Astronomy 5 Notes

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1 Lecture 2

1.1 Biology

Definition. *Biology*
Biology is the study of the formation and evolution of life.

- Planetary science and astronomy yield context for life.
- Biological research is limited to Earth-based life, yielding poor context for possibilities of universal life.
- Understanding the conditions that led to life on Earth helps us identify potential locations for extraterrestrial life.

1.2 The Human Adventure

- The development of Astronomy is deeply intertwined with the development of civilisation and changes in society.
- Revolutions in astronomy have gone hand in hand with giant leaps in technology and science.
- Astronomy is the science that asks the deep question about the origins of humanity.

1.3 Modern View of the Universe

- What is our physical place in the universe?
- What is known about planets, stars, galaxies, space and time?
- How do we know what we know?

1.4 Universal Objects

Definition. *Star*
A *star* is a large, glowing ball of mostly hydrogen gas that generated heat and light by nuclear fusion. Larger stars generally have shorter lifespans.

Note. Hydrogen is the lightest and most abundant element in the universe.

Definition. *Planet*
A *planet* is a moderately large object which orbits a star; it shines by reflected light. They may be rocky, icy, or gaseous in composition.

Pluto and the family of objects beyond Neptune are now called "dwarf planets".

Definition. *Moon*
A *moon* is an object which orbits a planet—may also be referred to as a *satellite*.

Definition. *Asteroid*
An *asteroid* is a relatively small and rocky object which orbits a star. They usually do not have the mass (and thus the gravity) to be spherical in shape.

Definition. *Comet*
Comets are icy dust balls that get vaporised when they get too close to a star, leaving a bright trail in the sky. They usually originate outside the solar system.

Definition. *Solar (Star) System*
A star and all the material that orbits it, including planets, asteroids and comets, and all the moons that orbit those planets.

Definition. *Nebula*
A *nebula* is a cloud of gas that is gravitationally attracted to itself, and will eventually become a star (system). Like most things, it is mostly composed of hydrogen, but also contains small solid particulates of carbon and silicon.

Definition. *Galaxy*
An enormous "island of stars" far out in space, all held together by gravity and orbiting a common centre.

Definition. *Universe*
The sum total of all matter and energy; that is, everything within and between all galaxies.

Definition. *Astronomical Unit*
The (average) distance from the Earth to the Sun is 150 million km or 93 million miles, and is called an *astronomical unit*.

Definition. *Atom*
Atoms are the microscopic "building blocks" of all chemical elements—92 of which occur in nature.

1.5 Where Do We Come From?

- The first (and simplest) atoms (hydrogen and helium) were created during the *Big Bang*.
- More complex atoms (like carbon and oxygen) were created much later, inside stars.
- As stars age and die, they expel matter into space, which in turn forms new stars and planets.

1.6 Light is the Measure of All Things

- The speed of light is the absolute speed limit of the universe.
- As far as we know, there are no methods of travelling faster than light.

1.7 A Universe in Motion

- We are constantly moving in space—on "spaceship Earth". The earth rotates around its axis once per day, which results in a speed of around 1000 mph at the equator.

2 Lecture 3

The Earth is non-stationary—it is moving through space at extreme speeds. The universe is also expanding, and things are all getting further and further away from us. The reason that we aren't getting further and further away from the Earth is because gravity is usually enough to hold things together (when things are close enough).

Note. We are not in a particularly special place in the universe, nor are we at a special time.

2.1 Planetary Science

Definition. *Planetary Science*
Planetary science is the study of the creation and evolution of planetary bodies, moons, asteroids, comets, etc.

Studying solar system bodies investigates why life formed on some worlds, and not others.

- All the planets orbit the Sun in elliptic paths, all in the same plane.
- The tilt of the planet is the main reason for the seasons.

2.1.1 Annual Motion Definitions

Definition. *Ecliptic*
The *ecliptic* is the apparent path of the Sun through the sky.

Definition. *Equinox*
The *equinox* is where the ecliptic intersects the celestial equator.

Definition. *Solstice*
The *solstice* is where the ecliptic is farthest from the celestial equator.

Definition. *Zodiac*
The *zodiac* is the constellations which lie along the ecliptic.

2.2 The Parsec

Definition. *Parsec*
We define one *parsec* to be 3.26 light-years.

We can calculate the distance to a star by using the parallax effect, namely

$$\text{Distance in parsecs} = \frac{1}{\text{Parallax in seconds}}.$$

2.3 The Science of Astronomy

Copernicus proposed the heliocentric model in 1543, but his model was no more accurate than geocentric models, because he used perfect circles for the orbits. Tycho Brahe tried, but failed, to detect stellar parallax, so he thought Earth was at the centre of the solar system and other planets went around the Sun. He would go on to hire Johannes Kepler, who used Tycho's observations to discover the *truth* of planetary motion. Johannes Kepler first tried to use circular orbits, but a discrepancy led him to propose elliptical orbits.

2.4 Kepler's Laws

1. The orbit of each planet around the Sun is an ellipse.
2. As a planet moves around its orbit, it sweeps out *equal areas in equal times*.

> **Note.** Planets move *faster* the closer they are to the Sun.

3. More distant planets orbit the Sun at slower *average* speeds, obeying the relationship

$$p^2 = a^3,$$

where p is the orbital period (in years) and a is the average distance from the Sun (in AU).

2.5 Galileo Discoveries

- Galileo showed that objects will stay in motion unless a force acts on them to slow them down.
- Galileo proved that there are imperfections on the celestial bodies: sunspots on the Sun, craters on the moon, etc.
- Galileo proved that stars are much further than Tycho thought, so the undetectable parallax was justified.
- There are objects that do not orbit the Earth (the moons of Jupiter).
- By observing the phases of Venus, he showed that Venus does not orbit the Earth.

2.6 Hallmarks of Science

1. Modern science seeks explanations for observed phenomena that rely solely on *natural* causes.
2. Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.
3. A scientific model must make *testable predictions* about natural phenomena that would force us to revise/abandon the model if it does not agree with observations.

> **Definition.** *Scientific Theory*
> A *scientific theory* must:
>
> - Explain a wide variety of observations with a few simple principles.
> - Must be supported by a large, compelling body of evidence.
> - Must not have failed any crucial test of its validity.

3 Lecture 4

3.1 Describing Motion

Definition. *Kinematics*
We define *speed* to be the rate at which an object moves, given by

$$\text{speed} = \frac{\text{distance}}{\text{time}}.$$

Velocity is similar to speed, but also has a direction. *Acceleration* is *any* change in velocity (magnitude or direction). Both velocity and acceleration have magnitude and direction, so they are *vectors*.

3.2 Acceleration Due to Gravity

All falling objects near the Earth's surface accelerate at the *same* rate, independent of the mass of each object. On Earth, this has the value 9.8 m/s^2.

3.3 Momentum and Force

Linear momentum is given by the mass of an object times the velocity of that object, or

$$p = m \cdot v.$$

Newton found that a net force changes momentum. The difference between mass and weight is that mass is the amount of matter in an object, whereas weight is the force that acts upon an object.

3.4 Newton's Laws of Motion

Newton realised that the same physical laws that operate on Earth also operate in outer space.

1. An object moves at a constant velocity unless a net force acts to change its speed or direction.
2. Force is mass times acceleration, or $F = ma$. In other words, force is the rate of change of momentum: $F = \frac{\mathrm{d}p}{\mathrm{d}t}$.
3. Every force has an equal and opposite reaction force.

Note. Reaction forces act upon different objects.

3.5 The Gravitational Force

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the square of the distance between their centres.

This is given by the equation

$$F_g = G\frac{M_1 M_2}{d^2},$$

where G is a constant.

3.6 “Conservation” Laws

There are three important conservation laws:

- Conservation of linear momentum (mv)
- Conservation of angular momentum (mvr)
- Conservation of energy

The conservation of angular momentum is the reason why planets move slowly the further away they are from the Sun, and faster when they are closer. It is also the reason why clouds of gas (large r) eventually contract into spinning disks (smaller r).

3.6.1 Energy

- Energy makes matter move.
- Energy is conserved, but it can transfer from one object to another and change in form.
- All energy can be traced back to the Big Bang.

3.6.2 Types of Energy

- Kinetic Energy (motion) is given by the equation: $K.E. = \frac{1}{2}mv^2$.
- Radiative (light).
- Potential (or stored).

Energy is measured in Joules, and power is measured in Joules per second, or Watts.

3.6.3 Thermal Energy

Thermal energy is a sub-type of kinetic energy—the collective *kinetic energy* of many particles. It is related to temperature, but *not* the same. Temperature is the *average* kinetic energy of the many particles in a substance, not the sum.

> **Note.** Absolute zero is the temperature when particles stop moving.

3.6.4 Gravitational Potential Energy

On Earth, it depends on the mass of an object (m), the strength of gravity (g), and the distance an object could potentially fall (h). Thus the gravitational potential energy is given by $U_g = mgh$.

3.7 Mass-Energy

Mass itself is a form of energy, given by $E = mc^2$, where c is the speed of light.

- A small amount of mass can release a lot of energy.
- Concentrated energy can spontaneously turn into particles, for example particle accelerators.

4 Lecture 5

4.1 Formation of the Solar System

An object's orbit cannot change spontaneously—it can only change if it gains or loses *orbital energy*, the sum of kinetic and gravitational potential energy.

4.1.1 Kepler and Newton

Kepler's first two laws apply to *all* orbiting objects, not just planets. In addition to being elliptic (bound paths), orbits can be unbound (hyperbolic or parabolic). Newton's Law of gravity permits all of these orbits.

Newton generalised Kepler's Third Law, observing that:

If a small object orbits a larger one, and if you measure the smaller object's orbital period and average orbital radius, then you can calculate the mass of the larger object. This is given by the equation:

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3,$$

where p is the orbital period, a is the average orbital distance (between centres), and $M_1 + M_2$ is the sum of the object masses.

Example. *Kepler's Third Law (Generalised)*

- You can calculate the mass of the Sun from the Earth's orbital period and average distance (1 year and 1 AU, respectively).
- You can calculate the mass of Earth from the orbital period and average distance of *any* orbiting satellite, including the Moon.
- You can calculate the mass of Jupiter from the orbital period and orbital radius of any one of Jupiter's moons.

4.1.2 Changing an Orbit

Conservation of angular momentum holds, always—orbits change either due to friction or gravitational encounters with another object.

Definition. *Escape Velocity*
If an object gains enough orbital energy, it may *escape* (change from a bound to an unbound orbit). For the Moon, this *escape velocity* is about 2 km/sec, for Mars it is about 5 km/sec, and for the Earth, it's about 11.1 km/sec.

Note. Escape velocity depends on the mass of the Earth, not the mass of the object.

4.2 A Brief Tour of the Solar System

The planets are tiny in comparison to the Sun and the solar system is mostly empty space in between planetary orbits.

4.2.1 The Sun

- Contains over 99.8% of the solar system's mass.
- Made mostly of *ionized* Hydrogen and Helium gas (plasma).
- Converts 4 million tons of mass into energy each second.

- Its radius is 696000 km, approximately 108 times the radius of the Earth.

4.2.2 Mercury

- Made of metal and rock; large *iron* core.
- Desolate, cratered like our Moon; long, tall, steep cliffs.
- Temperatures fluctuate drastically: from 425°C (day) to −170°C (night)

4.2.3 Venus

- Nearly identical in size to Earth; surface hidden by thick clouds.
- Hellish conditions due to an extreme *greenhouse effect*.
- Even hotter than Mercury: 470°, both day and night.
- Atmospheric pressure is equivalent to 1 km depth in Earth's oceans.
- No oxygen, no water.
- Venus may have been habitable (had liquid water) for 3 billion years.

4.2.4 Earth

- An oasis of life; bio-generated oxygen in the atmosphere.
- The only planet with liquid water in the solar system; about 3/4 of our surface is covered in water.
- A surprisingly large moon (1/4 radius, 1/80 mass).

4.2.5 Mars

- Giant volcanoes, a huge canyon, polar caps, and more.
- Water flowed in the distant past; could there have been life?
- Thin atmosphere of carbon dioxide.
- Water probably flowed; surface habitable; 1 billion years.

4.2.6 Jupiter

- Much farther from the Sun than the inner planets (5.2 AU).
- Very different composition—A large gas ball composed mostly of Hydrogen and Helium.
- No solid surface.
- Huge: 318 times Earth's mass and over 1000 times Earth's volume.
- Many moons and rings.

Moons of Jupiter

- Io: Yellowish, with active volcanoes all over.
- *Europa: Possible subsurface ocean; possible place to search for life.*
- Ganymede: Largest moon in the solar system—larger than Mercury.
- Callisto: a large, cratered "ice ball" with unexplained surface features.

4.2.7 Saturn

- Giant and gaseous like Jupiter.
- Most spectacular rings of the 4 jovian planets.
- Many moons, including cloudy Titan.
- *Enceladus has a warm, salty ocean.*
- The **Cassini** spacecraft spent 10 years studying Saturn.

4.2.8 Uranus

- Smaller than Jupiter or Saturn, but still much larger than Earth (4x).
- Made of Hydrogen and Helium gas, and hydrogen compounds (H_2O, NH_3, CH_4).
- Extreme axis tilt—nearly tipped on its "side". This causes extreme seasons during its 84 year orbit.
- It has moons and rings.

4.2.9 Neptune

- Similar to Uranus (except for the axis tilt).
- Many moons, including unusual Triton (it orbits "backwards").
- Triton is larger than Pluto.

4.2.10 Pluto and the Other Dwarf Planets

- Much smaller than other planets (0.18 Earth's radius).
- Icy, comet-like composition.
- Pluto's largest moon (Charon) is similar in size to Pluto itself.

In January 2006, the New Horizons probe was sent to investigate Pluto. It flew by Pluto on July 14, 2015. We now have incredible detail of Pluto's surface.

4.3 Clues to the Formation of the Solar System

- The Sun, planets, and large moons orbit and rotate in an organised way.
- There are two major planet types: small, rocky planets close to the Sun, and large, gaseous (jovial) planets further away from the Sun.

A successful theory of solar system formation must allow for exceptions to general rules, i.e.:

- Earth's relatively large moon.
- Uranus's odd tilt.

4.3.1 Nebular Theory

According to the *nebular theory*, our solar system formed from a giant cloud of interstellar gas which also contained tiny solid grains of heavier elements.

The conservation of angular momentum caused the gas cloud to rotate faster and faster as it shrank (due to gravity). The many particles in the cloud collided with each other, flattening the cloud.

4.3.2 The Formation of Planets

There are two types of planets because of temperature. Near the Sun, where it was extremely hot, only iron, nickel, and other heavy metals could condense out of the gas phase. Further away from the Sun, where it was cold, were the only regions where water, methane and ammonia to condense and make "ice". We call the border between these two areas the "frost line".

> **Definition.** *Planetesimals*
> Little pieces of matter that condensed out of the nebula.

> **Definition.** *Accretion*
> The assembly of planets from planetesimals due to gravity, with ice sticking pieces together, is called *accretion.*

> **Definition.** *Fragmentation*
> The process by which small, denser regions within the nebula can collapse more quickly than the rest.

There is further evidence for accretion:

- Asteroids are planetesimals that formed inside the frost line.
- Comets are planetesimals that formed outside the frost line.

Earth's moon was probably created when a large planetesimal crashed into the young Earth (nearly 4.5 billion years ago).

4.3.3 Finding the Age of the Solar System

We find the age of rocks that compose a planet via radioactive dating (which works by calculating the proportion of a radioactive isotope). Each radioactive isotope has a *half-life*, the time it takes for approximately half of the isotope to decay into something stable.

Using radioactive dating, we have found meteorites that are approximately 4.6 billion years old, which is also about the age of the Sun (found via separate analysis).

5 Lecture 6

5.1 Light

- Is both a particle and a wave.
- Massless.
- Has energy.
- Photon energy = h(frequency) = $\frac{hc}{\lambda} = h\nu$, where h is Planck's constant.
- Is oscillations of electric and magnetic waves.
- Light is produced when an electron is accelerated or oscillates.
- Electrons can absorb light, increasing their energy.

We can use the electron-volt (eV) to describe the energy of light. The electromagnetic spectrum, from highest to lowest energy: gamma, x-rays, ultraviolet, visible, infrared, microwaves, radio waves.

5.1.1 Composition of Matter

Electrons orbit the nucleus of an atom in an *electron cloud*. It is impossible to know exactly where an electron is and know its velocity. Electrons can only have set energy levels (quantized states).

5.1.2 Light and Matter

- Emission—Photons are produced.
- Absorption—Photons are consumed.
- Transmission—Photons pass through freely.
- Reflection or Scattering—Photons are redirected all in the same direction (reflection), or in random directions (scattering).

5.1.3 Three Types of Spectra

A *spectrum* is a plot of the intensity of light as a function of wavelength or energy. The laws of quantum physics tell us that energies in atoms are discrete, hence those lines. Distinct energy levels in atoms lead to distinct emission or absorption lines—photons are absorbed or emitted, moving electrons up or down an energy state.

Chemical Fingerprints

- Ever atom, ion, and molecule has a unique spectral "fingerprint" because of the unique set of electron energy level.
- This gives off a nique pattern of emitted or absorbed wavelengths of light.
- We can identify the chemicals in a gas cloud by looking at the absorption lines.

5.2 Thermal Radiation

- Nearly all large or dense objects emit thermal radiation.
- An object's thermal radiation spectrum depends on only one property—temperature.
- Electromagnetic radiation produced this way has a continuous spectrum of energy with a peak at one wavelength.

At low temperatures the emitted radiation is infrared, which our eyes cannot see. As heat increases, things turn blue-white.

5.2.1 Two Properties of Thermal Radiation

- Hotter objects emit more light at all frequencies *per unit area* (higher intensity).
  Stefan-Boltzmann Law: Luminosity per square metre = constant $\cdot T^4$.
- Hotter objects emit photons with a higher average energy.
  Wien's Law: $T(K) = \frac{3000000}{\lambda}$, where λ is the wavelength in nanometres.

Things to Know

- All objects emit a thermal spectrum.
- The shape of the spectrum is the same, but shifts to shorter wavelengths for hotter objects.
- The shape is *independent of the composition*.
- All stars can be considered to emit a thermal spectrum at a temperature T.

We can use light to tell us the *speed* of a distant object, using the Doppler Effect. The frequency changes when the source object is moving.

> **Note.** The Doppler Effect only tells us about the component of motion in our direction. If an object is moving perpendicular to the displacement vector to us, we detect no speed.

- Blueshift (shorter wavelength): motion towards you
- Redshift (longer wavelength): motion away from you
- Greater shift means greater speed

The luminosity (energy per second) passing through a given angular area is the same, regardless of how far away you are. Knowing this, and that the surface area of a sphere is $4\pi r^2$, we can see that the luminosity of an object is inversely proportional to square of the distance to the object.

> **Example.** *Light on Mars*
> Since Mars orbits around 1.5 AU away from the Sun, it gets around
>
> $$\left(\frac{1}{1.5}\right)^2 \approx 0.44$$
>
> the amount of light that the Earth gets.

5.3 Telescopes

- Telescopes collect more light than our eyes because they are bigger—more area to collect light.
- They can see more detail than our eyes because they provide magnification: angular resolution.
  The smallest detail you can see scales linearly with $\frac{\lambda}{D}$.
- A larger lens or shorter wavelength would allow for higher resolution.

The way that most telescopes work is either through refracting lenses or reflecting mirrors. Most research telescopes today use the latter. We put telescopes in space because that bypasses the absorption/distortion of light by Earth's atmosphere, and light pollution.
Interferometry allows two or more telescopes spread out over a large area to work together to obtain the angular resolution of a larger telescope (works well for radio astronomy).

6 Lecture 7

6.1 Geology

6.1.1 Earth and the Terrestrial Worlds

- Mercury has craters, smooth plains, and cliffs.
- Venus has volcanoes and a few craters. It is also extremely hot with a thick atmosphere.
- Mars has some craters, volcanoes, and potentially riverbeds. It is also freezing with a very thin atmosphere.
- The Earth has volcanoes, craters, mountains, and riverbeds. Earth is "just right".

Note. Mercury and Mars have much smaller mass than the Earth, while Venus is much more similar.

Note. The mass of a planet determines its long term ability to hold heat, and by extension whether it retains a heavy atmosphere. The mass of a planet and distance to the Sun are key.

6.1.2 The Evolution of the Solar System

- The Sun is powered by the fusion of Hydrogen into Helium.
- This process is stable over billions of years. However, as Helium builds up in the core of the Sun, it shrinks and heats—higher temperature increases nuclear fusion, making the sun brighter.
- The Earth's atmosphere has only become breathable to humans for a few hundred million years.
- Mars and Venus were once "habitable" worlds with thick atmospheres and flowing water on their surfaces.
  - Mars has cooled off, lacking a magnetic field and thick atmosphere.
  - Venus likely had 2-3 billion years of "comfortable" Earth-like conditions before entering the hellish, moist greenhouse phase.
  - Earth might have the same fate as Venus as little as 500 million years from now, due to the Sun's rising brightness from consumption of Hydrogen.

6.2 Earth as a Planet

6.2.1 Why is Earth Geologically Active?

The "lithosphere" is the cool rigid rock that forms a planet's outer layer: the crust and some of the mantle. From inner to outer, the layers of the Earth are:

- Core: Highest density, made of nickel and iron.
- Mantle: Moderate density, made of minerals with silicon, oxygen, etc.
- Crust: Lowest density, made of granite, basalt, etc.

Note. If the lithosphere is near the surface then the planet will be geologically active.

The internal heat of our planet comes from:

- Gravitational Potential Energy of accreting planetesimals colliding turns into heat.
- Differentiation (sinking of heavier elements adds heat).

- Radioactivity (emitted particles from radioactive atoms carry kinetic energy, which turns into heat upon collision).

Heat drives geological activity via convection currents (hot material rises, cool material falls). On Earth, one convection cycle takes 100 million years. Larger objects cool more slowly—Earth and Venus are active, whereas Mars and Mercury are not.

6.2.2 Geology and Life

There are three clues that we have for why Earth is habitable:

1. Volcanism—Releases trapped heat, gas, and material from deep within Earth.

2. Plate Tectonics—Plate tectonics continue to reshape Earth, consequentially regulating its climate.

3. Global Magnetic Field—Earth's magnetic field acts as a barrier that mitigates the loss of the atmosphere due to solar wind stripping.

6.2.3 What Processes Shape Earth's Surface?

Impact cratering shapes the surface of all terrestrial objects, but the Earth is protected by its atmosphere. Furthermore, the craters on the Earth are erased by erosion, volcanic activity, and plate tectonics.

Volcanoes erupt when there is a pressure build-up of gases inside it. Molten rock on the surface is called lava, and erases other geological features. Provided some of the water for our oceans.

> **Definition.** *Tectonics*
> Any surface reshaping from forces acting on the lithosphere.

> **Definition.** *Plate Tectonics*
> Pieces of the lithosphere moving around. Collisions of plates cause mountains to be built. Sideways motion of plates cause earthquakes.

> **Note.** Only Earth has plate tectonics.

Erosion is any weather-driven process that breaks down or transports rocks.

Small bacteria have caused our atmosphere to become rich with oxygen. Coal and oil has been deposited in the Earth from biological material. Humans have also had an enormous impact on the surface and climate.

To find the relative ages of fossils in sedimentary rock, we look at the layers (deeper means older). We can also get the absolute ages via radiometric dating.

6.2.4 How Does Earth's Atmosphere Affect the Planet?

> **Definition.** *Greenhouse Gas*
> Any gas that absorbs infrared light is a *greenhouse gas*.

- Molecules with two different elements—Carbon dioxide, water vapour, and methane are all examples of greenhouse gases.

- Diatomic elements or lone atoms are not greenhouse gases—O_2, N_2

- The Earth benefits from this effect to a certain extent. Too much and we turn into Venus.

Human activity has drastically increased the amount of greenhouse gases in the atmosphere, which has led to more global warming.

7 Lecture 8

7.1 The Nature of Life on Earth

7.1.1 Defining Life

In defining life, we look to six key properties shared by most or all living organisms on Earth.

1. Order
2. Reproduction
3. Growth and Development
4. Energy utilisation
5. Response to the environment
6. Evolutionary adaptation

7.1.2 Necessities of Life

- Nutrient source
- Energy (sunlight, chemical reactions, internal heat)
- Liquid water (or possibly some other liquid)

> **Note.** Finding liquid water is the hardest thing.

7.1.3 Order

> **Definition.** *Order*
> The idea that life tends to be non-random.

- Cells of different purpose and nature are spread throughout your body non-randomly, performing tasks in an ordered manner
- Order alone fails to categorise life, as order can be found in books, crystals, etc.
- Order is a *necessary but not sufficient condition for life*

7.1.4 Reproduction

- All life reproduce or are the product of reproduction

> **Definition.** *Reproduction*
> Cell division (almost exact copy) and sex (semi-random combination of genetic codes)

- Insufficient for life: a mule is sterile, but alive
- Viruses: incapable of reproduction on their own. They infect a host in order to reproduce

7.1.5 Grown and Development

- Similar to the idea of heredity, the passing of traits from parent to offspring, regardless of reproductive pathology
- Insufficient for life: Fire also "grows and develops"
- Heredity touches upon DNA, which might bring viruses and prions back into our "life" column, but they use RNA

7.1.6 Energy Utilisation

- First two laws of thermodynamics:
  - Any kind of energy can be turned into any other kind of energy.
  - There is always a cost to the first law.
- The second law also tells us about entropy; going from order to disorder
- If we place an organism in a sealed environment, it will use up all its energy and die
- Living organisms must have continual energy use to counter the effects of entropy
- Indefinite life without energy utilisation is impossible
- Insufficient for life: Any appliance at home uses energy to function
- Organisms obtain energy from the environment, which gets its energy from an internal or external source (i.e. heat of the planetary core or sunlight)

7.1.7 Response to Environment

- All life interacts with its surroundings
- Insufficient for life: A thermostat changes with its surroundings but is not alive

7.2 The Chemistry of Life

> **Note.** Life prefers carbon over silicon because the bonds in silicon are single bonds and weaker. Carbon-based molecules are also more versatile—they are gaseous in comparison to silicon, which is solid.

7.2.1 Proteins

Proteins are made from chains of amino acid monomers connected to form a polypeptide chain of monomers that fold.

- They can take the form of enzymes—catalysing or speeding up chemical reactions
- They can form the scaffolding and structure of tissue
- They can transport molecules to new locations
- Muscle contraction and cell motion
- Some hormones *are* proteins

> **Note.** Life only uses 20 amino acids to form all proteins.

7.2.2 Nucleic Acids

- DNA—Deoxyribonucleic acid, contains the genetic code
- RNA—Ribonucleic acid, active in the synthesis/transport of proteins

> **Note.** The failure of copying things perfectly results in mutations and evolution.

7.3 Mechanism of Evolution

Landmark work described by "two undeniable facts and an inescapable conclusion"

- Overproduction and competition for survival
- Individual variation

Conclusion: Unequal reproductive success: "survival of the fittest".

> **Note.** Humans have taken advantage of this by breeding many plants and animals into forms that very little resemble their wild ancestors.

7.4 Cells—The Basic Units of Life

- All living organisms are made of cells; the basic structure of life separated from one another via a membrane.
- The vast majority of organisms are single-celled.
- All cells share numerous similarities:
  - All pass hereditary information via DNA.
  - All have the same basic components for building cells.
  - All life is made from roughly 20 elements (96% of which are oxygen, carbon, hydrogen, nitrogen).

8 Lecture 9

8.1 History of Life on Earth

8.1.1 Major Groupings of Life

- Old idea: Major groupings of life fall to the kingdoms—animals, plants, protista, monera, and fungi.
- Modern theory: Superkingdoms or domains: bacteria, archaea, and eukarya. Bacteria and archaea consist almost entirely of microbes, whereas eukarya has multicellular life but also contains microbes.

8.1.2 Metabolism

- All cells use adenosine triphosphate (ATP) as the basic energy currency inside the cell.
- Humans and many life forms consume food for energy and carbon, but not all.
  - Heterotrophs get energy from their food.
  - Autotrophs get energy from their environment.

8.1.3 Liquid Water in Metabolism

1. Metabolism requires organic chemicals to be available for reactions. Water allows these chemicals to float within the cell.
2. Water transports chemicals to cells, and waste away from cells.
3. Water is necessary for reactions that store and release energy in ATP.

8.1.4 The Theory of Evolution

- The fossil record shows that evolution of species has occurred through time.
- Darwin's theory tells us *how* evolution occurs: through natural selection (via mutations).
- The fact that all DNA is made of more or less the same stuff suggests a common ancestry.

8.1.5 Life at the Extreme—Extremophiles

- Thermophiles live near volcanic vents, usually above the boiling point of water.
- Psychrophiles, or lovers of cold, usually live in Antarctica.
- Endoliths (within rocks) live several kilometres below the surface.

> **Definition.** *Convergent Evolution*
> Under comparable evolutionary pressures, evolution will take a comparable path.

8.2 Unique Features of Earth that are Important for Life

- Surface liquid water
- Plate tectonics
- Climate stability (greenhouse effect and plate tectonics)
- Atmospheric oxygen

8.2.1 Carbon Cycle

1. Atmospheric CO_2 dissolves in rainwater
2. Rain erodes minerals that flow into the ocean
3. Minerals combine with carbon to make rocks on the ocean floor
4. Subduction carries these carbonate rocks into the mantle
5. Rock melts in the mantle and releases CO_2 back into the atmosphere via volcanoes

8.2.2 Role of the Atmosphere

- Greenhouse effect stabilises the temperature
- Protects against radiation
- Provides water and life sustaining gases

8.2.3 When Did Life Arise on Earth?

- Life arose about 3.85 billion years ago, shortly after the period of heavy bombardment, which was about 4.2–3.9 billion years ago.
- Evidence from fossils and carbon isotopes.

> **Definition.** *Stromatolites*
> *Stromatolites* are ancient rocks that show structure similar to bacterial colonies today.

8.2.4 Origin of Life on Earth

- There is clear evidence that life *changes and evolves through time*
- There is clear evidence that life *shares a common ancestry*
- We may never know exactly how the first organism arose, but modern experiments suggest plausible scenarios

8.2.5 Brief Timeline

- 4.4 billion years ago—Early oceans form
- 3.5 billion years ago—Cyanobacteria start releasing oxygen
- 2.4 billion years ago—Great oxidation event (nearly all iron ore on Earth is formed at once)
- 2.0 billion years ago—Oxygen begins building up in the atmosphere
- 540–550 million years ago—Cambrian explosion
- 225–65 million years ago—Dinosaurs and small mammals (dinosaurs ruled)
- Few million years ago—Earliest hominids

9 Lecture 10

9.1 Searching for Life in our Solar System

9.1.1 Mass Extinctions

There are various dips in the total species diversity in the fossil record. The most recent was 65 million years ago, when the dinosaurs went extinct. The evidence of this is that all around the world, there is a thin layer of sediment that contains iridium. Below that layer, dinosaur fossils can be found. Above it, no dinosaur fossils are found.

> **Note.** Iridium is rare on Earth, but not that rare for asteroids.

> **Note.** Asteroids are darker than charcoal—visible light is horrible for finding them. Instead, we use infrared cameras to find thermal radiation. We can use this to find dangerous "city killers" and deflect them.

The larger the object, the less frequently the impact occurs. The 6^{th} extinction is already underway—the Anthropocene. We have already killed off many species via climate change.

9.1.2 The Building Blocks of Life

- Fundamentally requires 25 of the 92 natural elements
- 96% of biomass is hydrogen, oxygen, carbon, and nitrogen
- Life needs basic organic molecules to begin
- Observations show organic material covers the solar system

> **Note.** Energy decreases with the square of the distance (think Gaussian surface).

Life also requires a liquid, which plays roles such as being a solvent, transporting chemicals, and other important jobs.

9.1.3 Why Water?

1. Broad and high liquid range
2. Density of ice is less than density of water
3. Water is a polar molecule and so has Hydrogen bonds

> **Note.** The presence of water is usually the bottleneck for searching for life.

9.1.4 Calculating the Surface Temperature of a Planet

Planets radiate *thermal radiation*, given by

$$L = (4\pi R^2)(\sigma)T^4.$$

Furthermore, the more distant a planet is from the Sun, the less radiation it receives. Thus we have

$$T^4 = \frac{L}{4\pi R^2 \cdot \sigma},$$

where R is the planetary radius.

Note. Comets are extremely unlikely to contain life, because it is too cold for liquid water.

9.2 A Tour of the Solar System

- Probably no life on the Moon/Mercury, because it's too cold for liquid water.
- There could be life high in the Venusian atmosphere, where there are liquids. Venus has no tectonic activity, but is geologically active (volcanoes). Venus might have used to be habitable.
- Most of Earth's CO_2 is in (carbonate) rocks.
- Evidence that there used to be running water on Mars.
- Jupiter has a strong magnetic field generated by its convection layer of metallic Hydrogen. Both Jupiter and Saturn have massive vertical winds.
- Uranus and Neptune could have deep "oceans", but there's no way to explore this.
- The icy moons and dwarf planets in the Solar system could possibly contain life (Europa could have a subsurface ocean via tidal heating). Ceres has bright spots that could be water-rich.

9.2.1 Spacecraft Exploration

- Flyby—Cost-effective and practical
- Orbiter—More data from prolonged observations (can minimise cost with gravitational slingshots and aero braking)
- Landers/Probes—Direct measurements
- Sample return—Benefits of a lander/probe as well as large scale Earth facilities
- Tethered capture—For outer solar system? Avoids brief flyby

10 Lecture 11

10.1 Mars

- It would take a long time to get there because it is 1.5 AU away from the Sun (it would take a few years)
- You have little to no protection from radiation (little atmosphere)

10.1.1 Mars vs The Earth

- It has half Earth's radius and a tenth Earth's mass
- It gets 44% less heat/light
- The axis tilt is about the same as the Earth's—has seasons but the tilt is more variable
- Similar rotation period
- Orbit is more elliptical than the Earth's
- Very thin CO_2 atmosphere: little greenhouse effect
- Cold deser; red look due to soil color from oxidation
- The main difference is that *Mars is smaller*

Note. Because Mars is so small, it is not geologically active (because it is not hot enough).

10.1.2 Martian Seasons

- Martian axial tilt is 25 degrees compared to Earth's 23.5
- Mars' orbit is significantly more elliptical, which leads to more variable seasons
- Martian winters are cold enough to freeze a portion of the atmosphere
- Winds associated with cycling of carbon dioxide gas lead to large, sometimes global wind storms

10.1.3 Mars Today

- It has atmospheric CO_2 just like Venus, but 10000 times thinner
- Low atomspheric pressure causes water to sublimate

  Note. Liquid water cannot exist on Mars.

10.1.4 Features of Mars

- It seems to be split into Northern lowlands and Southern highlands
- The southern hemisphere seems more cratered (there is evidence of erosion in some craters)
- There are three regions of varying age on Mars

10.1.5 Martian Volcanism and Tectonics

- Evidence for Martian volcanism includes four massive volcanoes of the Tharsis Bulge
- Sedimentary walls are similar to the Grand canyon

10.1.6 Evidence for Ancient Water

- Orbital evidence—missions yield evidence of riverbeds
- Rover evidence—both orbiters and rovers have found hydrated minerals
- Phoenix lander found water ice on Mars

10.1.7 Evidence for Recent Water

- Dark streaks on crater walls seem to grow in the summer months
- All evidence points to a planet that was once much wetter and perhaps still contains water ice or subsurface liquid water

10.1.8 The Climate History of Mars

- Early Mars might have had a hot convecting core that would've protected it from the solar wind (too small to have a convection core)
- Mars' axial tilt could vary from 0 to as much as 60 degrees

10.1.9 The Viking Experiments

- Carbon assimilation experiment—mixed martian soil with CO_2 and CO to look for metabolic results (no indication of life)
- Gas exchange experiment—mixed martian soil with a nutrient "broth" (no indication of life)
- Labeled release experiment—mixed martian soil with a radioactive nutrient "broth" (expected signs of life)
- Gas chromatograph experiment—no organic material in martian soil

The results of these tests are inconclusive—more testing is needed.

> **Note.** We need to make sure that we don't contaminate Mars with Earth life.

There are four lines of evidence for life from ALH84001:

1. Layered carbonate grains similar to biological activity on EArth
2. Polycyclic aromatic hydrocarbonds produced by both living and non-living processes (high relative amounts)
3. Crystals match similar crystals on Earth produced by bacteria
4. Images of rod-shaped structures resemble fossilized bacteria

However, this is equally refuted by:

1. Non-biological mechanisms also produce these carbonates
2. PAHs are produced by both living and nonliving reactions
3. Similarities between crystals may be coincidence
4. These structures have also been seen on other meteorites and seem too small for RNA/DNA

10.1.10 Terraforming Mars

- In the future, it might be possible to make Mars habitable
- However, this is currently impractical, because the scale is too massive

11 Lecture 12

11.1 The Moons of the Outer Solar System

- In 1610, Galileo discovered four objects that were orbiting Jupiter
- Moons of Saturn, Uranus, and Neptune soon followed
- Jovian moons differ enormously in size, composition, density, atmospheres, and more
- Ganymede and Titan are larger than Mercury, while other moons are tiny misshapen mountains

11.1.1 What kinds of Moons orbit the Jovian Planets

- Medium and large moons probably formed at the same time as their planets
  - Enough self-gravity to be *spherical*
  - Are or were geologically active
  - Have substantial amounts of ice
  - Formed in orbit around Jovian planets
  - Circular orbits in the *same* direction as the planet rotation (likely due to accretion)
- Small moons are mostly *captured* asteroids and comets
  - Far more numerous than medium-large moons
  - Not spherical
  - Orbits can be tilted, elliptical, and even backwards

11.2 Galilean Moons

Note. They have very few craters and have white spots—they are geologically active.

- Io has active volcanoes (the most geologically active)
- Europa may have a subsurface ocean of warm water
- Ganymede and Callisto may also have subsurface oceans

Smaller worlds can be geologically active by *tidal heating*, where they are squished and stretched by their planet's gravitational pull. For example, Io and Europa are tidally heated.

11.2.1 Europa

- Energy source? Sun's energy is decreased due to distance
- Tidal energy and rock/water interface might fuel redox reactions and provide energy for 10^5 kg of biomass
- Pressure at the rocky bottom of the oceans likely are too high for cell walls to exist (much deeper than Earth)
- Radiation from Jupiter radiation belts might split molecules of water, enabling creation of OH and other energy-releasing chemical reactions
- This could bathe the upper few metres of water under the ice in nutrients; life protected from radiation at depths greater than 1 metre

11.2.2 Ganymede

- The largest moon in the solar system
- Clear evidence of geological activity
- Tidal heating not as effective, probably additional heat due to radioactive decay

11.2.3 Callisto

- "Classic" cratered ice ball
- Older surface
- No tidal heating, because no orbital resonance
- It has a magnetic field—often an indication of sub-surface water
- Could Jupiter have three water worlds?

11.3 Titan

- It is made of 90% nitrogen, the rest is argon, methane, ethane, and other hydrogen compounds
- Methane and ethane are greenhouse gases
- Chemical reactions on Titan could produce organic chemicals
- Methane rain
- Cassini/Huygens space mission (2005) gave us first look at Titan's surface (liquid methane lakes and "rocks" made of ice)

11.4 Neptune's Moon Triton

- Similar to Pluto, but larger
- Probably a captured object from the Kuiper belt (opposes Neptune's orbit)

12 Lecture 13

12.1 Life in the Solar System Beyond Earth

- Mars is the best place to search
- Water on Europa and Enceladus has been confirmed
- Various factors—chemical energy sources are questionable, high pressures at the base of Europa ocean make life questionable
- Venus' atmosphere or Jovian atmospheres?
- Titan is probably too cold to host life as we know it
- Life precursors like complex organics are identified in meteorites

We still don't know where life came from on Earth—we know that DNA is the basis for all life and undersea vents are a good place to start, but there is no consensus nor key evidence.

12.2 Searching for Past Life on Mars

1. Cameras will search for fossilized structures like stromatolites
2. Other instruments will measure composition of rocks and minerals
3. Samples will be cached and returned to Earth in the 2030s

12.2.1 Potential Problems

- Origin of Mars "blueberries"—hematite
- Does the hematite have a biological origin?
- Finding minerals that require water to form does not prove that life existed
- Organised structures can have a non-biological origin
- Sample return is the only certain way to search for life
- Potentially Martian meteorites as well

12.3 Habitable Zones

> **Definition.** *Habitable Zone*
> The range of distances at which worlds similar to Earth could exist.

- Existing within a star's habitable zone is insufficient
- Stars brighten as they age, shifting the habitable zone
- Whether a planet can possibly have water is dependent on the atmosphere

12.3.1 Life Outside the Habitable Zone

- In principle, life can exist outside the habitable zone
- Europa, Ganymede, and Enceladus provide us evidence of liquid water heated via non-solar means
- Rogue planets number in the billions
- Titan could give possible conditions for life, but is outside the habitable zone

12.3.2 Venus: An Example in Potential Habitability

- Venus receives twice the solar energy that the Earth does
- Moving Earth to Venus' orbital distance would increase global temperatures by 30° C
- The worlds are similar, but Venus' greenhouse gas effect is too extreme
- Venus probably lost its water due to solar winds
  - There is evidence for this water loss—there is 100 times more deuterium in Venus' atmosphere compared to Earth's atmosphere

12.3.3 Runaway Greenhouse Effect

Evaporation leads to water vapour which leads to even more greenhouse effect

12.3.4 Surface Habitability Factors

- Stellar factor—Luminosity of a star determines the radius of the habitable zone
- Planetary factor—A world must be large enough to retain internal heat and have plate tectonics for climate regulation
- Atmospheric factor—A world must have an atmosphere to retain liquid surface water (might imply magnetic field)

Note. The habitable zone changes with time because stars get brighter and dimmer in their lifetimes.

13 Lecture 14

13.1 Death of the Sun

- Fusion within the Sun will slow, making the Sun turn into a red giant
- The Sun will eventually become a white dwarf

13.2 Global Warming

- Earth's CO_2 cycle is sensitive to subtle changes in CO_2, and human activity is increasing the greenhouse effect
- While evidence is most reliable over the last 50 years, the last 140 years of evidence show a 0.85° C increase in average global temperatures
- Careful measurements show that natural sources of CO_2 contribute only a small amount of CO_2
- The geological record correlates high levels of CO_2 with high average global temperatures

13.3 Evolution of Venus, Earth, and Mars

- Venus was in the habitable zone of the early Sun, but a thick atmosphere, lack of plate tectonics and rotation, and brightening Sun all contributed to the runaway greenhouse effect
- Venus could have been habitable for 1–3 billion years
- Earth has been in the habitable zone for its entire history and has 500 million years–1 billion years of habitability left
- Mars would have been in the habitable zone today if it were a more massive planet, but as it stands, does not have internal heat, magnetic field, nor atmosphere

13.4 Other Planetary Systems

13.4.1 Discovery of Brown Dwarfs and Exoplanets

- Astronomers discovered the first "failed star" or brown dwarf object in 1995
- The same year, astronomers discovered the first planet orbiting another Sun-like star

> **Definition.** *Exoplanet*
> The term *exoplanet* means a planet that orbits another star. It is a contraction of the term extrasolar planets.

Exoplanets are very very hard to detect because their stars are usually about 1 billion times brighter than its planets, and are very close to their stars, relative to the distance from us to the star.

13.4.2 Methods for Detecting Exoplanets

- Direct: Pictures or spectra of the planets themselves (isolated from the parent star)
- Indirect: Precise measurements of a star's properties may indirectly reveal orbiting planets
  - Initial successes all used indirect methods

13.4.3 Gravitational Tugs

- Two *indirect* methods are the Astrometric and Doppler techniques
- Both rely on observing the gravitational tugs from orbiting planets
- The Sun and Jupiter both orbit the centre of mass of the solar system

> **Note.** For the solar system, the centre of mass is just outside the surface of the Sun. This means that the Sun's position *wobbles* in space because of our planetary system.

13.4.4 The Doppler Technique

- An easier way to use the *gravitational tug* of a planet is through the Doppler Effect
- The star moves alternately slightly towards and away from us as a part of its tiny orbital motion
- This results in the star's spectral lines shifting

  > **Note.** Current techniques can measure movements as small as 1 m/s.

13.4.5 Deriving the Mass of an Extrasolar Planet

Simply by using conservation of momentum, we have

$$m_{\text{planet}} = \frac{m_{\text{star}} v_{\text{star}}}{v_{\text{planet}}}.$$

We know the star's mass from its spectral type, and the Doppler effect measures the star's velocity. The periodic nature of the star's velocity variations gives us the orbital period of the planet, which we can then use to give us $v_{\text{planet}} = 2\pi \frac{a_{\text{planet}}}{T_{\text{planet}}}$. Thus we have

$$m_{\text{planet}} = \frac{m_{\text{star}} v_{\text{star}} T_{\text{planet}}}{2\pi a_{\text{planet}}}.$$

From the Doppler effect, we get the period and semi-major axis of a planet's orbit. We also get the eccentricity of the orbit. Faster oscillations on top of slower variations means multiple planets in different orbits. The planet mass deduced via the Doppler effect is a lower limit.

13.4.6 Transits and Eclipses

- A *transit* is when a planet crosses in front of a star
- The planet reduces the star's apparent brightness, which tells us the planet's radius
- Sometimes an eclipse—where the planet passes behind the star, can also be detected using infrared cameras
- The change in infrared brightness determines the planet's temperature

Approximately 11 billion planets in the Milky Way are orbiting in the habitable zones of Sun-like stars.

Using mass determined by the Doppler technique, and size determined via transit observations, density can be calculated

13.4.7 Direct Methods

- It's hard to "see" the planets because of a lack of contrast and a lack of angular resolution
- Jupiter is 1 billion times fainter than the Sun
- Atmospheric turbulence blurs images, and this is especially bad considering how far away these objects are
- The giant Keck telescope in infrared can see things on the scale of 2 AU as opposed to 100 AU

14 Lecture 15

14.1 Results From Doppler Shift

- Period and semi-major axis
- Eccentricity of orbit
- Faster oscillations on top of slower variations implies multiple planets
- Mass, although with a caveat (the Doppler shift only provides velocity along our line of sight)

> **Note.** Thus the planet mass deduced is a lower limit for the actual mass of the planet. In 2/3 cases, the *true* mass is no more than double the Doppler mass.

The Doppler technique is best suited for finding massive planets that orbit close to their stars—the Doppler effect is more visible. Using Doppler mass and getting the size from transit observations, one can calculate the density.

14.2 Other Strategies

- Gravitational lensing—A planet bends light towards the observer and produces extra brightening (only mass can be measured)
- Look for the effects of planets on disks of dust
- White dwarfs can have bands of metals (if other things collide with it)

The *Earth similarity index* is a function of all the parameters of a planet, and compares other worlds to Earth.

A star's *full classification* includes *spectral type* (line identities that yield temperature) and *luminosity class* (line shapes related to the size of the star).

(I) Super giant

(II) Bright giant

(III) Giant

(IV) Sub giant

(V) Main sequence

For example, the Sun is classified by "G2 V", and Betelgeuse by "M2 I".

15 Lecture 16

Most "rocky" exoplanets are more massive than the Earth. We can look at emission spectra to see what elements are a part of the atmosphere, to detect potentially habitable planets.

15.1 Why Image Young Planets?

- Much more radiation expected from hotter, younger planets
- Young planets are the only ones that we can image directly

Most normal stars are fusing hydrogen and helium in their cores (just like the Sun). The biggest red stars have a radius 1000x that of the Sun. The smallest red stars have a radius 0.1x that of the Sun.

15.2 Mass and Lifetime of Stars

If a star has 10x the mass of the Sun, then it has 10x as much fuel, but uses it 10^4 times as fast. If a star has 0.1x the mass of the Sun, then it has 0.1x the fuel, but uses it 0.001 times as fast.

> **Note.** The habitable zones of stars range with the mass of the star.

15.3 Binary Stars

About 50% of stars are formed in binary systems

- For it to host complex life, both stars must be low mass
- The system lifetime is limited by the evolution of the most massive star
- If both stars are on the main sequence then you're more likely to have a habitable planet

The *Hertzprung-Russell Diagram* plots the luminosity of stars as functions of their temperature. The temperature decreases from left to right.

> **Note.** Low-mass stars are more likely to be seen than high-mass stars.

Stellar properties depend on both mass and age—stars that have exhausted their supplies of hydrogen and helium are no longer on the main sequence. All stars becomes larger and redder after exhausting their core hydrogen. Low-mass stars on the main sequence will change the least over time.

> **Note.** The life of a star is determined by its starting mass.

15.4 Star Clusters

- Open clusters are groups of a few thousand loosely packed stars
- Globular clusters are tightly packed groups of around half a million stars
- The stars in each cluster usually form around the same time
- More blue stars implies younger cluster

  > **Note.** Thus the cluster is the same age as the age of the hottest star.

Degeneracy pressure does not depend on the temperature.

15.5 Brown Dwarfs

- An object less massive than 0.08 M_{sun}
- Radiates mostly infrared light
- No heat from fusion
- Brown dwarfs cool off after degeneracy pressure stops gravitational contraction

15.6 3-alpha process

Two Helium collide to form a Beryllium atom, which then collides with a third helium atom to make a carbon atom. This requires very high temperatures to occur (100M Kelvin).

Hydrogen fuses in a shell around the Helium core once it's too cold to continue the 3-alpha process.

When the core temperature rises enough to fuse helium again, helium fusion rises very sharply (helium flash).

Helium burning stars neither shrink nor grow because the thermostat is temporarily fixed. Helium fuses into carbon into the core. When the core becomes carbon, the star stars fusing helium in a shell around the carbon core. These double shells generate enough heat to push away the outer layers of the star, which results in a *planetary nebula*. The small hot core is left, which is a white dwarf.

> **Note.** When the Sun uses up the nuclear fuel, it will expand and become larger. It will become brighter.

16 Lecture 17

16.1 High-Mass Star's Life

A high-mass star is one with more than 10x the mass of the Sun.

- Main sequence stars fuse hydrogen into helium
- Red super giants fuse hydrogen into helium around an inert helium core
- Helium core burning: Helium fuses to carbon in the core but there is no "flash" this time

> **Definition.** *CNO Cycle*
> The *CNO cycle* is another way to fuse H into He, using carbon, nitrogen and oxygen as catalysts.

High-mass stars make the elements necessary for life (heavier elements). At a certain point, massive stars go through multiple shell fusion (different elements at different shells). Iron is the end for fusion because nuclear reactions involving iron *don't* release energy.

For a massive star with a core of inert iron dies, it turns into a neutron star. Energy is added during supernova explosions, and is created in the death of stars.

16.1.1 Summary

- A star with a mass 8 M_{sun} or higher becomes a black hole or neutron star.
- These make most oxygen, silicon, magnesium, sulfur
- Type I supernovae are merging or exploded white dwarfs
- These stars make most of the iron and nickel
- Source of heavier elements—rare earth metals not fully known. Either merged neutron stars or massive star supernova
- The sun cannot become a supernova

Incidence of planets higher near metal rich stars

16.2 SETI

Low mass stars may have more planets than higher mass stars (although having smaller habitability zones). While lower mass stars are longer lived, their close-in planets might be tidally locked and suffer from stellar flares.

- The first life forms might have arisen more than 5B years ago
- Their legacy might be Terra formed planetary systems

16.3 The Drake Equation

An equation that is a way to estimate the number of civilisations in our galaxy at this time. It is given by:

$$\text{Number of civilisations} = N_{\text{hab}} \cdot f_{\text{life}} \cdot f_{\text{civ}} \cdot f_{\text{now}}.$$

- N_{hab} is the total number of habitable planets in the galaxy (20–200 billion)
- f_{life} is the fraction of those planets with life
- f_{civ} is the fraction of those that have ever had tech civilisations
- f_{now} is the fraction of those that are transmitting now

By random approximations, there might be between 0 and 10 tech civilisation in the Milky Way.

16.4 The Future of Civilisation

- Unless a star has very low mass, a solar mass host star eventually leaves main sequence
- This requires migration to a new planet

16.4.1 Why Bother Broadcasting?

- The closest star is 4 light-years away (8 year round trip)
- Everything points towards the speed of light being the fastest thing in the universe

Definition. *Convergent Evolution*
Different organisms evolving towards the same features.

Definition. *Encephalisation Quotient*
The EQ of an organism is the ratio of its brain mass to body mass.

There are many species that have deep intelligence and are conscious, but not technological.

16.5 How does SETI Work?

- Use radio telescopes to look for signals
- Searches millions of frequencies at once

Modern SETI signals fall into three categories:

1. Local communications (Earth-based radio)
2. Interplanetary or interstellar signals (communicating over long distances)
3. Signal beacons (broadcasting their signals specifically to attract attention)

Note. The 1420 MHz or 21 cm hydrogen band is seen as important.

Modern SETI uses radio, because it's cheap. If aliens knew about our galaxy, they would probably leave artifacts at the L4 and L5 points in orbit because items are stable there.

Fermi's Paradox: Where are all the aliens?

17 Lecture 18

The LIGO observatory measures wobbles of space-time from merging black holes. We can use LIGO to observe these gravitational waves traverse space-time at the speed of light.

17.1 Where are the Aliens?

Fermi's paradox: Plausible arguments suggest that aliens should be common. So why haven't we detected them?

No substantiated evidence for visitations has been presented

17.2 Interstellar Travel

Rockets achieve thrust by igniting mixtures of chemical propellants and expelling them at high velocity (Newton's 3$^{\text{rd}}$ law). Rockets are limited by the mass ratio (ratio of the mass of the rocket before and after its fuel is burned). Reaching escape velocity requires a mass ratio of roughly 39, so single stage rockets need to carry 38x as much fuel as rocket.

With conventional technology, higher energy efficiency can be achieved with nuclear fission. Nuclear fission has an efficiency of roughly 0.07%, whereas fusion has an efficiency of roughly 0.7%.

- Ion drives are low-power, high-efficiency options
- Solar sails catch the solar wind for thrust (perhaps with a terrestrial laser)
- Interstellar arks might put people into *suspended hibernation*
- Generation ships have multiple generations of people live and die on the voyage to a new home

17.2.1 Relativity in Interstellar Travel

- Time dilation is a natural consequence of moving close to the speed of light

Energy concerns—nuclear fusion would be limited in achieving relativistic speeds. Interstellar ramjets could work, as well as using matter-antimatter annihilations.

Colonisation is part of humanity's drive for exploration.

17.3 Solutions to the Fermi Paradox

- We are alone (rare Earth hypothesis)
- Civilisations, but no colonisation—perhaps technological difficulties or sociological difficulties, or there is a galactic civilisation that is indifferent (or treats us like zoo animals or only appears once we reach a technological level)

Theorem — *Rocket Equation*
For initial and final masses M_i and M_f, and exhaust speed v_c, we have

$$v = v_c \ln \frac{M_i}{M_f}.$$

Perhaps civilisations are common but interstellar travel is not.

Mars, Europa, Enceladus are at the top of the list for habitability.