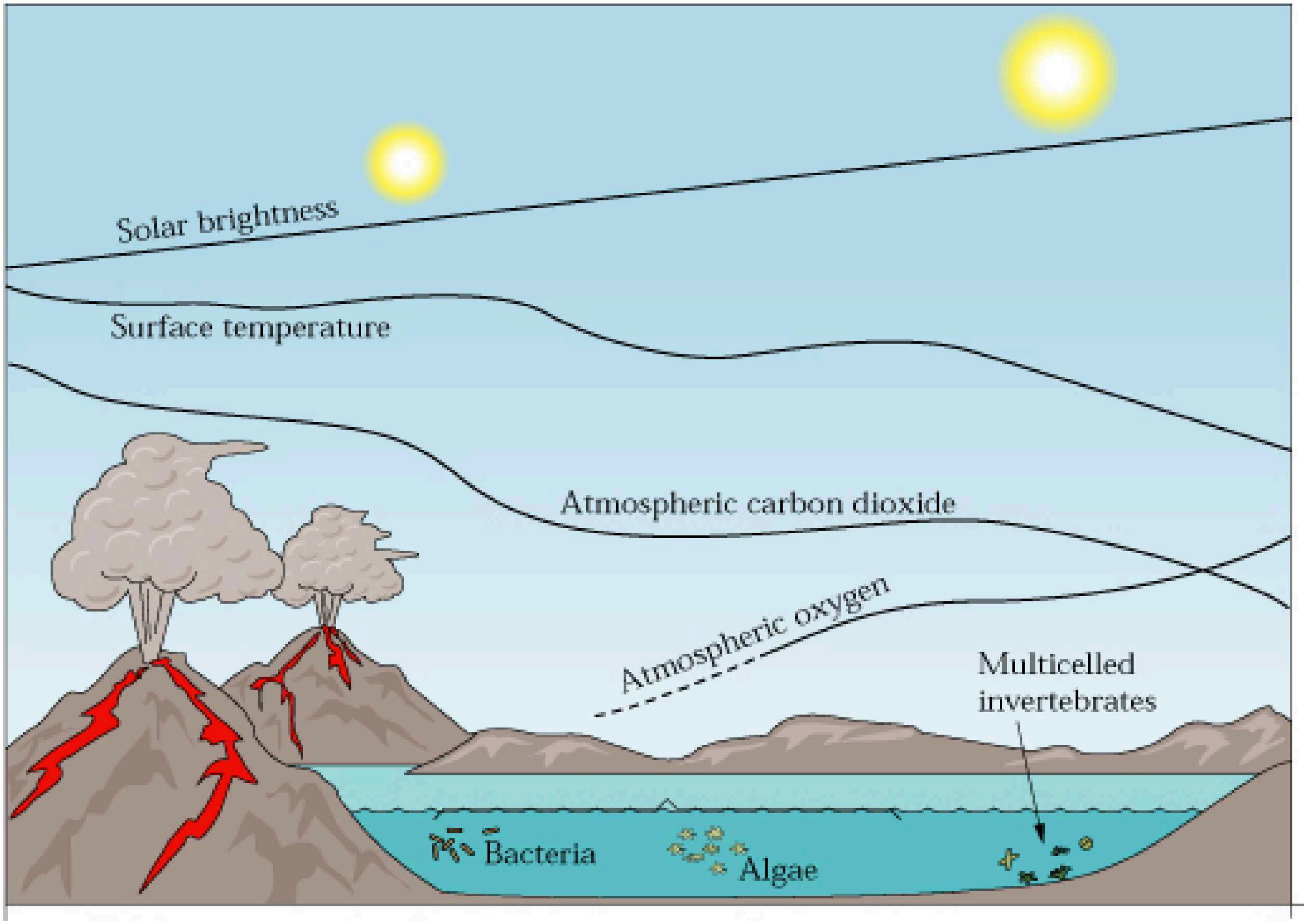


How is it that oxygen can provide us evidence of life on early Earth? The atmosphere of early Earth actually had low levels of oxygen compared to what we have now. At about XX years ago, there was a sudden increase in atmospheric oxygen around the same time as fossil evidence shows the first photosynthetic organisms appear.

These photosynthesizers produced the oxygen that was increasing in the atmosphere. One of these super old photosynthesizers are cyanobacteria (a group that still exists today), and another are the stromatolites the cyanobacteria create. Stromatolites are big, lump-like sedimentary structures that have been well preserved as fossils (side note – not all biological material preserves well as fossils, so there are probably a lot we are missing in the fossil record) and can been seen in some amazing fossil beds in Australia.

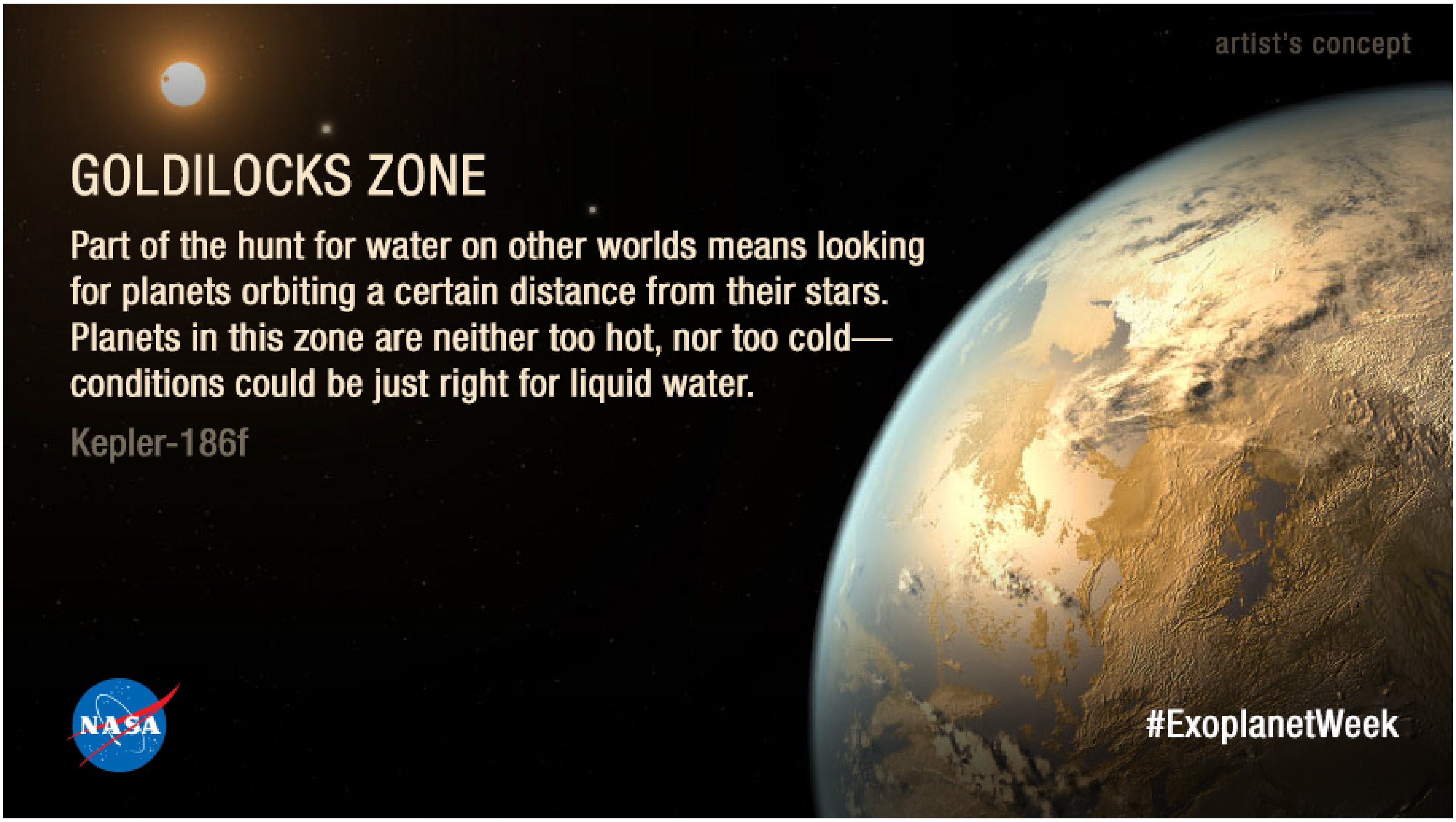
Where on Earth did this amazing Primordial Soup happen? It is likely that this all went down in the relatively protected but highly energetic environments in the deep ocean at hydrothermal vents or cold seeps. We will learn more about those in the next lecture, but in terms of the origins of life, these places had all the right conditions that Miller identified in his experiments. There is also some consistent evidence from molecular biology (DNA) that links lineages of microbes back to these deep ocean habitats. There are three broad groups of life forms – the Eukarya, Bacteria, and Archaea – and the diversity and linkages among them in marine habitats is an active field of ongoing research and discovery.

The origins of photosynthesis had a profound impact on oxygen in the atmosphere of early Earth, but what else was changing as life evolved? The Earth was cooling which meant temperatures were going down. The atmosphere was also clearing of volcanic ash and other debris, and as that happened, light from the sun got brighter. Photosynthetic plants were using that solar energy to convert CO_2 (carbon dioxide) to O_2 (oxygen) which meant the amout of CO_2 in the atmosphere decreased as O_2 increased. Pretty amazing that this was all happening because of the evolution of life on Earth!



In fact, Banded Iron Formations (BIF) provide a rock record of evidence of the role that life played in oxygenating the ocean. BIFs are striped rock formations that come from alternating layers of iron oxides, and iron-deficient chert. As photosynthetic organisms that use sunlight to produce organic carbon and oxygen started to evolve in the ocean, the oxygen they produced reacted with dissolved iron in the ocean to form iron oxides which were heavy and settled to the bottom of the ocean.   and the great oxidation event. Include discussion of changes in atmospheric oxygen over millions of years and what drives dynamics. Then when the iron became depleted, or the photosynthetic organisms stopped producing oxygen, the chert settled on top forming the next band, and so on. The ocean and atmosphere are now well oxygenated – a good thing for us humans!

Oxygen is only one aspect that makes Earth a place where life has evolved and flourished. There are a number of amazing things about planet Earth that all make life possible. The ozone layer is an important shield for the otherwise damaging solar radiation. Earth is also large enough to have a molten core, which creates a magnetic field that also helps protect life on Earth from solar radiation. Liquid water is also a key to life on Earth, but why don't we find that on other nearby planets? The key is how far that planet is from the sun – scientists refer to this as the Goldilocks Zone, which is a distance that is not too far away from the sun that it is too cold for water to remain liquid, and not too close to the sun that the water boils away. Earth has tectonic activity (we will talk about that soon!) which constantly recycles crust material on the planet which allows chemicals to be brought from that molten core to the surface. Even our moon is important – the moon helps stabilize the planet on it's tilted axis which creates seasons and the moon pulls and pushes the tides (more on this concept soon!) which likely mattered to how easily life evolved from marine to terrestrial habitats. And of course we have huge, vast oceans on Earth that circulate water, a great way to move heat around, around the planet to help stabilize the climate – again, we will learn all about that soon.



What conditions would limit life on Earth? Are there places on Earth that can help us answer that question? Yes! The Dry Valleys of Antarctica are perfect, and scientists study this area because it is the closest thing we have to the terrestrial environment of Mars. The Dry Valleys have extremely low humidity and no snow or ice. We already talked about liquid water being critical for life, but we can still find life in the Dry Valleys. Photosynthetic bacteria have been found in the somewhat moist insides of rocks there! Studying the life that exists in this extreme desert provides keys to where we might find extraterrestrial life.

Lecture 2: Keywords and definitions

Nebula = a cloud of gases and space dust from which all bodies in the solar system formed

Galaxy = huge rotating aggregation of stars, dust, gas and debris held together by gravity

Fun fact, there are ~100 billion galaxies in the universe, and ~100 billion stars in each galaxy

Star = spheres of incandescent gases (our sun is an example)

Isostatic Adjustment = the vertical movement of crust which results from the buoyancy of the lithosphere over the denser asthenosphere

Density = mass per unit volume

Primordial Soup = a solution containing organic compounds in the early Earth, from which some have assumed that the first living systems evolved.