**Chapter 5: The Architecture and Birth of Solar Systems**

**LECTURE NOTES**

SLIDE 2: THE REST OF THE SOLAR SYSTEM

Learning goals

* Planets and the 2,000 Year-Old Question
* Who is Giordano Bruno?

SLIDE 3: THE REST OF THE SOLAR SYSTEM

* The Kuiper belt exists at the edges of the solar system beyond Neptune’s orbit.
* Kuiper Belt Objects (KBOs) are small bodies made of ice and rock.

SLIDE 4: THE REST OF THE SOLAR SYSTEM

* How did Giordano Bruno fit into his times? He was a martyr for science and was burned at the stake for his beliefs.
* Why was he persecuted? The Catholic Church charged Giordano Bruno with heresy. He believed that the Sun was the center of the solar system and that other stars had their own worlds.
* How did Bruno’s ideas influence society? Ancient Greek philosophers pondered the same radical view of the Universe more than 2,000 years before Bruno’s time. It was not until 1995 that two French astronomers announced that there were extrasolar planets, verifying what Bruno and others had theorized long before.

SLIDE 5: CLASS QUESTION—THE REST OF THE SOLAR SYSTEM

* The students should know where the Kuiper belt is located in the solar system.
* The correct answer is C.

SLIDE 6: JUST THE FACTS: A SOLAR SYSTEM CENSUS

Learning goals

* The Inhabitants of Our Solar System
* Planets
* Asteroids
* Comets
* Meteoroids
* Three Flavors of Planets
  + Terrestrial Planets
  + Gas Giants
  + Ice Giants

SLIDE 7: JUST THE FACTS: A SOLAR SYSTEM CENSUS

* What is a planet?
  + A planet is a body that orbits a star, massive enough for gravity to have pulled it into a spherical shape, and that has cleared smaller objects from the neighborhood of its orbit.
* What is an exoplanet?
  + A planet orbiting any star other than the Sun.

SLIDE 8: JUST THE FACTS: A SOLAR SYSTEM CENSUS

* In the inner solar system, we find the class of **terrestrial** (comes from the Latin word terra, which means land) **planets.** These planets are Mercury, Venus, Earth, and Mars. They are composed mostly of solid material, and they orbit very close to the Sun. The terrestrial planets have some degree of atmosphere, slow rotation rates, few or no satellites, moderate to weak magnetic fields, and no rings.

SLIDE 9: JUST THE FACTS: A SOLAR SYSTEM CENSUS

* Beyond the terrestrial planets are the **gas giants**. Both Jupiter and Saturn are primarily composed of hydrogen and helium. They are massive: Jupiter is 318 times more massive than Earth and Saturn is 95 times more massive. They orbit far from the Sun and rotate quickly. Jupiter has 67 known moons (4 famous Galilean moons; Io, Europa, Ganymede, and Calisto), and Saturn has 62, with Titan being the largest moon in the solar system. Both gas giants have strong magnetic fields and are surrounded by ring systems.

SLIDE 10: JUST THE FACTS: A SOLAR SYSTEM CENSUS

* Farther out are the **ice giants**, Uranus and Neptune. These large, icy worlds are not mostly gaseous but rather are composed of water, methane (CH4), carbon dioxide (CO2), and heavy compounds. Students should be familiar with chemical symbols. The ice giants orbit farthest from the Sun and have many moons. They too have strong magnetic fields and are surrounded by ring systems.

SLIDE 11: JUST THE FACTS: A SOLAR SYSTEM CENSUS

* Pluto is an example of a **dwarf planet** because it has not cleared its neighboring region of small objects. Eris and Ceres are also examples of dwarf planets. These objects are small in size, and most reside in a region beyond Neptune’s orbit. They are composed of rock and ice, have few or no satellites, and have no rings.

SLIDE 12: JUST THE FACTS: A SOLAR SYSTEM CENSUS

* Three Flavors of Planets
  + How should we categorize the objects in the solar system? Each of the eight planets can be classified as being terrestrial, a gas giant, or ice giant. See Table 5.1 to compare the properties of each of the bodies in our solar system.

SLIDE 13: CLASS QUESTION—JUST THE FACTS: A SOLAR SYSTEM CENSUS

* The students should know the distinguishing characteristics of the planets in our solar system.
* The correct answer is B.

SLIDE 14: CONSTRUCTION DEBRIS: ASTEROIDS, COMETS, AND METEOROIDS

Learning goals

* Asteroids
* Asteroid belt
  + Trojan asteroids
  + Earth-crossing asteroids
  + Identifying asteroids
* Comets
  + Short-period
  + Long-period
* Meteoroids
* Meteors
* Meteorites

SLIDES 15–20: CONSTRUCTION DEBRIS: ASTEROIDS, COMETS, AND METEOROIDS

* **Asteroids**—These objects are found in the disk-shaped region known as the asteroid belt. Their distance from the sun is in the range of 2.1–3.5 AU, where many asteroids orbit. Asteroids are rocky objects that range in diameter from hundreds of meters to 1,000 km.
  + The asteroid belt is located between Mars and Jupiter.
  + Planetesimals are rocky objects that might have been the building blocks of planets.
  + Trojan asteroids are two groups of objects that move around the Sun along the same orbit as Jupiter, with one group always preceding and the other group following behind the gas giant.
  + Earth-crossing asteroids, also known as ECAs, have highly elliptical orbits that cross Earth’s orbit. These are of grave concern to the human race because they pose a threat to civilization if one hits. They can be hundreds of kilometers across. The impact that happened about 66 million years ago is associated with the extinction of the dinosaurs.
  + Scientists can identify asteroids by their properties, such as composition, size, or shape. There are two main classes of asteroids: 1) c-type or carbonaceous (rich in carbon), which are very dark and reflect little sunlight, and 2) s-type, which contain more silicates and are more reflective. A full 75 percent of the solar system’s asteroids are of this type; 15 percent are c-type, and the rest fall into other classes.
* **Comets** are made up of rock and ice. The nucleus of a comet ranges in size from 100 meters to 50 km. Comets reside in the Oort cloud.
* The anatomy of a comet:
  + A nucleus, which is a mix of rock, dust, water ice and icy frozen gases like carbon monoxide (CO), carbon dioxide (CO2), ammonia (NH3), and methane (CH4).
  + The nucleus is surrounded by a coma that is formed as it passes close to the Sun.
  + It has two tails—an ion tail, which is made of ionized gas, reacts to the solar wind and always points directly away from the Sun; the dust tail is composed of small grains of solid matter blown off the nucleus.
  + Jets of high-pressure H2O, CO2, and NH3 vapor, and CH4 break through the surface of the nucleus; a stream of liquid, gas, or small solid particles shoot outward from the comet in a focused beam.
* Comets move in orbits with higher eccentricities than those of any of the other classes of solar system objects. Studies show that there are two distinct comet classes:
  + **Short-period comets** (e.g., Halley’s comet) originate in the Kuiper belt or scattered disk and have periods of 200 years or less.
  + **Long-period comets** (e.g., Shoemaker-Levy 9) originate in the Oort cloud and have highly eccentric orbits with orbital periods that can range from thousands of years to a million years.
  + Figure 5.8A of Hale-Bopp is very controversial when discussing the cult of Heaven’s Gate.
* **Meteoroids** are smaller chunks of rock ranging in size from a grain of sand to a boulder.
  + **Meteors** are meteoroids that have entered into Earth’s atmosphere.
  + **Meteorites** are meteors that have reached Earth’s surface.

SLIDE 21: CLASS QUESTION—CONSTRUCTION DEBRIS: ASTEROIDS, COMETS, AND METEOROIDS

* The students should investigate where the ECAs are located in the solar system.
* The correct answer is D.

SLIDE 22: US VERSUS THEM: OUR SOLAR SYSTEM AND OTHERS

Learning goals

* Evidence for the Origin of Our Own Solar System
* Interstellar Gas
* Annulus
* Discovering Exoplanets
* Center of Mass
* Three Primary Methods to Identify Exoplanets
* Learning from Exoplanets
* Hot Jupiters
* Planet Migration
* Scattering

SLIDE 23: US VERSUS THEM: OUR SOLAR SYSTEM AND OTHERS

* Evidence for the Origin of Our Own Solar System
  + The first clue of the solar system’s origin is that all of the planets orbit the Sun in the same counterclockwise direction, and most spin counterclockwise.
  + The Sun also spins or rotates in a counterclockwise direction.
* **Interstellar gas** can be ionic, atomic, or molecular gas that is found in diffuse clouds in the regions between the stars.
  + Due to the common direction of spin and rotation of the Sun and planets, astronomers believe that the solar system formed out of a large object, such as an interstellar cloud that was itself rotating.
  + The parent cloud imparted its sense of rotation to all the spinning/orbiting material in the newly formed solar system.
  + The next important clue comes from its shape. If viewed from the Sun’s equator, we would find that all the planets move on orbits that are roughly aligned in the same plane.
* An **annulus** is a ring or donut-shaped area or structure.
  + This is an indication that the primitive material that formed the planets must have had a disk shape. The asteroid belt looks like a disk and so does the Kuiper belt, which extends beyond Neptune.

SLIDES 24–27: US VERSUS THEM: OUR SOLAR SYSTEM AND OTHERS

* Discovering **Exoplanets**
  + Exoplanets are hard to find because they are far away and next to a very bright object. Scientists believe that as many as one-third to a half of Sun-like stars may have Earth-like planets.
* The **center of mass** is the point around which two orbiting bodies move; it lies closer to the more massive of the two objects.
  + In other words, both objects rotate around a **common center of mass** that can be thought of as the average location of all of the matter in the system.
  + Example 1: If two equal-mass objects orbit each other, then the center of mass would be the midpoint between the two.
  + Example 2: If one body is much more massive than the other, as in the case of the Sun and Earth, then the center of mass would lie almost at the center of the more massive object.
* Three primary methods to identify exoplanets:
  + The **radial velocity method** is based on finding an exoplanet’s gravitational influence on its parent star. In Example 2, the gravitational influence of Earth on the Sun would cause a tiny wobble in the star’s spectrum. By using high-precision instruments, astronomers could track the Doppler shifts and look for planet-induced motion, also known as **reflex motion**.
    - By measuring the period of the shift, astronomers can calculate the planet’s orbital period and by measuring the amplitude of that shift, astronomers can calculate the mass of the object. The more massive the planet, the bigger the wobble.
    - Figure 5.17A illustrates the Doppler shift. Light moving toward an observer is blue shifted. Light moving away from an observer is red shifted.
  + The **transit method** is an exoplanet detection method that measures the changes in the brightness of a star as a planet passes in front of it.
    - This method gives the physical size of the planet. Astronomers look for small decreases in starlight as the planet passes in front of the star.
    - When the transit method is combined with the radial velocity method, and if the planet passes in front of the star, then its orbital inclination can be determined.
    - Measuring the amount of light blocked allows the planet’s radius to be determined. From mass and radius, the planet’s density can be calculated. Now the planet can be categorized!
    - Astronomers have used the transit method to find **super-Earths**—planets with masses higher than that of Earth but lower than those of gas and ice giants.
  + **Direct imaging of exoplanets** shows the star in one part of the image and the planet separate from the star in the other part. However, a planet must be very large for this method to show it.
    - Astronomers are developing methods to screen out the light of the star. An example of this method is the **ADONIS high contrast infrared imaging of Sirius-B (**Astronomy & Astrophysics manuscript no. 8937 c ESO 2008, September 29, 2008).

SLIDES 28–30: US VERSUS THEM: OUR SOLAR SYSTEM AND OTHERS

* Learning from Exoplanets
  + Astronomers have discovered that the way our solar system is divided into inner and outer planets is not universal.
  + **Hot Jupiters** are a new class of planet the size of Jupiter that orbits very close to its star—about 0.1 AU or less. Hot Jupiters could have formed at larger distances and migrated inward.
  + Example 1: HD 209458 b, a giant gas planet, orbits a star similar to our Sun in the constellation Pegasus, approximately 150 light-years from Earth. It has a semimajor axis of 0.045 AU with a period of 3.5 days (see Math Box 5.1 to determine the orbital period of this planet). The transit method detected this planet.
  + **Planet migration** takes place when a change in the planet’s orbit occurs after it has formed.
    - The big question is: How does the star migrate inward without being pulled into the star? Astronomers are still debating the migration mechanism of Hot Jupiters.
    - Another surprise discovered by astronomers was the shapes of exoplanets orbits. They have large orbital eccentricities—very elliptical orbits instead of circular orbits as seen in our solar system.
  + Scattering happens when the rearrangement of the orbits of planets is due to mutual gravitational interactions. An example of this is when a planet in a circular orbit is flung out into a highly eccentric orbit (See Figure 5.22).
    - Evidence for **scattering** interactions of exoplanets comes from the orbital inclination of planets relative to their host star’s spin. In comparison to our solar system (low inclination angles), exoplanetary systems show a wide range of inclinations, as seen in Figure 5.22).

SLIDE 31: CLASS QUESTION—CONSTRUCTION DEBRIS: ASTEROIDS, COMETS, AND METEOROIDS

* The students should know how astronomers detect exoplanets. They often cannot separate out the facts of a method unless clearly articulated.
* The correct answer is A.

SLIDE 32: DEVELOPING A THEORY OF PLANETARY SYSTEM FORMATION

Learning goals

* Condensation Theory and Conservation of Angular Momentum
  + Condensation theory
  + Protoplanetary disk
* Condensation Theory, Dust Grains, and Planet Formation
  + Interstellar dust grains
* Accretion, Fragmentation, and Planet Building
  + Binary accretion
  + Fragmentation
  + Core accretion model
  + Hydrodynamic instability model

SLIDES 33–34: DEVELOPING A THEORY OF PLANETARY SYSTEM FORMATION

* **Condensation theory**, which states that our solar system formed from a spinning interstellar cloud of gas and dust that collapsed under its own weight, accounts for many of the observed characteristics of our planetary system and others.
  + Figure 5.23 shows a dense interstellar dust cloud floating in space. The basic theory is that stars are born from a slowly rotating cloud with some initial spin in space. The inward pull of gravity is balanced by outward push of the cloud’s internal pressure, which comes from internal heat within the cloud. Because the balance between gravity and pressure is unstable, the cloud collapses due to gravity, and its rotation forces it to trace out a spiral path. The closer the gas gets to the center, the faster it rotates, according to the law of conservation of angular momentum. However, it is the centripetal force that prevents the gas from falling into the center where the star is forming.
* The law of conservation of angular momentum explains the physics behind many of the results seen in the condensation theory.
  + The law states that when a spinning object decreases in size, its rotation rate must increase. The mathematical relationship is:

*MR*1*V*1 = *MR*2*V*2

* + - An everyday example would be that as a skater pulls in his or her arms, rotation becomes faster; the cloud will follow this same principle as it shrinks in size. Students can easily calculate the changes in an object’s size related to a velocity change by using the formula shown above and by consulting Math Box 5.2).
  + Conservation of angular momentum helps to explain how planetary systems form. It explains why planets spin in the same direction and orientation as the original interstellar cloud.

SLIDE 35: DEVELOPING A THEORY OF PLANETARY SYSTEM FORMATION

* A **protoplanetary disk** is a region that surrounds a young star, from which planets may form. The collision of the gas particles at midplane as they spiral inward will flatten the disk.
  + Therefore, what began as a spherical rotating cloud ends up as a rotating disk surrounding a new star as seen in Figure 5.24.

SLIDE 36: CONDENSATION THEORY, DUST GRAINS, AND PLANET FORMATION

* Condensation Theory provides a useful framework for understanding the formation of both our own solar system and the solar systems we continue to discover.
  + **Interstellar dust grains** are tiny bits of solid matter found in diffuse clouds in the regions between the stars.
    - The cloud that forms the star and disk are already full of dust grains as tiny as 0.1 mm that formed in the winds of dying stars and were ejected into space.
    - The dust grains condense at different locations within the disk to form planets.
    - The temperature in the disk close to the star is very high—approximately 2,000 K—while farther out the temperature drops to 100 K.
    - At high temperatures, dust grains get turned into vapor. As the temperature cools, the dust grains condense out of the gas.
      * An everyday example of condensation is raindrops that form in a cloud, i.e., the drops condense out of water vapor.
    - The new dust grains are not like the old ones before condensation because they are now sensitive to location. In the higher temperature region where Mercury is in our solar system, they will condense out into metals. At lower temperatures, where Venus, Earth, and Mars are now, the condensed particles will be mostly silicates (silicon and oxygen) and other rocky materials.
    - Beyond the snow line, temperatures are even lower, low enough for water ice to form, and at even larger radii, ices of other compounds, such as ammonia and methane, can condense.
    - From Mercury out to Neptune, the condensation theory explains the sequence of planet formation (See Figure 5.25).

SLIDE 37: DEVELOPING A THEORY OF PLANETARY SYSTEM FORMATION

* Accretion, Fragmentation, and Planet Building
  + During **binary accretion**, the dust grains grow into larger and larger objects orbiting in the disk.
    - Accretion answers the question: How do young planetary systems go from making grains to making rocky planets? The collisions of larger and larger particles lead to **planetesimals**. Eventually the objects are large enough for gravity to compress and heat the interior of the planetesimals. As the planetesimals grow even larger, gravity pull them into a spherical shape, and the heaviest material sinks to the center of the body. Finally, full-sized terrestrial planets, the rocky cores of gas giants, and moons are formed through the accretion process.
    - The timescale for the accretion process depends on the density of the gas and dust in the protoplanetary disk.
  + **Fragmentation** occurs by the shattering of solid bodies, such as planetesimals, due to collisions.
    - Fragmentation occurs alongside binary accretion, as microscopic grains become full-sized planets or moons.
    - Fragmentation is an ongoing process; we can see evidence of this in the asteroid belt as collisions break asteroid-sized planetesimals apart.
* The **core accretion model** is a theory of how the gas and ice giants formed. The model states that a giant gas planet formation occurs when an icy terrestrial planet grows by binary accretion up to a critical point and then rapidly pulls gas in from the surrounding disk.
  + - Jewitt explains that a very rapid flow of gas into the core occurs through the accretion process. The planet pulls in enough gas around the disk to form gas giants, such as Jupiter or Saturn.

SLIDE 38: DEVELOPING A THEORY OF PLANETARY SYSTEM FORMATION

* The **hydrodynamic instability model** is a model of giant gas planet formation in which small regions collapse to form planets within a gravitationally unstable disk.
  + Jewitt explains that the planet can form directly without a core because it would take too long to build up a rocky center.
  + This model is very popular amongst astronomers who study extrasolar planetary systems.

SLIDE 39: DEVELOPING A THEORY OF PLANETARY SYSTEM FORMATION

* The students should know what the conservation of angular momentum represents physically.
* The correct answer is B. The condensation theory is needed as well.

SLIDE 40: The Architecture and Birth of Solar Systems

* What have we learned?
* The Rest of the Solar System
* Just the Facts: A Solar System Census
* Construction Debris: Asteroids, Comets, and Meteoroids
* Us Versus Them: Our Solar System and Others
* Developing a Theory of Planetary System Formation
  + Instructors can review the material above with their students, depending on how it was taught, as a “What have we learned” slide at the end of the lecture.