Origin and Age of the Earth

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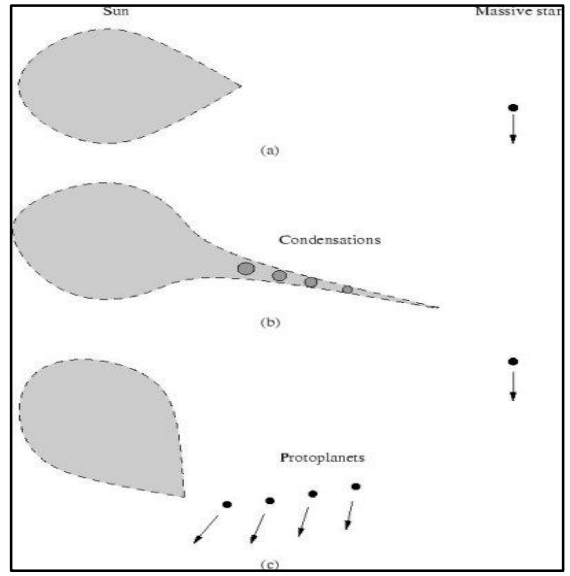
Origin of the Earth

The origin, evolution and development of the Earth is a journey that began around 14 billion years ago, with the formation of atoms and molecules shortly after the big bang. Those raw materials became the building blocks of stars, which in turn produced all of the elements that would form the Earth and other rocky planets.

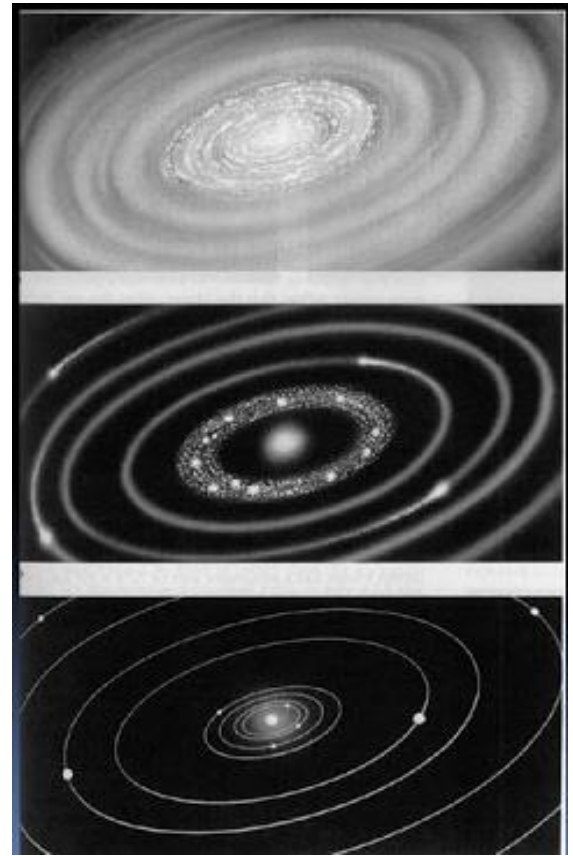
The Early Theories

- *Catastrophic Theory of Buffon*: George Buffon (1749) envisioned that a lonely Sun had a collision with a comet that came from the depth of interstellar space. The impact tore a number of '*drops*' from the Sun, which went spinning about the sun due to the gravitational attraction, and later condensed into planets.
- *Kant's Evolutionary Hypothesis*: Immanuel Kant (1755) visualized the early state of the sun as a giant, cool mass of gas (a *nebula*) rotating slowly around its axis. As the cloud condensed, the constancy of angular momentum would require it to increase the rotational speed. The increasing centrifugal force resulting from rapid rotation must have led to the progressive flattening of the gaseous body in the form of a disc. Secondary condensations formed in the disc and planets developed from these, whilst the primary condensation in the central region formed the Sun.
- *Kant-Laplace Hypothesis* (*also known as Nebular hypothesis*): According to Laplace (1796), the increase of rotational speed due to contraction of the nebular cloud would not only flatten it into a lens shape, but also eject a series of gaseous rings along its extended equator. These rings later condensed into planets circling at different distances around the Sun.
- *Jeans and Jeffreys tidal Hypothesis*: Jeans and Jeffries modified the earlier catastrophic theory by replacing the comet by a star which supposedly came very close to the Sun. Its gravitational pull and the consequent ***tidal force*** tore away parts of the sun's body like a ribbon. As the star went away from the sun, the ribbon-like structure went spinning round the sun, and slowly condensed to form the planets.

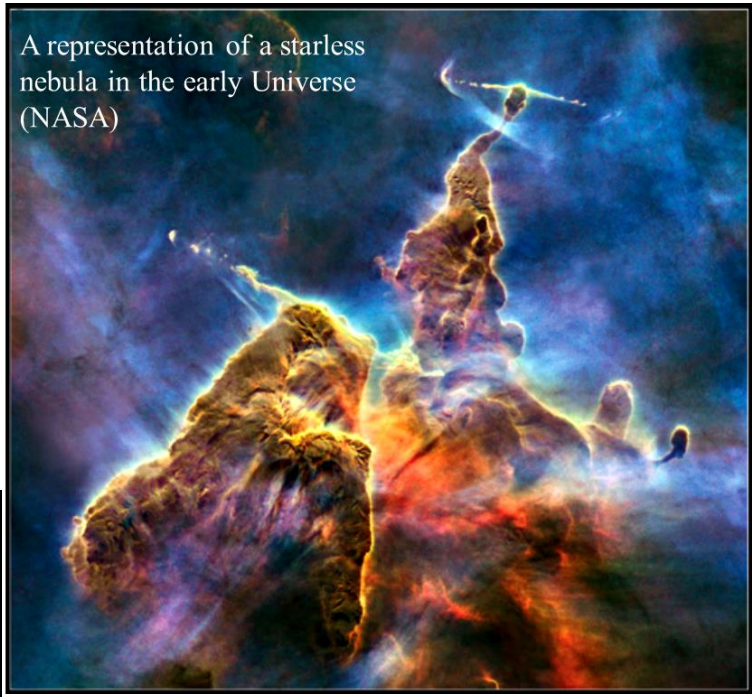
Jeans & Jeffreys Hypothesis



Kant-Laplace Hypothesis



Origin of the Earth

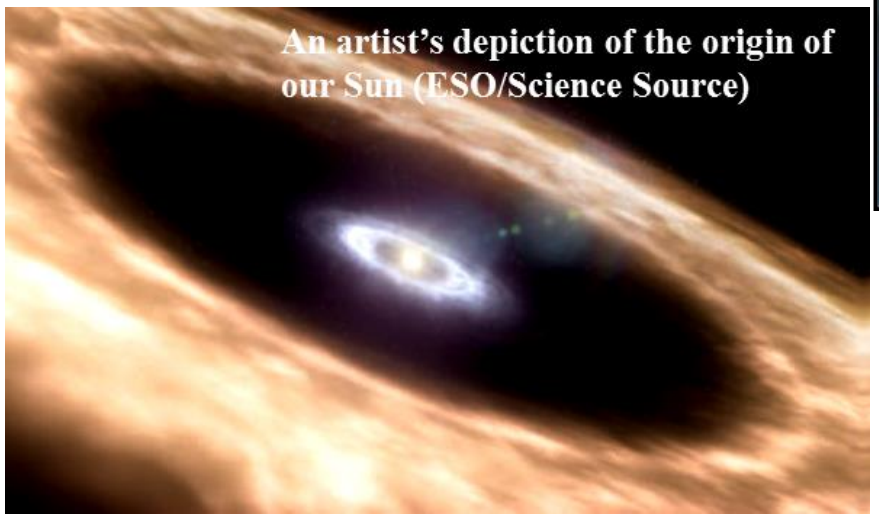

A representation of a starless nebula in the early Universe (NASA)

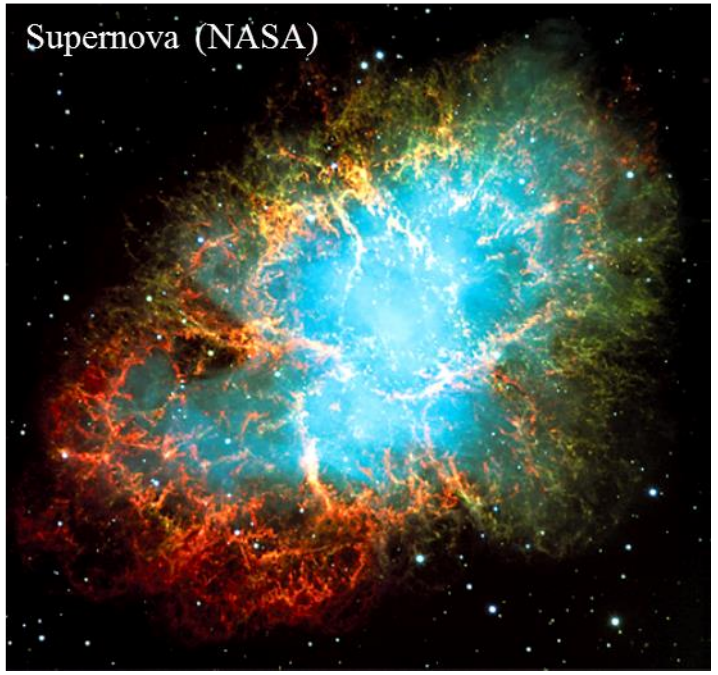
The Modern Theory: Nebular or Condensation Theory

The Sun, Earth and all other objects in the Solar System coalesced out of the same nebular cloud. According to the theory, the process of the Solar System formation begins when tiny ice and *dust particles* (specks of solids made of materials that do not evaporate easily) condense in a *nebula*.

1. Life of a Star

The life of a star begins when a diffuse area of a spinning nebula begins to shrink and heat up under the influence of its own weak gravity. Gradually, the cloudlike sphere flattens and condenses at the center into a knot of gases called a *protostar*. The gravitational contraction, and the compression raises its internal temperature. When the temperature of ~10 million degrees Celsius, nuclear fusion (that fuses H to He) begins. This rapid release of energy marks the transition from protostar to star.


An artist's depiction of the origin of our Sun (ESO/Science Source)

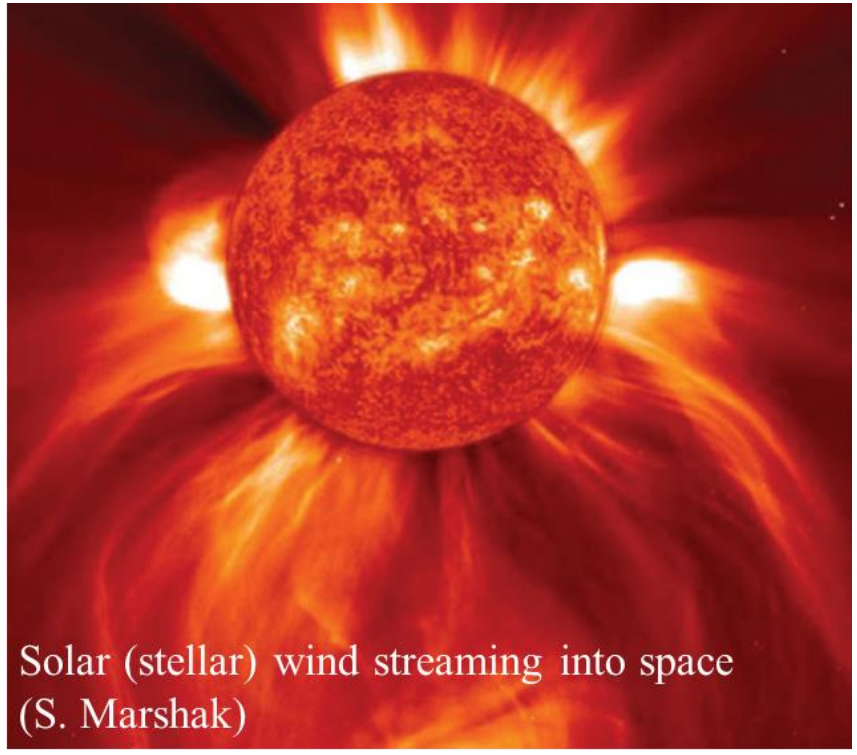

Supernova (NASA)

2. Death of a Star

Stars die due to depletion of the hydrogen fuel. When no more H is left to fuse, the high mass star collapses and heats up internally. This causes violent explosion and the star is blown to dust, thus forming **supernova**. At such ultrahigh temperatures, otherwise repulsive atoms fall in a celestial embrace to form atoms of heavy elements. Most very large atoms (>26 atomic numbers) can form only at the ultrahigh temperatures that develop in a supernova explosion. The process of forming these larger, heavier atoms is, therefore, called *supernova nucleogenesis*. Due to this, stars are consider to be "*element factories*".

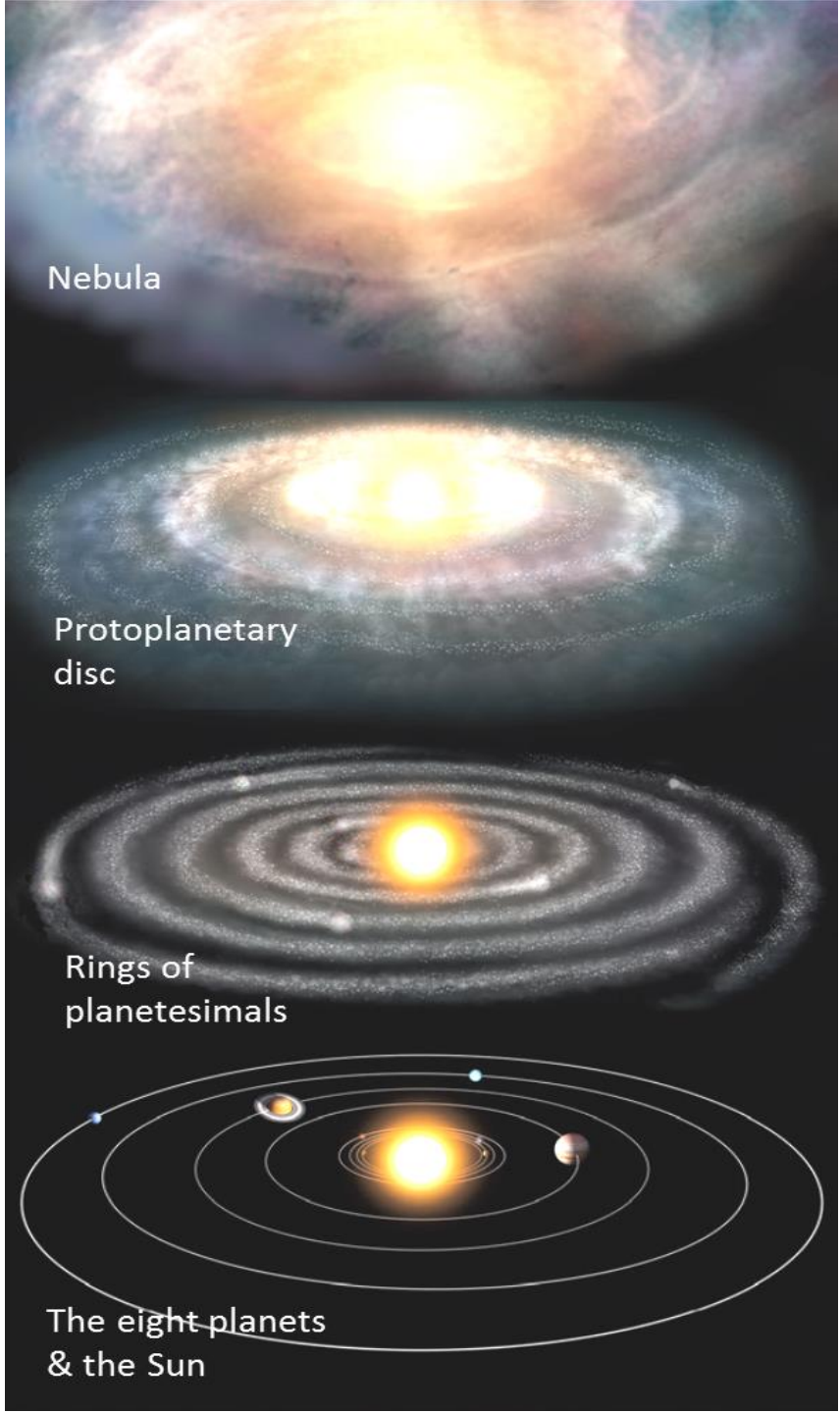
Formation of the Solar System

1. It all started from a great interstellar nebula. Hydrogen and helium formed much of its material, while the other heavier elements constituted only about 1% of its mass. At low temperature (beyond the *frost line*, from the center of nebula), the ***volatile compounds*** like hydrogen, helium, water, ammonia, carbon dioxide, methane etc., were in solid '*ice*' form. There were iron and silicates (***refractory material***) in the form of small solid grains or '*dust*'. The whole gas-ice-and-dust cloud was rotating slowly about an axis. At some point the nebula began to condense under its own gravity. Since angular momentum cannot change, as the nebula condensed, its rotational speed increased. This caused the nebula to take the shape of a flattened disc, called the *protoplanetary disc*. More mass accumulated near the centre and a compressed central part developed, which is termed as the *proto-sun.*



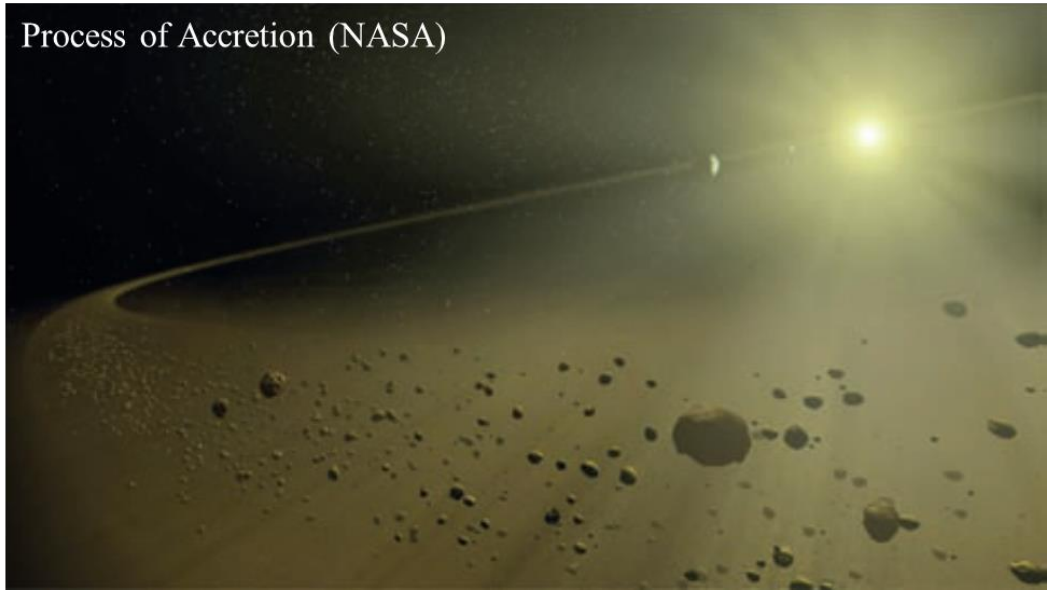
Solar (stellar) wind streaming into space (S. Marshak)

2. When the Sun became a nuclear inferno, the *solar wind* (the stellar wind produced by the Sun) evaporated volatile materials and blew them outward, to distances beyond the frost line. Consequently, the inner part of the protoplanetary disk ended up with higher concentrations of dust, whereas the outer portions ended up with higher concentrations of ice. As this was happening, gravity caused the gas, dust, and ice of the disk to separate into a series of concentric rings in which density exceeded that of the space between the rings.



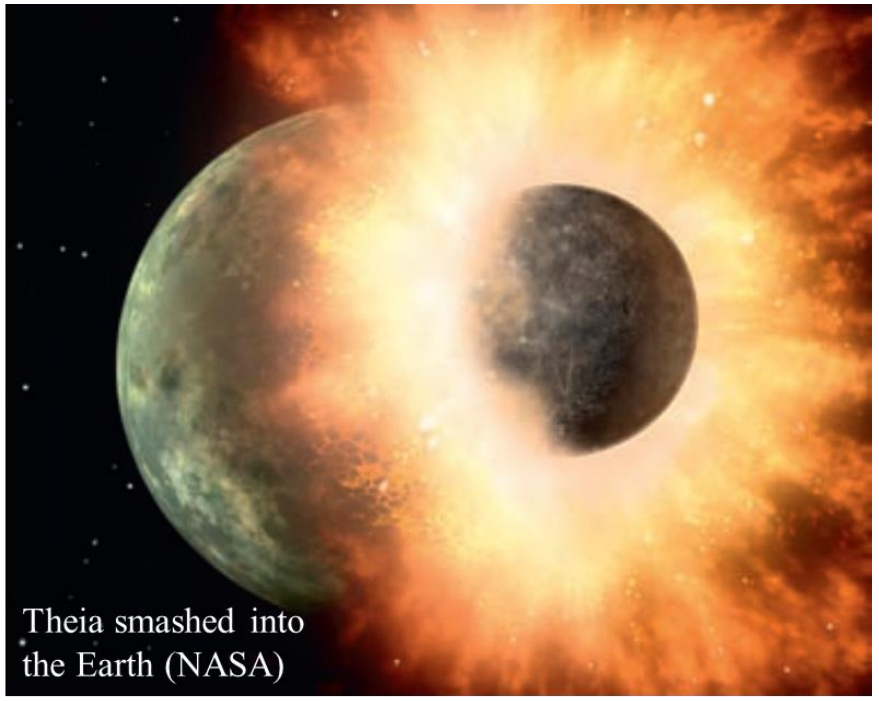
3. Transformation of dusty, icy, and gassy rings into planets (Accretion)

The material of the surrounding rings began to clump and bind together due to gravity. First, soot-sized particles merged into sand-sized grains. Then these grains stuck together to form grainy basketball-sized blocks, which in turn collided. Eventually, enough blocks coalesced to form planetesimals (solid bodies with diameter >1 km). Due to coalescing, planetesimals grew progressively larger—astronomers refer to this process of planetary growth as ***accretion***. Eventually, planetesimals grew into protoplanets (bodies approaching the size of today's inner planets) and once a protoplanet succeeded in incorporating virtually all the debris within its orbit, it became a full-fledged planet.


Process of Accretion (NASA)

4. Age of the Earth

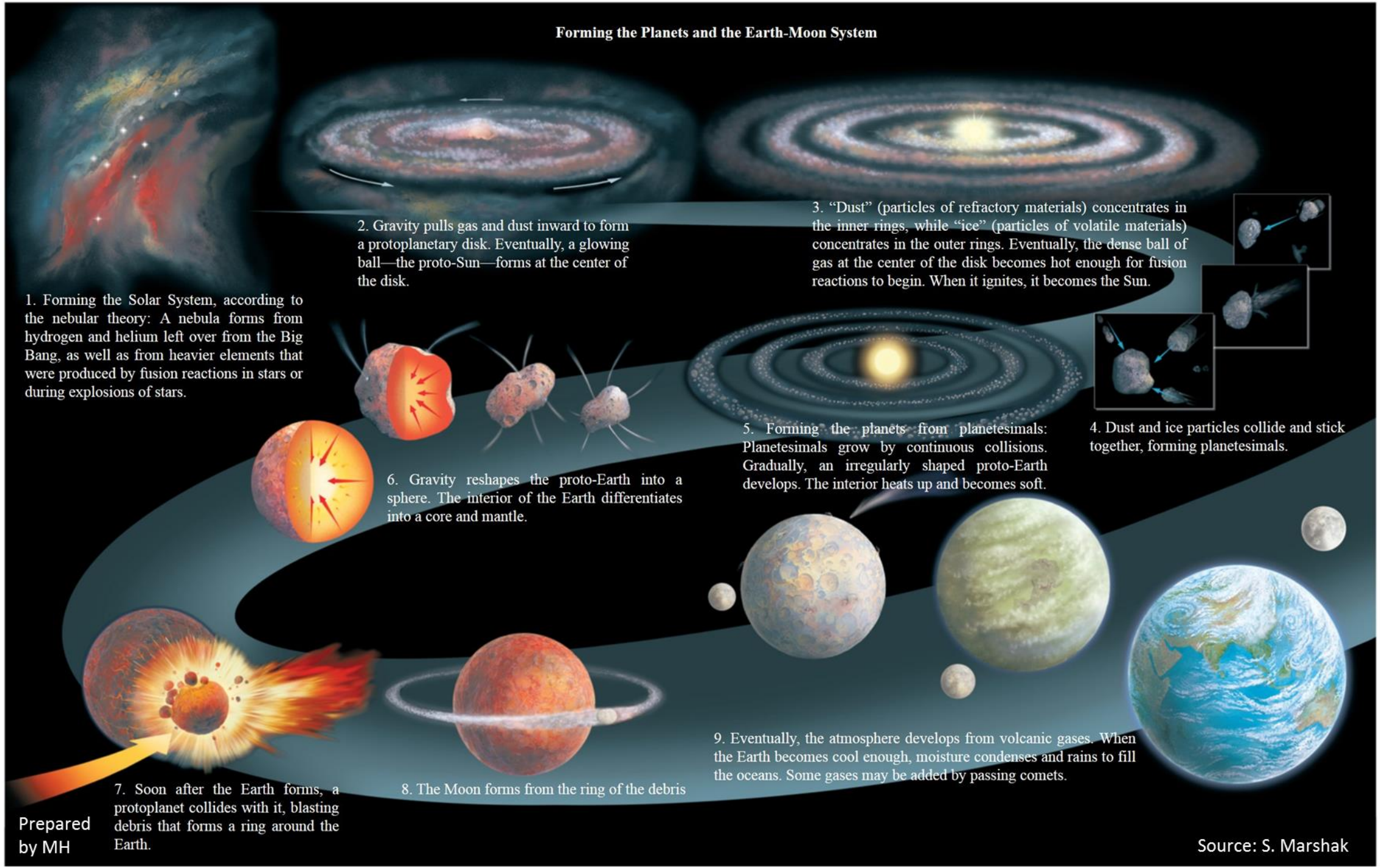
Rocks now exposed on the surface of the Earth are much younger than the Solar System. But certain *meteorites*, objects that have fallen to the Earth from space, appear to be leftover planetesimals. Using radiometric dating techniques, geologists have determined that some materials in these meteorites formed as long as 4.57 billion years ago (±0.5 billion years; inferred from the Canyon Diablo iron meteorite that impacted at the Barringer Crater, Arizona, USA), and consider that date to be the birth date of the Solar System. This date means that the Earth formed 4.57 billion years ago, about 9 billion years after the Big Bang.


Theia smashed into the Earth (NASA)

5. Formation of the Earth's Moon

Most geologists favor a model in which a particularly large collision between the Earth and a large planetesimal or protoplanet (named *Theia*) at about 4.5 Ga (Ga = billion year) produced our Moon. Moon formation happened because the collision was so cataclysmic that much of the colliding body disintegrated and evaporated, along with a large part of the Earth's mantle. A ring of debris formed around the remaining, now-molten Earth. This ring quickly coalesced by accretion to form the Moon.

Forming the Planets and the Earth-Moon System



1. Forming the Solar System, according to the nebular theory: A nebula forms from hydrogen and helium left over from the Big Bang, as well as from heavier elements that were produced by fusion reactions in stars or during explosions of stars.

2. Gravity pulls gas and dust inward to form a protoplanetary disk. Eventually, a glowing ball—the proto-Sun—forms at the center of the disk.

3. "Dust" (particles of refractory materials) concentrates in the inner rings, while "ice" (particles of volatile materials) concentrates in the outer rings. Eventually, the dense ball of gas at the center of the disk becomes hot enough for fusion reactions to begin. When it ignites, it becomes the Sun.

4. Dust and ice particles collide and stick together, forming planetesimals.

5. Forming the planets from planetesimals: Planetesimals grow by continuous collisions. Gradually, an irregularly shaped proto-Earth develops. The interior heats up and becomes soft.

6. Gravity reshapes the proto-Earth into a sphere. The interior of the Earth differentiates into a core and mantle.

7. Soon after the Earth forms, a protoplanet collides with it, blasting debris that forms a ring around the Earth.

8. The Moon forms from the ring of the debris

9. Eventually, the atmosphere develops from volcanic gases. When the Earth becomes cool enough, moisture condenses and rains to fill the oceans. Some gases may be added by passing comets.

Prepared by MH

Source: S. Marshak

Questions to Consider

1. How are the heaviest elements (uranium in nuclear reactor or gold in your ring) thought to be formed?
2. Why do the gas giant planets orbit farther from the Sun than the terrestrial planets?
3. How old is the Earth? How do we know?
4. Describe a process that may have produced the moon.
5. Why is the Earth round?

Suggested Readings: Earth – Portrait of a Planet by Stephen Marshak
Origin of the Solar System by Soumitro Banerjee
The Origin and Evolution of Earth by Robert Hazen