DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

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Unit-V Solar System

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UNIT 5

SOLAR SYSTEM

5.1 Introduction

The solar system is our cosmic neighborhood, an awe-inspiring arrangement of celestial bodies held together by the gravitational influence of our central star, the Sun. It is estimated to be about 4.6 billion years old, formed from a colossal molecular cloud of gas and dust. This intricate system is vast, stretching approximately 287.46 billion kilometers (or 19 billion miles), encompassing everything from the blazing core of the Sun to the icy reaches of the Kuiper Belt and the mysterious Oort Cloud.

Key Components of the Solar System

1. **The Sun**:
    - The Sun, a G-type main-sequence star, is the lifeblood of our solar system.
    - It accounts for more than 99.8% of the system's total mass and powers life on Earth through its radiant energy.
    - The Sun’s core reaches temperatures of around 15 million degrees Celsius, driving nuclear fusion that fuels its luminosity.
2. **The Planets**:
    - **Inner Planets**: Mercury, Venus, Earth, and Mars, also known as terrestrial planets, are rocky, dense, and small in size.
    - **Outer Planets**: Jupiter, Saturn, Uranus, and Neptune are massive, primarily composed of gas and ice, and are encircled by rings and numerous moons.
    - Each planet has its unique features, such as Jupiter's Great Red Spot, Saturn's spectacular ring system, and Earth’s ability to harbor life.
3. **Dwarf Planets and Small Bodies**:
    - Dwarf planets like Pluto, Eris, and Haumea add variety, often residing in regions like the Kuiper Belt.
    - Asteroids and meteoroids populate the asteroid belt between Mars and Jupiter, while comets, with their icy nuclei, grace our skies with spectacular tails when nearing the Sun.
4. **Moons**:
    - The solar system boasts over 200 known moons, ranging from Earth’s singular Moon to the dozens orbiting Jupiter and Saturn.
    - These moons display immense diversity, including Europa’s potential subsurface oceans and Titan’s methane lakes.

5. **Other Regions**:
    - **The Kuiper Belt**: A disk of icy bodies beyond Neptune, home to Pluto and many comets.
    - **The Oort Cloud**: A theoretical spherical shell of icy objects that may extend up to 100,000 AU from the Sun, marking the boundary of the Sun's gravitational influence.

Interesting Facts

- Jupiter, the largest planet, is so massive that it influences the orbits of other celestial objects in the solar system.
- A day on Venus is longer than a year due to its slow rotation on its axis.
- The solar system moves through the Milky Way galaxy at an average speed of 828,000 km/h.

The Importance of Studying the Solar System

Exploring the solar system helps us understand fundamental questions about the origin of life, planetary formation, and Earth's place in the cosmos. Space missions like Voyager, Mars rovers, and the James Webb Space Telescope continuously expand our knowledge, inspiring innovation and sparking curiosity for future generations.

5.2 Nebular theory of formation of our Solar System

The Nebular Theory posits that the solar system formed from a large, rotating cloud of gas and dust, called the **solar nebula**, approximately **4.6 billion years ago**. The step-by-step transformation of this nebula into the Sun, planets, moons, and smaller celestial bodies involves a series of dynamic, interconnected processes governed by physics, chemistry, and astrophysical phenomena.

1. Initial State: The Solar Nebula

The solar nebula was part of a larger molecular cloud (or stellar nursery) composed primarily of **hydrogen (H)** and **helium (He)** with trace amounts of heavier elements. This material was likely enriched by earlier supernovae, which injected heavier elements like carbon, oxygen, silicon, and iron into the interstellar medium.

Key Features of the Solar Nebula:

- **Mass and Composition**:
    - 98% Hydrogen and Helium (light elements).

- 2% Heavier elements, called "metals" in astrophysics (e.g., silicon, carbon, iron).

- **Density and Temperature**:
    - Cold (~10 K to 20 K) with regions of slightly higher density.
    - Low temperature allowed volatile compounds (like water and methane) to remain in solid or gaseous forms.
- **Trigger Event**:
    - External disturbances (e.g., shockwaves from a supernova or collisions between clouds) compressed a region of the molecular cloud, increasing its density.

2. Gravitational Collapse and Formation of the Protoplanetary Disk

The triggered collapse of the nebula initiated a chain reaction:

A. Gravitational Instability

- Under its own gravity, the nebula began contracting. As it did, gravitational potential energy was converted into **thermal energy**, heating the core region.

B. Conservation of Angular Momentum

- Even a slight initial rotation of the cloud caused it to spin faster as it contracted, due to the conservation of angular momentum.
- The spinning nebula flattened into a **disk-like structure**, called the **protoplanetary disk**.

C. Differentiation of the Disk

- **Central Region (Proto-Sun Formation)**:
    - The central concentration of mass, where material accumulated, became increasingly dense and hot, forming the **protostar** (early Sun).
- **Outer Regions (Disk Formation)**:
    - The rest of the material flattened into a rotating disk of gas and dust.

3. The Protostar Phase: Birth of the Sun

The formation of the Sun proceeded through several stages:

A. Accretion of Material

- The increasing density and temperature at the center of the disk caused the protostar to grow by accreting surrounding material.

B. Onset of Nuclear Fusion

- When the temperature in the core reached **~10 million K**, nuclear fusion of hydrogen into helium began.
- The Sun entered the **T-Tauri phase**, characterized by intense solar winds and radiation that began clearing the inner regions of the disk of gas and dust.

4. Planetesimal Formation in the Protoplanetary Disk

The gas and dust within the disk began to coalesce into solid objects through complex physical and chemical processes:

A. Condensation of Solid Materials

- Temperature gradients in the disk determined which materials could condense into solid particles:
    - **Inner Disk (Hotter, >500 K)**: Only refractory materials (e.g., metals, silicates) condensed, forming rocky particles.
    - **Outer Disk (Cooler, <200 K)**: Volatile compounds (e.g., water, methane, ammonia) condensed into ices.

B. Formation of Planetesimals

1. **Coagulation**:
    - Dust grains stuck together through electrostatic forces, forming larger aggregates.
2. **Growth into Kilometer-Sized Bodies**:
    - These aggregates grew into **planetesimals** (~1 km in size) through repeated collisions and accretion.
3. **Gravitational Accretion**:
    - Larger planetesimals began attracting nearby material via gravity, accelerating their growth.

5. Differentiation of the Solar System

The distinct characteristics of the inner and outer solar system emerged due to the temperature-dependent condensation process and the gravitational influence of the forming Sun:

A. Terrestrial Planets (Inner Solar System)

- Mercury, Venus, Earth, and Mars formed close to the Sun, where only metals and silicates could survive the intense heat.
- These rocky planets were small, dense, and composed primarily of heavy elements.

B. Gas Giants and Ice Giants (Outer Solar System)

- In the colder outer regions, volatile materials like water, ammonia, and methane condensed into ices.
- Jupiter and Saturn, the gas giants, accreted massive envelopes of hydrogen and helium due to their strong gravitational fields.
- Uranus and Neptune, the ice giants, formed further out with compositions dominated by ices and some gases.

6. Clearing the Disk

After the Sun became a main-sequence star, its intense radiation and stellar winds cleared the protoplanetary disk:

- Lighter gases were blown away from the inner solar system.
- Remaining planetesimals were either accreted into planets, ejected into distant regions, or remained as smaller bodies like asteroids and comets.

7. Formation of Smaller Solar System Bodies

1. **Asteroid Belt**:
    - Located between Mars and Jupiter, composed of rocky debris that failed to form a planet due to Jupiter’s gravitational influence.
2. **Kuiper Belt and Oort Cloud**:
    - The Kuiper Belt, beyond Neptune, contains icy bodies like Pluto.
    - The Oort Cloud, a theoretical spherical shell, harbors long-period comets.

In a Nutshell….

- **Collapse –** the solar system comes from a high temperature gas ball. The mass of gas ball collapse, and then heating and then become a disc shaped.
- **Spinning –** the disc spinning faster and faster, so that no part of the disc that was thrown out and then the temperature decreased.
- **Flattening –** the disc become a sphere due to rotation, because of fast rotation, some of the fog from gas ball mass escape.
- **Condensation –** some fog formed the core of the largest mass in the middle, while the small part formed around cooling process.
- **Accretion –** the cores of smaller masses turn into planets, while most of the remains in a state of high temperature flare and called the sun.

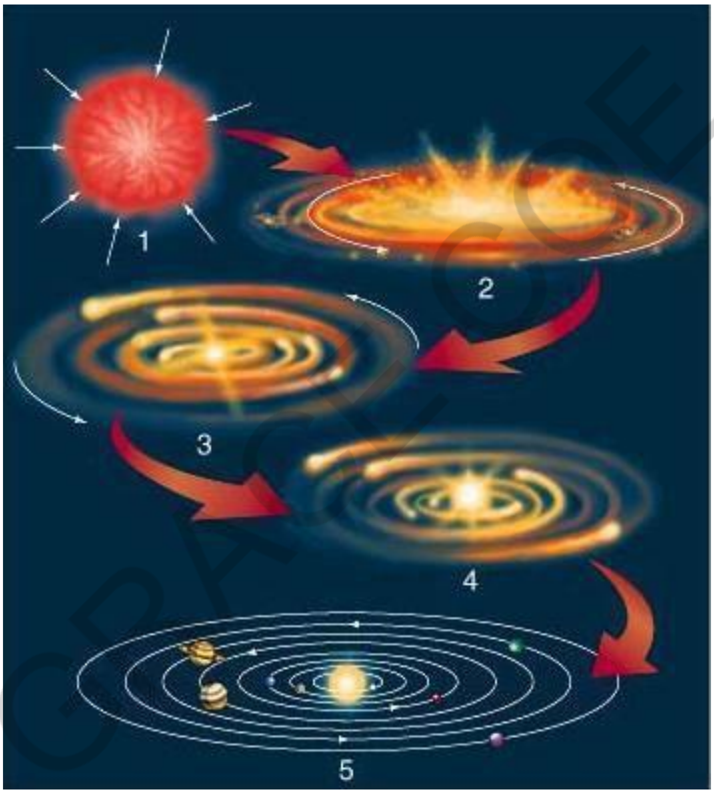

Fig: Nebular theory of formation

Evidence Supporting the Nebular Theory

1. **Protoplanetary Disks**:
    - Observed around young stars, confirming the initial stages of planetary formation.
2. **Planetary Orbits**:
    - Nearly circular and coplanar, consistent with formation in a rotating disk.

3. **Meteorite Composition**:
   - Preserves primitive materials from the early solar system.
4. **Temperature Gradients**:
   - Explains the compositional differences between terrestrial and giant planets.

Challenges and Modern Refinements

While the Nebular Theory explains much, some puzzles remain:

- The exact mechanism for transitioning from dust grains to planetesimals.
- The influence of turbulence, magnetic fields, and spiral density waves in the disk.
- The origin of anomalies like Uranus's tilted axis and Neptune's eccentric orbit.

5.3 Solar wind and nuclear reaction as the source of energy

The Sun, a G-type main-sequence star, is the dominant source of energy for the Solar System. Its immense power comes from **nuclear reactions** occurring in its core, which release vast amounts of energy as light, heat, and particles. A portion of this energy is carried into space as the **solar wind**—a stream of charged particles that permeates the heliosphere.

1. Nuclear Reactions: The Core Energy Mechanism of the Sun

A. Stellar Nucleosynthesis in the Sun's Core

1. **The Sun as a Plasma Reactor**
   - The Sun's core, spanning about 25% of its radius, operates as a thermonuclear reactor.
   - Plasma, a state of matter where electrons are stripped from nuclei, facilitates the fusion process under extreme:
     - **Temperature**: ~15 million Kelvin.
     - **Pressure**: $\sim 3.5\times10^{11}$ Pascals (Pa).
     - **Density**: $\sim 150\ g/cm^3$.
2. **Gravitational Confinement**
   - The Sun's immense gravitational force compresses hydrogen nuclei (protons), overcoming their electrostatic repulsion (Coulomb barrier). This makes nuclear fusion possible.

B. Proton-Proton (p-p) Chain Fusion Process

The p-p chain is the dominant energy production mechanism in stars like the Sun. Let's detail its steps:

1. **Step 1: Proton Fusion to Form Deuterium**
   - Two protons collide at high speed. One proton undergoes a beta-plus decay:

$$p+p \rightarrow D+e^{+}+\nu_e$$

     - Produces: Deuterium (D, ^{2}H), a positron (e^{+}), and an electron neutrino (ν_e).
     - Energy released: ~0.42 MeV.
     - Timescale: ~10 billion years for a single proton to participate in fusion (statistical probability).
2. **Step 2: Formation of Helium-3**
   - The deuterium nucleus fuses with another proton:

$$D+p \rightarrow {}^{3}He+\gamma$$

     - Produces: Helium-3 (^{3}He) and a gamma photon (γ).
     - Energy released: ~5.49 MeV.
3. **Step 3: Helium-3 Fusion to Helium-4**
   - Two ^{3}He nuclei collide:

$${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$$

     - Produces: Helium-4 (^{4}He) and two protons.
     - Energy released: ~12.86 MeV.
4. **Net Energy Yield**:
   - Total energy released per cycle: ~26.7 MeV.
   - Efficiency: About 0.7% of hydrogen mass is converted into energy.

C. Transport of Energy to the Surface

The energy produced in the core travels outward through distinct layers:

1. **Radiative Zone (0.25–0.7 Solar Radius)**
   - Energy moves outward via **radiative diffusion**:
     - Photons are absorbed and re-emitted by plasma particles, taking millions of years to exit.
     - Photon "random walk" occurs due to high opacity.

2. **Convective Zone (Outer 30% of Radius)**
   - Convection currents transfer energy more efficiently.
   - Hot plasma rises, cools at the surface, and sinks back.
3. **Photosphere (Surface)**
   - Energy emerges as electromagnetic radiation, primarily visible light, infrared, and ultraviolet.
4. **Energy Output Metrics**:
   - Luminosity: ~3.846×10^{26} W.
   - Energy equivalent to converting ~4 million tons of mass into energy every second.

D. Fundamental Principles Supporting Fusion

1. **Quantum Tunneling**
   - Despite the Coulomb barrier, quantum tunneling allows nuclei to come close enough for the strong nuclear force to take over.
2. **Mass-Energy Equivalence**
   - Explained by Einstein's equation $E=mc^2$, the lost mass during fusion converts to energy.

2. Solar Wind: The Sun's Dynamic Particle Stream

The **solar wind** is the continuous stream of charged particles emitted by the Sun. It originates from the solar corona and extends through the Solar System, shaping its space environment.

A. Origin of Solar Wind

1. **The Corona**
   - The Sun's outer atmosphere (corona) reaches temperatures of ~10^6 K.
   - This extreme temperature imparts high kinetic energy to particles, allowing them to overcome the Sun's gravitational pull.
2. **Coronal Holes**
   - Regions of the corona with open magnetic field lines, allowing plasma to escape freely, are the main sources of **fast solar wind**.
3. **Energy Source**
   - Energy driving the solar wind comes from:
     - Magnetic reconnection in the corona.
     - Conversion of thermal and magnetic energy into particle kinetic energy.

B. Characteristics of the Solar Wind

1. **Components**:
   - **Protons** (~95%).
   - **Alpha Particles** (~4%).
   - **Electrons**.
   - Trace ions (e.g., oxygen, carbon).
2. **Speed**:
   - **Fast Solar Wind**: ~700–800 km/s.
   - **Slow Solar Wind**: ~300–500 km/s.
3. **Density**:
   - ~5 particles/cm³ near Earth.
4. **Temperature**:
   - Electrons: ~10^5 K.
   - Protons: ~10^4 K.

C. Propagation and Interaction

1. **Heliosphere**
   - The solar wind creates a protective bubble, the heliosphere, extending well beyond Pluto.
   - The termination shock marks where the solar wind slows down as it interacts with the interstellar medium.
2. **Effects on Planets**
   - Earth's **magnetosphere** deflects most solar wind particles, but some penetrate at the poles, creating auroras.
   - Stripping effects on Mars and Venus (lacking strong magnetic fields) have eroded their atmospheres.

D. Solar Wind Energy Dynamics

1. **Kinetic Energy of Particles**
   - Energy carried by the solar wind contributes to space weather phenomena.
2. **Magnetic Energy**
   - Embedded magnetic fields transport energy, which can reconnect and release explosive bursts (e.g., coronal mass ejections, CMEs).

3. Interconnection: Fusion and Solar Wind

The relationship between nuclear fusion and the solar wind is symbiotic:

1. **Fusion Energy Drives Coronal Heating**
   - Energy from the Sun’s core propagates outward, heating the corona to the temperatures needed to generate the solar wind.
2. **Magnetohydrodynamic (MHD) Waves**
   - Fusion-powered convection creates the Sun’s magnetic fields, which accelerate the solar wind through MHD phenomena.
3. **Energetic Feedback Loops**
   - Solar wind carries a fraction of the Sun’s energy into interplanetary space, influencing planetary systems and the interstellar environment.

4. Applications and Implications

1. **Solar Energy on Earth**
   - Studying fusion provides insights for harnessing clean energy on Earth.
   - Solar panels rely on electromagnetic radiation emitted by the Sun.
2. **Space Exploration**
   - Understanding solar wind helps design spacecraft capable of withstanding space weather.
3. **Planetary Protection**
   - Earth's magnetic field protects life by shielding the planet from the solar wind.