MODULE 2 ORIGIN AND DEVELOPMENT OF THE UNIVERSE

Introduction

The universe is vast and complex. In terms of scale in time and space, human beings are just a negligible speck of dust in the universe. Yet, this seeming insignificance has not stopped us from pondering the composition, origin, and evolution of the physical world. We have gained significant progress in this quest for answers, not only in terms of the quantity and quality of answers to the original questions asked by our ancestors but also in terms of refinement of the questions themselves. As a result, we now know more about the large-scale features of the universe, its building blocks, and the rules governing the interaction of these building blocks. We consider our understanding to be better than before because our ideas not only satisfy the criteria for valid scientific explanation but also are fewer in number compared to the range and diversity of the phenomena being explained.

The first part of this module will orient you to the key ideas of the Big Bang Theory, which is widely accepted as explanation of the origin and evolution of the universe. The second part describes the formation of element – nucleosynthesis. The third part of the module focuses on the Standard Model, which is a widely accepted but incomplete description of the building blocks of matter and the rules of their interactions. The final sections gives some key ideas in our current understanding of the formation of stars and planets.

Learning Outcomes

After completion of this module, you should be able to:

1. Discuss the issues and challenges that have shaped our present understanding of the composition, origin, and evolution of the physical world;
2. Describe the crucial experiments and discoveries behind modern approaches to explaining the composition, origin, and evolution of the physical world;
3. Describe how chemical elements, from hydrogen to iron, were formed in the Big Bang and the stars;
4. Discuss how a series of nuclear reactions leads to the formation of elements heavier than iron;
5. Summarize the key ideas in our current understanding of the formation of stars and planets; and
6. Discuss some of the questions concerning the formation of stars and planets.

I. THE BIG BANG THEORY

The Big Bang Theory is currently our best answer to the old question about the origin and evolution of the physical world. By “theory” we do not mean it as a loose guess or hunch, but rather a highly credible complex idea consisting of rigorous arguments, solid experimental and computational evidence, and well-articulated and accounted limitations. The term “big bang” is a crude and misleading reference to some similarities between the dominant feature of the event referred to in the theory and an explosion. It originated from a taunt or joke of a scientist who disagreed with the earlier proponents of the theory. It is a catchy name so it stuck. However, it is a poor choice of name because it generates many misconceptions, which hopefully you will avoid or correct after studying this module.

You can easily state the essential “ideas” of the Big Bang Theory in a few paragraphs and doing so may make you feel confident that you fully understood it. This may be true, but in most cases it is not. Many events in the earlier parts of Big Bang (it is still happening now and continues to do so to the far future) have no counterpart in our experience. Thus, the familiar words we use to state the theory are actually crude analogies. Indeed, this module has a humble but hopeful expectation of you — humble because you will only gain a cursory knowledge of the line of reasoning used by scientists to understand and argue the accuracy and precision of the Big Bang Theory, but hopeful because learning the ideas about the Big Bang will make you more curious about the topic.

The module activities are exercises demonstrating crudely what chain-of-reasoning led scientists to formulate the Big Bang Theory. These chain-of-reasoning also allowed them to know what details are not yet clear in the theory and what questions this theory does not answer at all. BEFORE you begin the activities, pause and reflect on the main challenge faced by our oldest ancestors and our smartest scientists and their “tools” to face the challenge, as described in this passage:

The universe is a much larger and way older than any human being curious about it. The reach of human senses and their extensions are almost negligible. Almost all the crucial events happened before humans started to exist. The only clues are the remnants and debris of these events. Fortunately, human thoughts and imaginations, especially in collaboration, can slightly but significantly exceed the bounds of space and time.

Reading

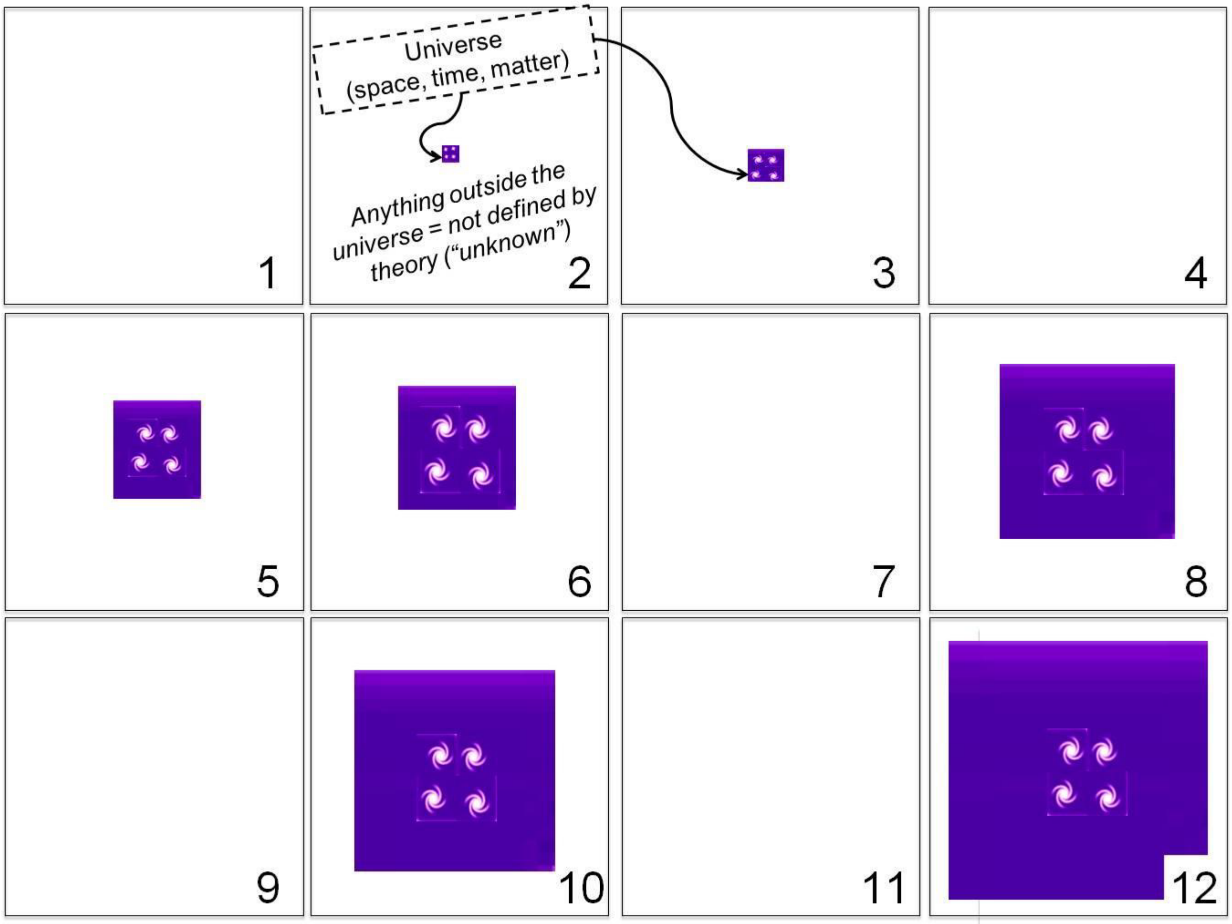
The 1929 scientific article “A relation between distance and radial velocity among extra-galactic” by Edwin Hubble, which reports his astronomical observations, is crucial in promoting the prevailing idea about the origin and evolution of the physical world. It presented the first convincing observational evidence of the Big Bang. Although this paper is only six pages long, it requires some prerequisite knowledge that a typical GE student may not have. Thus, in lieu of that paper, we will read the following review article written for a public audience by a respected astrophysicist, Neta Bachall:
Bahcall, N. A. (2015). Hubble’s Law and the expanding universe. *Proceedings of the National Academy of Sciences*, 112(11), 3173-3175.

This article analyzes Hubble’s paper in great detail and adds her own insights on the subject. (After you read Bachall’s article, you may able to read and appreciate Hubble’s paper.)

Activity 2.1
Hubble’s Law: Missing comic panels

Instruction: This is a group activity. Your teacher will ask you to form groups of 4-6 members each. In your group, agree among yourselves who will serve as moderator, secretary, and reporter. The moderator ensures that all members have a fair opportunity to participate and the discussion stays on topic and on schedule. The secretary collates and records submissions (e.g., assignments) and takes notes of the important points of the discussion. Using the secretary’s notes, the reporter delivers in behalf of the group the summary or highlights of the group discussion during the plenary (whole class) session.

Your group can perform this activity in 30 minutes or less. Study the comic panels below. Complete the "story" by filling in the empty panels, observing strictly the following constraints: 1) you can draw only the same number and features of elements present in the other panels; and 2) your drawing must follow the trend shown in the other panels.



Source: NASA Wilkinson Microwave Anisotropy Probe Website https://map.gsfc.nasa.gov/universe/

Discussion

The reasoning you used (bounded by the constraints given) in accomplishing the task is similar to how scientists deduced the implication of Edwin Hubble's 1922 discovery that the other galaxies move away from the Milky Way Galaxy (where the Solar System belongs) at a speed proportional to their distance from the Milky Way.

The distances between galaxies are expanding — i.e., the galaxies are moving away from each other — and the expansion is accelerating. If we assume the simplest scenario such that accelerating expansion is the trend of the change, and we imagine going back in time by reversing the event, then there must be a point in history where both matter and space are confined to a point. Thus, the scientists' answer to the question "What is the origin and evolution of the universe/physical world?" is essentially "The universe is all this space and matter lumped into a pea-sized volume, which suddenly expanded and still continues to expand today."

You may argue that a more elaborate trend is possible and you could be right. However, scientists heed the principle called Occam’s Razor ("The explanation requiring the fewest assumptions is most likely to be correct"), which suggests that it is wise to stick to the simplest possibility unless there is evidence to do otherwise.

Basic Ideas of The Big Bang Theory

The Big Bang Theory is the idea that about 14 billion years ago, there was a sudden expansion and cooling of space itself from a pea-sized volume, which contains space itself and the building blocks of matter. The expansion and cooling is still ongoing. The cooling allowed the building blocks of matter to form lighter elements (e.g., hydrogen, helium, and lithium) and the stars. The heavier elements later formed in the core of the stars.

The changes in or evolution of the universe involves very large masses and very fast speed. A thorough description and prediction of this phenomenon requires ideas on the distribution of matter in space and how matter moves as a result of their interactions with each other. Scientists are convinced that the first requirement is fulfilled by the Cosmological Principle, which states that matter and the expansion of space is homogenous (independent of location) and isotropic (independent of direction). This principle is based on the observation that galaxies are evenly distributed in space

The second requirement is fulfilled by Einstein’s Theory of General Relativity, which explains gravitational interaction. Einstein taught us that the movement of matter is defined by the “distortion of space and time” made by other matter. His ideas have a wider range of validity, including cases involving very massive objects and speeds approaching or equal to the speed of light. Isaac Newton’s ideas on gravitational interaction have the same purpose but are valid only for phenomena involving slow moving and smaller masses.

(Encouragement and CAUTION: As an encouragement for you to study further and a caution against premature confidence, please note that the preceding paragraphs are a condensed and simplified presentation of highly technical ideas, which you can only truly understand if you study advanced physics courses.)

We close this section with a brief and simple enumeration of some clarifications on the limits and common misconceptions about the Big Bang Theory:

a) There is NO bomb in some “center” of the universe. In fact, the concept of center can only make sense if there is space. Before the Big Bang, there was no space and there was no universe. It is space itself that “exploded.”

b) The theory has NOTHING to say about the “place” where the pea-sized volume of space and building block of matter is located.

c) The theory has NOTHING to say about what caused the Big Bang and what occurred/came/was before it.

d) The expansion due to the Big Bang affects only space, not the objects in it. (If there is any expansion of galaxies and other coherent objects in space, it is not due to the Big Bang.)

e) By “matter” we refer not only to matter already understood by scientists, such as atoms and radiation, as well as Dark Matter and Dark Energy. For your purposes, you can think of these latter two terms as fancy names for “that component of the universe that we still do not understand.”

f) The red-shift (stretching of wavelength) of light from other galaxies is NOT due to the movement of the galaxies, but rather due to the expansion of space itself in between galaxies.

II. NUCLEOSYNTHESIS: FORMATION OF ELEMENTS

The Big Bang Nucleosynthesis

Truran and Heger (2010) define nucleosynthesis as the study of nuclear processes responsible for the formation of the elements. The first stage of element formation started in the Big Bang, and is thus called the Big Bang nucleosynthesis.

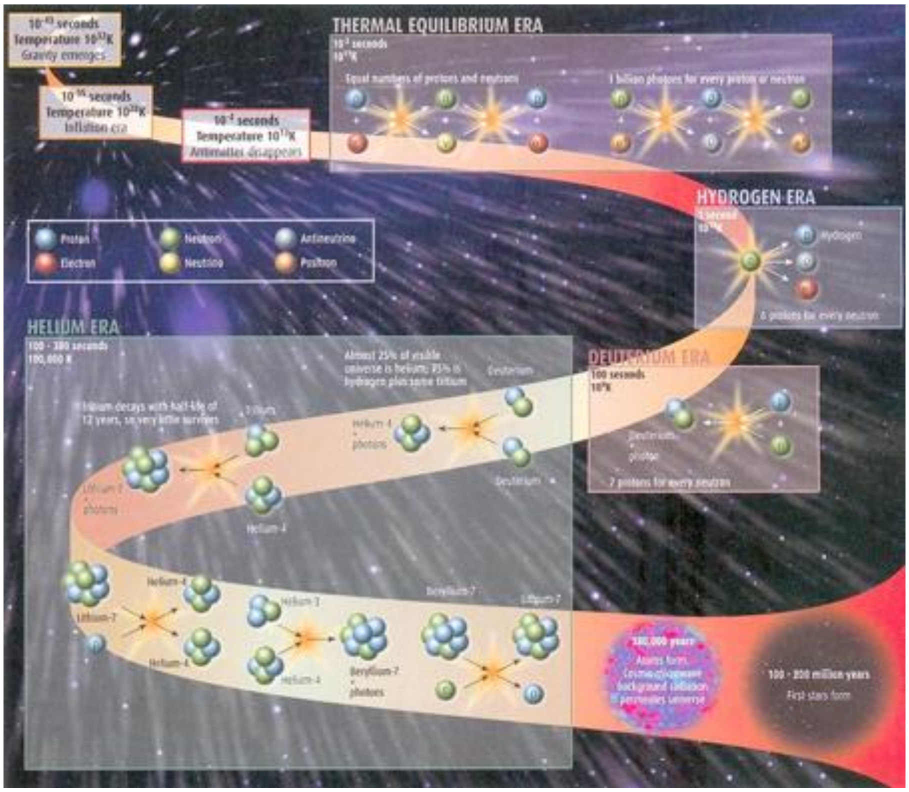


Figure 1. Illustration of the Big Bang Nucleosynthesis

(Source: https://universe-review.ca/I02-09-nucleosynthesis1.jpg)

All hydrogen and most of the helium in the universe were produced during the Big Bang nucleosynthesis. A small amount of lithium was also produced. Element formation in our universe relies on **nuclear fusion** reactions. In nuclear fusion, smaller nuclei collide to make larger nuclei, and energy is released in the form of electromagnetic radiation.

Stellar Nucleosynthesis

We learned how the light elements eventually merged into loosely knit nebulas which then condensed to form the stars. Clustering of these stars later formed the galaxies. Interwoven with this evolution of stars and galaxies is the formation of other lighter elements (from hydrogen to helium, from helium to lithium) and the remaining heavier elements.

Activity 2.2

Before going to class, read pages 23-27 ("Elements between helium and iron were produced in the centers of stars") of Chapter 2 of *Origin of Life: On Earth and in the Cosmos* by Zubay (2000), and then answer the following questions.
1. How are elements heavier than helium formed in the stars, particularly until iron?
2. Describe a likely route for the nucleosynthesis of nitrogen (N) (or any element between lithium and iron).

A star is a very hot ball of gas or a "nuclear fire". Stars create elements by combining lighter nuclei into heavier nuclei via nuclear fusion reactions in their cores, in the process releasing energy in the form of electromagnetic radiation. That's why they shine! They are natural nuclear reactors!

Supernova Nucleosynthesis

Activity 2.3
Before going to class, read pages 27-29 ("Formation of elements heavier than iron starts with neutron capture") of Chapter 2 of *Origin of Life: On Earth and in the Cosmos* by Zubay (2000).

Forming heavier nuclei from a cooler universe and larger space is difficult. This type of event happens only on supernovae, or stars that explode upon death. These supernovae are important in providing the energy needed for the fusion reactions required in the synthesis. This is the prevailing theory among scientists today when it comes to the initial formation of the post-iron elements in the universe

III. THE STANDARD MODEL

The Standards Model of Particle physics is currently our best answer to the old question about the composition of the physical world. Consistent with most of the earlier efforts with regard to this question, for example that of Democritus, the framework is the "reductionist perspective" — i.e., we understand a system if we understand its building blocks. Accordingly, the improvement in our knowledge is largely measured in the smallness of the building block that we are able to probe and explain.
The success of the Standard Model is due to the improvement not only in the technology (stronger particle accelerators) but also heavier use of advanced mathematics and the development of physical theories about other phenomena.
BEFORE you begin the activities in this section, pause and reflect on the main challenge faced by our oldest ancestors and our smartest scientists in understanding the composition of the universe:

In the reductionist perspective, the problem is not simply answering the question "What is the physical world made of?" and related questions such as "Why is it that we have coherent objects distinguishable from other objects?" and "Why do we need to break objects apart?" Otherwise, this is simply the issue of precision settled by making better and better tools for breaking smaller objects into far smaller chunks.
The problem is also about the manner or form of the answers themselves, i.e., "Can the answer to those questions be concise and beautiful?" This second problem became more urgent in the earlier days of particle accelerators (e.g., CERN) when there was a flood of discoveries of elementary particles. Some scientists even joked about forbidding their colleagues from reporting new finds because they are

overwhelmed by how to make sense of the information. Scientists were surprised because, as the focus became smaller and smaller objects they were expecting fewer and simpler fragments."

What is an elementary particle?
In 1967, physicist Steven Weinberg published "A model of leptons," which is one of the most, if not the most, influential and consequential papers about the composition of the universe. Although this paper is only 2½ pages long, it might be too abstract for a typical of GE student to understand. In lieu of that paper, we will read the essay "The first elementary particle," which is roughly about the same topic by Weinberg himself —
Weinberg, S. (1997). The first elementary particle. *Nature*, 386, 213-215.

Discussion
(The discussion is contained in Weinberg's paper itself.)

Activity 2.4
Are you an acquaintance, a friend, or the surgeon of the atom?
Instruction: In this activity, you will learn that the Standard Model essentially presents a more intimate picture of the atom. Do the following:

1. (Optional) Before coming to class, watch the YouTube video "The Standard Model Explains Force And Matter" (at https://www.youtube.com/watch?v=p5QXZ0__8VU) and other videos.
2. Using the information on the Standard Model given in Tables 1 to 4 below, sketch on a large sheet of paper (e.g., manila paper or whole bond paper) the structure and interaction within an atom with details as fine as describing quarks and their gauge bosons. Label the structures, such as building blocks (e.g., leptons or quarks), gauge bosons, and combinations of building blocks (e.g., neutron or proton). Include also scale bars to indicate range, label for mass, charge, and other properties, and other features that you think are relevant.
3. Present the sketch to the class and compare it with those of other groups. Assess each other for accuracy and detail. For fun, you may award to the group who made the best sketch the title "Surgeon," to the second best group the title "Friend," and to the third best the title "Acquaintance."

Table 1. Interactions

Force/ Interaction	**Property**	**Strength** *(compared to Strong Force)*	**Maximum Range** *(meters)*	**Mediating Particles/ Exchange Particles/ Force Carriers/ Gauge Bosons** (Bosons, i.e., spin = 1)
Strong	color charge	1	10^{-15}	gluons (g)
electromagnetic	electric charge	10^{-2}	Infinity	photon (γ)
weak	weak charge	10^{-5}	10^{-18}	vector bosons (w^+ , w^- , z^0)
gravity	mass or energy	10^{-38}	Infinity	graviton (not yet observed)

Table 2. Quarks (Fermion, i.e., spin = ½)

Quark	**Mass** (MeV/c^2)	**Charge**	**Color Charge**
up, *u*	~5	+2/3	"red" r, "green" g, "blue" b
down, *d*	~10	-1/3	r, g, b
strange, *s*	~200	-1/3	r, g, b
charm, *c*	~1.5x10^3	+2/3	r, g, b
bottom, *b*	~4.5x10^3	-1/3	r, g, b
top, *t*	~1.8x10^5	+2/3	r, g, b

Table 3. Leptons (Fermion, i.e., spin = ½)

Quark	Mass (MeV/c^2)	Charge
electron, e	0.511	-1
electron neutrino, νe	$<10^{-6}$	0
muon, μ	106	-1
mu neutrino, νμ	<0.17	0
tauon, τ	1.78×10^3	-1
tau neutrino, ντ	<24	0

Table 4. Baryons

Baryon	Quark Content	Mass (MeV/c^2)	Charge
proton, p	uud	938	1
anti-proton,		938	-1
neutron, n	udd	940	0
lambda, λ	uds	1,116	0
omega, Ω	Sss	1,672	-1

Note: Every particle has its associated antiparticle. The antiparticle has the same mass as the particle but with opposite physical charges. (For example, antiproton is the antiparticle of proton and it has the same mass but negative electric charge. Another example, positron is the antiparticle of electron and it has the same mass but positive electric charge.

Discussion

In the same way that the Periodic Table of Elements tells us the rules on how atoms combine to form compounds and molecules based on how they share the electrons, the Standard Model tells us the rules on how fundamental particles combine to form atomic and subatomic particles based on how they exchange gauge bosons or force carriers with other fundamental particles. Furthermore, the Standard Model encompasses the Periodic Table

Basic Ideas of the Standard Model

The Standard Model is the organizing principle behind the combination of building blocks of matter — i.e., leptons and quarks — into the more complex configurations we call matter. The properties of the building blocks and their combinations determine their interactions or forces, which occur through the exchange of particles called gauge bosons or force carriers.

The Standard Model is made possible by combining certain key concepts of Quantum Mechanics and Einstein's Theory of Special Relativity into a theory known as Relativistic Quantum Mechanics or Quantum Field Theory. The crucial component of the Standard Model is the creation and destruction of the exchange particles, whose existence violates the conservation of energy. Special Relativity accounts for the conversion of mass to energy and vice versa. Quantum Mechanics, the theory for phenomena at the microscopic (subatomic) scale, accounts for the duration and range of the energy-mass conversion using the Heisenberg Uncertainty Principle for energy and time ("the uncertainty ΔE in the energy of a system is inversely proportional to the time interval Δt that it is observed").

As another successful unification of several theories in physics, the Standard Model affirms the reductionist perspective. Unification basically means that different physical phenomena are described using the same "story plot" or organizing principle. In the case of the Standard Model, the common plot is that a wide variety of coherent structures are simply combinations of few building blocks of matter interacting through exchanges of particles. This theory is not only quantitative but also precise. Its predictions are already tested and/or testable by experiments. However, it is not yet complete — i.e., gravity not yet integrated in the story.

(Encouragement and CAUTION: We encourage you to study further because the preceding paragraphs are condensed and simplified versions of highly technical ideas, which you can only truly understand if you study advanced courses, such as quantum field theory.)

IV. FORMATION OF STARS AND PLANETS

Introduction

In their article "The First Stars in the Universe," Richard Larson and Volker Bromm write:

The universe was featureless and dark for a long stretch of its early history — the Cosmic Dark Ages. The first stars did not appear until perhaps 100 million years after the Big Bang, and nearly a billion years passed before galaxies proliferated across the cosmos. Astronomers have long wondered: How did this dramatic transition from darkness to light come about?

Using sophisticated computer simulation techniques, cosmologists have devised models that show how the density fluctuations left over from the Big Bang could have evolved into the first stars. The new models indicate that the first stars were most likely quite massive and luminous and that their formation was an epochal event that fundamentally changed the universe and its subsequent evolution. These stars altered the dynamics of the cosmos by heating and ionizing the surrounding gases. The earliest stars also produced and dispersed the first heavy elements, paving the way for the eventual formation of solar systems like our own. And the collapse of some of the first stars may have seeded the growth of supermassive black holes that formed in the hearts of galaxies and became the spectacular power sources of quasars. In short, the earliest stars made possible the emergence of the universe that we see today—everything from galaxies and quasars to planets and people.

Formation of Stars
Let there be light!

Reading

A. Before coming to class, read the following articles and answer the study questions below:

• Larson, Richard B. & Volker Bromm. (2009). The first stars in the universe, *Scientific American.* Available online athttps://www.scientificamerican.com/article/the-first-starsin- the-un/

The first small systems capable of forming stars appeared between 100 million and 250 million years after the Big Bang. These first protogalaxies consisted mostly of dark matter, a type of matter which does not interact with the electromagnetic force. This means it does not absorb, reflect, or emit light, making it extremely hard to detect. Researchers have been able to infer the existence of dark matter from the gravitational effect it seems to have on visible matter. Dark matter seems to outweigh visible matter roughly six to one, making up about 27% of the universe. The matter we know and that makes up all stars and galaxies only accounts for 5% of the content of the universe! (Source: https://home.cern/about/physics/dark-matter)

The first protogalaxies also contained no significant amounts of any elements besides hydrogen and helium. The Big Bang produced hydrogen and helium, but most of the heavier elements are created only by the thermonuclear fusion reactions in stars, so they would not have been present before the first stars had formed. The very first generation of stars, called Population III stars, were stars with no metals at all. The old metal-poor stars are called Population II stars, while young metal-rich stars are called Population I. Moreover, the protogalaxies were 100,000 to one million times more massive than the sun and would have measured about 30 to 100 light-years across. In the absence of metals, the physics of the first star-forming systems would have been much simpler than that of presentday molecular gas clouds. In contrast, the stars that arise from molecular gas clouds are born in complex environments that have been altered by the effects of previous star formation.

Formation of Protogalaxies

The first star-forming clumps were much warmer than the molecular gas clouds in which most stars currently form. Dust grains and molecules containing heavy elements cool the present-day clouds much more efficiently to temperatures of only about 10 kelvins. The minimum mass that a clump of gas must have to collapse under its gravity is called the Jeans mass, which is proportional to the square of the gas temperature and inversely proportional to the square root of the gas pressure. The first star-forming systems would have had pressures similar to those of present-day molecular clouds. But because the temperatures of the first collapsing gas clumps were almost 30 times higher than those of molecular clouds, their Jeans mass would have been almost 1,000 times larger

Star Formation Today

What are the factors that affect star formation at present?

Formation of Planets

Credit: ESO/L. Calçada (https://www.scientificamerican.com/article/planet-formation-its-a-drag/)

This artist's rendition depicts a disk of gas and dust whirling around a young star. Planets are born within such disks, but the exact details of their formation remain topics of intense debate among astrophysicists.

Reading

Before coming to class, study the resources listed and answer the study questions below.

A. Read the following articles:

• Podolak, Morris. *Planet Formation*. Available online at http://planetaryscience.oxfordre.com/view/10.1093/acrefore/9780190647926.001.0001/acrefore-9780190647926-e-108

It is generally accepted that the solar system began as a giant cloud of molecular gas and dust around 4.6 million years ago (Nebular Hypothesis). The Nebular Hypothesis posits that a giant cloud of molecular gas and dust underwent gravitational collapse, possibly due to shock waves from a nearby supernova explosion. Pockets of dust and gas began to collect into denser regions. As the denser regions pulled in more and more matter, conservation of momentum caused it to begin rotating, while increasing pressure caused it to heat up. Most of the material ended up in a ball at the center while the rest of the matter flattened out into a disk that circled around it. While the ball at the center formed the Sun, the rest of the material would form into the protoplanetary disk.

Credit: www.nasa.gov

There is no single theory at present that accurately explains how planets within and outside of the solar system evolved from the protoplanetary disk. Planet-formation theories are subject to observational constraints from our own solar system, from observed protoplanetary disks in nearby star-formation systems, and from the extrasolar planets. The conditions in protoplanetary disks are the initial and boundary conditions for the planetformation process. Young stars have gas disks, composed mostly of hydrogen and helium, surrounding them, and observations tell us that these disks dissipate after about 5 to 10 million years. If planets like Jupiter and Saturn, which are very rich in hydrogen and helium, are to form in such a disk, they must accrete their gas within 5 million years of the time of the formation of the disk. Any formation scenario one proposes must produce Jupiter in that time, although the terrestrial planets, which don't contain significant amounts of hydrogen and helium, could have taken longer to build. Modern estimates for the formation time of the Earth are of the order of 100 million years.

Extrasolar planets, discovered in the last two decades, are found to be very diverse both in mass and distance from the parent star. There are very massive Super Jupiter planets (with masses exceeding ten times the mass of Jupiter), many Hot Jupiters, Hot Neptunes and Super-Earth planets, or planets on very eccentric orbits. All these findings were not expected from studies of our own planetary system.
Based on current understanding, planet formation is believed to follow a sequence of steps (which may partially overlap) (see Mordasini *et al*):

Step 1: Gravitational collapse

- The gravitational collapse of a dense gas cloud forms a protostar with a surrounding protoplanetary disk consisting of gas and dust.

Step 2: From dust to planetesimals

- Micrometer-sized dust grows either via coagulation (sticking), or via a gravitational instability in the dust layer to form kilometer-sized planetesimals.

Step 3: From planetesimals to protoplanets

- Planetesimals grow through two-body collisions to form protoplanets, with sizes of typically a few thousand kilometers.

Step 4: From protoplanets to giant planets

- Some protoplanets grow so large that they can accrete massive hydrogen/helium envelopes, and become giant planets.
- Two competing theories : the core accretion - gas capture model (most widely-accepted), while the other theory is the direct gravitational collapse model.

Step 5: From protoplanets to terrestrial planets

- Other protoplanets remain too small for gas accretion to be effective. These protoplanets collide in the inner system after the dispersal of the disk to form terrestrial planets.

Step 6: Orbital Migration

- The formation both of giant and terrestrial planets is influenced by orbital migration, i.e. a change in the semi-major axis of the protoplanets due to angular momentum exchange with the disk .

Our solar system has three basic types of planets:

• The terrestrial planets — Mercury, Venus, Earth, and Mars — are closer to the Sun and they consist of a core composed mostly of iron, a mantle composed of rock (mostly silicates), and an atmosphere whose mass is a negligible fraction of the total mass of the planet.

• The gas giants Jupiter and Saturn are 300 and 100 times more massive than the Earth, respectively, and are mostly composed of a mixture of hydrogen and helium in the same proportion as is found in the Sun.

• The ice giants Uranus and Neptune are at the outer edge of the solar system, are roughly 15 times more massive than the Earth, and are composed of roughly equal parts each of rock, ice, and a hydrogen-helium mix.

The exoplanets seen so far fall into three categories:
▪ Hot Jupiters (about 1%): Jupiter-like planets orbiting very close to their stars with periods of only a few days;
▪ Giant planets with eccentric orbits (about 10%); and
▪ Super-Earths (about 40%), which are generally found in compact systems of two to four planets each, orbiting their stars at distances from 0.006 to 1 au in periods ranging from more than 100 days down to hours. Although there are no super-Earths in our Solar System, they orbit at least 40% of all nearby Sun-like stars, which makes them the most common type of planet found.

How do we account for such diversity in planetary systems? This is a question that still largely remains unanswered.

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