Cosmology and the Birth of Earth

Our Island in Space
- We pass our lives on our one planet Earth.
- Earth may seem endless; it isn’t.
- Viewed from space, Earth is a small, shiny globe.
- It is truly our island oasis in space.

Our Island in Space
- The Earth is a very special and unique planet.
  - Its temperature, composition and atmosphere favor life.
  - It is dynamic and ever-changing.
  - It has a long and complex history.

Cosmology
- Conscious thought distinguishes humans.
  - Developed across thousands of generations.
  - Lends us curiosity, insight, and the ability to learn.
- As a result, we seek to explain our surroundings.
  - Where do we come from?
  - Where do we fit in the Universe?
  - Why are we here?

Cosmology
- Study of the structure and evolution of the Universe.
- Cosmology is a complicated science.
  - Requires thinking in unfamiliar scales of space and time.
    - Spatial scales.
      - Attometers ($10^{-21}$ meters), to
      - 10s of billions of light years ($9.46 \times 10^{22}$ meters +).
    - Temporal scales.
      - Attoseconds ($10^{-21}$ seconds), to
      - 10s of billions of years ($3.15 \times 10^{17}$ seconds +).

Cosmology
- Ideas about the Universe have a rich history.
  - These ideas are often culturally determined.
  - Commonly include supernatural forces.
- The Western tradition applies scientific discovery.
Science
- The systematic analysis of natural phenomenon.
- Has evolved as the most significant human development for understanding the natural world.
- Rationally explains cosmological evolution.
- Scientific understanding can evolve and change.

An Evolving Image of Earth
- The ancients thought the Universe was geocentric.
  - Heavenly bodies circle around a motionless central Earth.
  - Proven by Ptolemy (100-170 C.E.), the idea was still wrong.
  - Yet it held as doctrine for 1,400 years during the dark ages.
  - It became religious dogma supporting the importance of Earth in the scheme of heaven.

The Enlightenment
- Sir Isaac Newton (1642-1727) devised...
  - The Law of Universal Gravitation.
  - The Three Laws of Motion.
  - The mathematics of change (calculus).
- He proved that natural law governs natural events.
- Geocentricity faded away.

Earth’s Changing Place
- 3,000 years ago, humans knew the heavens well.
  - They knew that stars were fixed relative to other stars.
  - They knew that stars moved predictably across the sky.
  - They saw retrograde motion separating planets from stars.
  - They did not think of Earth as a planet, however.
- Movement in the heavens was attributed to deities.

The Renaissance
- A rebirth of rational thinking in 15th-century Europe.
  - Copernicus – Published evidence for heliocentricity.
  - Kepler – His elliptical planetary orbits refuted Ptolemy.
  - Galileo – Observed moons orbiting Jupiter.
- These ideas were considered to be heresy.
  - Earth didn’t center the Universe.
  - Planetary orbits weren’t circular.
  - Not all bodies orbited Earth.

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Earth as a Sphere
- A flat Earth was dispelled by ~ 250 B.C.E.
- Abundant evidence suggested a spherical Earth.
  - A curved shadow crossed the Moon during eclipses.
  - Only the tops of distant sailing ships were visible.
- In 1520, Magellan circumnavigated this sphere.
Current concepts differ wildly from 100 years ago. We must consider huge expanses of space and time.

How do we know that Earth rotates about Polaris?
- Clearly visible in a time-lapse photograph of the night sky.
- Foucault’s pendulum (1851) proved Earth’s rotation.

The dimensions of the Universe are staggering!
- The speed of light \( c \) is 186,000 miles/s (300,000 km/s).
  - The Moon is 1.3 light seconds (~237,000 miles) away.
  - The Sun is 8.3 light minutes (~93 million miles) away.
- A light year measures a distance of 5.87 trillion miles.
- Alpha Centauri, the closest star, is 4.3 light years away.
- The end of visible Universe is > 13 billion light years away.

Eratosthenes calculated ~25,000 miles in ~ 200 B.C.E.
- He measured shadows in deep wells 800 km apart.
- Measurement taken at noon on the same day.
- Syene – Shadow absent (directly overhead).
- Alexandria – Shadow at 7.2°.
- He calculated that 800 km was 1/50th of Earth’s circumference.
- He was correct!!

Modern View of the Universe
- Current concepts differ wildly from 100 years ago.
  - Earth is one of nine planets in the solar system.
  - The solar system is on an arm of the Milky Way galaxy.
  - Our Sun is one of 300 billion stars in this galaxy.

The Doppler Effect permits us to detect star motion.

Science is the basis for addressing hard questions.
- How did the Universe form?
- Do galaxies move with respect to each other?
- Is the Universe expanding? Contracting?
- How do we know anything about these matters?
- The Doppler Effect permits us to detect star motion.
When did the expanding Universe begin?
- The best answer so far? The big bang.
- All of the mass and energy in the Universe was packed into a single small point.
- It exploded 13.7 Ga and has been expanding ever since.
**Big Bang**
- Rooted in the Laws of Physics.
- Started as a rapid cascade of events.
  - Protons and neutrons formed within 1 second.
  - Hydrogen atoms formed within 3 minutes.
  - Hydrogen fused to form new light elements (He, Be, Li, B) via big bang nucleosynthesis.
  - The Universe continued to...
    - Expand.
    - Cool.
    - Decrease in density.

**After the Big Bang**
- With expansion and cooling, atoms began to bond.
  - Hydrogen formed H₂ molecules - the fuel of stars.
  - Atoms and molecules coalesced into gaseous nebulae.
  - Gravity caused collapse of gaseous nebulae.
  - Collapse resulted in increases in...
    - Temperature.
    - Density.
    - Rate of rotation.

**Nucleosynthesis**
- The mass of a star governs its element production.
  - Smaller-mass stars (like the Sun).
    - "Burn" slowly.
    - Live longer (10 Ga).
    - Create lighter elements up to carbon (C).
  - Larger-mass stars (10-100x the mass of the Sun).
    - "Burn" rapidly.
    - Are shorter lived (10s of Ma).
    - Create heavier elements up to iron (Fe).

**Nucleosynthesis**
- Stars are truly "element factories."
  - Big bang nucleosynthesis formed lighter elements.
  - Atomic #s 1, 2, 3, 4 and 5 (H, He, Li, Be, and B).
  - Heavier elements are from stellar nucleosynthesis.
  - Atomic #s 6 - 26 (C to Fe).
  - Elements with atomic #s > 26 form during supernovae.

**Nucleosynthesis**
- When fuel dwindles, stars heat by inward collapse.
  - This leads to a cataclysmic explosion (a supernova).
  - The supernova creates heavier elements.
    - Uranium (atomic # 92) is the heaviest natural element.
Earth: Portrait of a Planet, 3rd edition
2008, by Stephen Marshak
© W. W. Norton & Company

The Solar System
- Our solar system also includes...
  - The Sun – An average star.
  - Asteroids – Rocky or metallic fragments.
  - Comets – Fragments of ice orbiting the Sun.
  - Kuiper Belt and Oort Belt objects.

The Planets: An Overview
- Two groups of planets occur in the solar system.
  - Terrestrial (Earth-like) - Small, dense, rocky planets.
    - Mercury, Venus, Earth, and Mars.
  - Jovian (Jupiter-like) - Large, low-density, gas-giant planets.
    - Jupiter, Saturn, Uranus, and Neptune.

Solar System Formation
- The ball at the center grows dense and hot.
- Fusion reactions begin; the Sun is born.
- Dust in the rings condenses into particles.
- Particles coalesce to form planetesimals.

The Solar System
- Earth shares the solar system with 7 other planets.
  - Planet – A precise definition developed in 2006. A planet...
    - Is a large solid body orbiting a star (e.g., the Sun).
    - Has a nearly spherical shape.
    - Has cleared its neighborhood of other objects.
    - Thus, Pluto, previously defined as a planet, is excluded.
  - Moon – A solid body locked in orbit around a planet.

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Planetary systems have been found near other stars.

Solar System Formation
- A 3rd, 4th or n-th generation nebula forms 4.56 Ga.
  - Hydrogen and helium left over from the big bang.
  - Heavier elements produced by stellar fusion and supernovae.
  - The nebula condenses into an accretion disc.

The Solar System
- The interior differentiates into...
  - a stony (silicate) mantle.
  - a nickel-iron core, and

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Solar System Formation
- Planetesimals accumulate into a larger mass.
- An irregularly-shaped proto-Earth develops.
  - The interior heats and becomes soft.
  - Gravity shapes the Earth into a sphere.
  - The interior differentiates into...
    - a nickel-iron core, and
    - a stony (silicate) mantle.
Soon, a small planetoid collides with Earth.

Debris forms a ring around the Earth.

The debris coalesces and forms the Moon.

The atmosphere develops from volcanic gases.

When the Earth becomes cool enough, moisture condenses and accumulates, and the oceans are born.

The Nebular Theory of Solar System Formation is supported by the configuration of planets.

The orbital planes of the planets lie within 3° of the Sun’s equator.