

Lecture 16

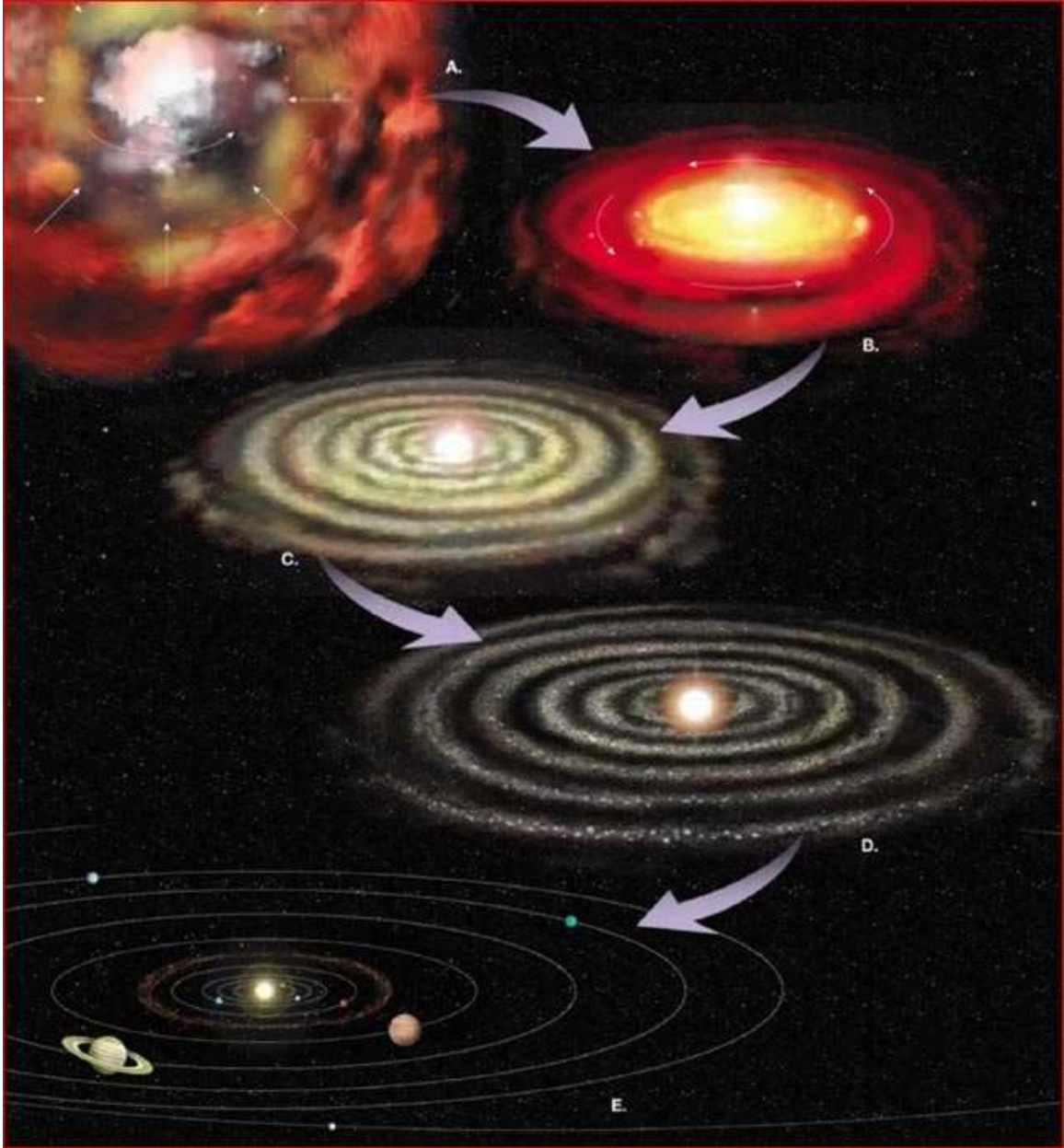
1. Formation of Solar System

The radioactive dating of meteorites says that the Sun, planets, moons, and solar system fluff formed about 4.6 billion years ago. What was it like then? How did the solar system form? There are some observed characteristics that any model of the solar system formation must explain.

Observables:

- 1) All the planets' orbits lie roughly in the same plane.
- 2) The Sun's rotational equator lies nearly in this plane.
- 3) Planetary orbits are slightly elliptical, very nearly circular.
- 4) The planets revolve in a west-to-east direction. The Sun rotates in the same west-to-east direction.
- 5) The planets differ in composition. Their composition varies roughly with distance from the Sun: dense, metal-rich planets are in the inner part and giant, hydrogen-rich planets are in the outer part.
- 6) Meteorites differ in chemical and geologic properties from the planets and the Moon.
- 7) The Sun and most of the planets rotate in the same west-to-east direction. Their obliquity (the tilt of their rotation axes with respect to their orbits) are small. Uranus and Venus are exceptions.
- 8) The rotation rates of the planets and asteroids are similar---5 to 15 hours, unless tides slow them down.
- 9) The planet distances from the Sun obey Bode's law---a *descriptive* law that has no theoretical justification. However, Neptune is a significant exception to Bode's "law".
- 10) Planet-satellite systems resemble the solar system.

The model that best explains the observed characteristics of the present-day solar system is called the *Condensation Model*. The solar system formed from a large gas nebula that had some dust grains in it. The nebula collapsed under its own gravity to form the Sun and planets. What triggered the initial collapse is not known. Two of the best candidates are a shock wave from a nearby supernova or from the passage through a spiral arm. The gas cloud that made our solar system was probably part of a large star formation cloud complex. The stars that formed in the vicinity of the Sun have long since scattered to other parts of the galactic disk. Other stars and planets in our galaxy form in the same basic way as will be described here. The figure below summarizes the basic features of the *Condensation Model*.



2. Condensation Model

1. A piece of a large cloud complex started to collapse about five billion years ago. The cloud complex had already been "polluted" with dust grains from previous generations of stars, so it was possible to form the rocky terrestrial planets. As the piece, called the *solar nebula* collapsed, its slight rotation increased. Centrifugal effects caused the outer parts of the nebula to flatten

into a disk, while the core of the solar nebula formed the Sun. The planets formed from material in the disk and the Sun was at the center of the disk.

2. Most of the gas molecules and dust grains moved in circular orbits. Those on noncircular orbits collided with other particles, so eventually the noncircular motions were dampened out. The large scale motion in the disk material was parallel, circular orbits. As the solar nebula collapsed, the gas and dust heated up through collisions among the particles. The solar nebula heated up to around 3000 K so everything was in a gaseous form. The solar nebula's composition was similar to the present-day Sun's composition: about 93% hydrogen, 6% helium, and about 1% silicates and iron, and the density of the gas and dust increased toward the core. The inner, denser regions collapsed more quickly than the outer regions.
3. When the solar nebula stopped collapsing it began cooling, though the core forming the Sun remained hot. This meant that the outer parts of the solar nebula cooled off more than the inner parts closer to the hot proto-Sun. Only metal and rock materials could condense (solidify) at the high temperatures close to the proto-Sun. Therefore, the metal and rock materials could condense in all the places where the planets were forming. Volatile materials (like water, methane and ammonia) could only condense in the outer parts of the solar nebula.
4. Around Jupiter's distance from the proto-Sun the temperature was cool enough to freeze water (the so-called "snow line"). Further out from the proto-Sun, ammonia and methane were able to condense. There was a significant amount of water in the solar nebula. Because the density of the solar nebula material increased inward, there was more water at Jupiter's distance than at the distances of Saturn, Uranus, or Neptune. The greater amount of water *ice* at Jupiter's distance from the proto-Sun helped it grow larger than the other planets. Although, there was more water closer to the Sun than Jupiter, that water was too warm to condense.
5. Small eddies formed in the disk material, but since the gas and dust particles moved in almost parallel, near-circular orbits, they collided at low velocities. Instead of bouncing off each other or smashing each other, they were able to stick together through electrostatic forces to form *planetesimals*. The larger planetesimals were able to attract other planetesimals through gravity and increase in size. This process is called *accretion*. More massive planetesimals had stronger gravity and could pull in more of the surrounding solar nebula material. Some planetesimals formed mini-solar nebulae around them which would later form the moons. The Jupiter and Saturn planetesimals had a lot of water ice mass, so they swept up a lot of hydrogen and helium. The Uranus and Neptune planetesimals were smaller so they swept up less hydrogen and helium (there was also less to sweep up so far out). The inner planetesimals

were too small to attract the abundant hydrogen and helium. The small icy planetesimals near the forming Jupiter and Saturn were flung out of the solar system. Those near Uranus and Neptune were flung to very large orbits. This explains the Oort cloud. There was not enough material to form a large planet beyond Neptune. Also, accretion of material at these great distances progressed more slowly than material closer to the Sun. The icy planetesimals beyond Neptune formed the Kuiper Belt. The large planets were able to stir things up enough to send some of the icy material near them careening toward the terrestrial planets. The icy bodies gave water to the terrestrial planets.

6. The planets got big enough to retain heat and have liquid interiors. The heavier materials like iron and nickel sank to the planet cores while the lighter materials like silicates and gases rose toward the surface, in a process called *differentiation*. The sinking of the heavy material created more heat energy. The planets also had sufficient radioactive decays occurring in them to melt rocky material and keep it liquid in the interior. The small planetesimals that were not incorporated into the large planets did not undergo differentiation.
7. The proto-Sun had a magnetic field and spewed out ions. The ions were dragged along by the magnetic field that rotated with the proto-Sun. The dragging of the ions around slowed down the proto-Sun's rotation rate. Also, *accretion disks* like the solar nebula tend to transfer angular momentum outward as they transfer mass inward. This explains item (1) above.
8. Because of its great compression, the core of the proto-Sun core reached about 10 million Kelvin and the hydrogen nuclei started fusing together to produce helium nuclei and a lot of energy. The Sun "turned on." The Sun produced strong winds called *T-Tauri winds* that swept out the rest of the nebula that was not already incorporated into the planets. This whole process took just a few hundred million years and was finished by about 4.6 billion years ago.