SPARKCHARTS™

ASTRONOMY

OVERVIEW

LIGHT

Wave description: The periodic oscillation of electric and magnetic fields in space. Characterized by the following:

1. **Frequency** of the oscillation, ν, measured in cycles per second (hertz).
2. **Wavelength** of the oscillation, λ, measured in meters. This is the distance from one peak to the next.
   - Wave equation: All light travels at a finite speed, $c = 3 \times 10^8$ meters per second. This results in an inverse relationship between the frequency and wavelength.
   - Mathematically: $c = \lambda \times \nu$.
   - Thus, light with a high frequency has a short wavelength, and vice versa.

Particle description: A stream of **photons,** individual particles of light that each carry a specific amount of energy, which is directly proportional to the frequency of the light.

- Mathematically, **Planck's Law:** $E = h\nu$
  E, energy (Joules, J)
  ν, frequency (Hertz, hz)
  $h = 6.63 \times 10^{-34}$, Planck's constant (J $\times$ s)
- Light with a high frequency (short wavelength) is also very energetic.

Electromagnetic spectrum: The collection of all frequencies of light.

- Includes (in order of increasing energy) **radio, infrared, visible, ultraviolet, x-ray,** and **gamma ray** frequencies.
- Different physical processes in the universe emit radiation at different frequencies, so each frequency band probes different phenomena in the universe.

Light quantities:

- **Energy:** The capacity to cause change (Joules, J)
- **Power:** Energy emitted per unit of time (J/s= Watts, W=J s^{-1})
- **Luminosity:** Light energy emitted per unit time (power from a star) (J s^{-1}=Watts, W)
- **Flux:** Energy emitted per unit time per unit area (J $s^{-1}m^{-2} = Wm^{-2}$)
  Mathematically, $F = \frac{L}{4\pi D^2}$
  F, flux from surface of a spherical object (Wm^{-2})
  L, luminosity of object (W)
  D, distance to object (m)

Spectroscopy: The technique astronomers use to separate light into its intensity at different wavelengths or **spectrum.** Components:

1. **Continuum:** The smooth part of the spectrum (see Figure 1). Most objects emit light at all frequencies, but the shape of the spectrum depends on the physical process that produces the light.
   - **Blackbody:** A dense object that reflects no light, and thus emits light only because of the thermal motion of its atoms, measured by its temperature.
     - Most objects produce their own continuum approximately as a blackbody (e.g., the Sun, an incandescent light bulb, and the human body).
     - The shape of the curve depends only on temperature. A hot object emits more light at higher frequencies (higher energies) than a cool object (e.g., hot stars appear blue, cool stars appear red).
   - **Wien's Law** for a blackbody: $\lambda_{max} = \frac{3 \times 10^{-3}}{T}$
     - λ_{max}, wavelength of maximum intensity (m)
     - T, temperature of blackbody (Kelvins, K)
   - **Stefan-Boltzmann Law** for a blackbody: $F = \sigma T^4$
     F, energy flux from surface of blackbody (W m^{-2})
     $\sigma = 5.67 \times 10^{-8}$ (W $m^{-2}K^{-4}$), Stefan-Boltzmann constant
     T, temperature of blackbody (K)
     - This flux is equal to the area under the curve of intensity versus wavelength for a blackbody.
2. **Atomic lines:** According to quantum mechanics, electrons bound to an atom can only have particular values of energy; they are unique to that element. Absorption or emission of a photon of light by the atom occurs when the energy of that photon matches the difference between two of these energy levels.
   - **Absorption lines:** Narrow, dark regions in a spectrum produced when an electron uses up a photon to jump to a higher energy level in an atom.
   - **Emission lines:** Narrow, bright regions in a spectrum produced when an electron spontaneously drops to a lower energy level in an atom.

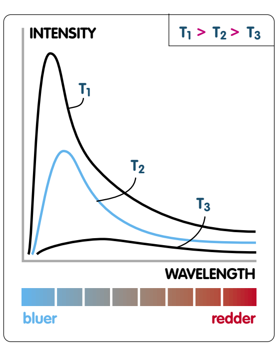

Figure 1
Blackbody curves for different temperatures. The emission from a hotter object will peak at shorter wavelengths.

Doppler shift: The difference between the wavelength at which light is observed and the wavelength at which it was originally emitted due to the motion of the emitter relative to the observer.

- Mathematically (for objects moving much slower than the speed of light): $z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = \frac{v}{c}$
  z, redshift (dimensionless)
  λ_{obs}, observed wavelength (any length unit, usually nanometers, nm ($= 10^{-9}$ m) or angstroms, $\AA$ ($= 10^{-10}$ m))
  λ_{em}, wavelength emitted by the source (same length unit)
  v, velocity of moving source (m/s)
  c, speed of light (m/s)
- **Note:**
  $z > 0$: Source moving away, shift to longer wavelength (redder)
  $z < 0$: Source moving toward, shift to shorter wavelength (bluer)

MOTION

Kepler's Laws of Planetary Motion

1. Planets move in elliptical orbits with the Sun at one focus of the ellipse (see Figure 2).
   - For a circular orbit, semimajor axis = radius.
   - Implication: Orbits are not perfect circles, but are slightly elongated.
2. Pick an interval of time (e.g., a month). In that amount of time, the line connecting a planet to the Sun will sweep over the same area, regardless of where it is on its elliptical orbit.
   - Implication: Planets move faster when they are closer to the sun (see Figure 2).

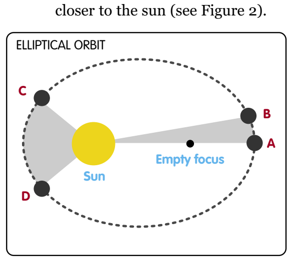

Figure 2: Kepler's Second Law
The two shaded areas are equal. According to the second law, equal time passes between A and B and also C and D. Thus, the planet travels faster between C and D.

3. The square of the period of revolution (P) of a planet is directly proportional to the cube of the semimajor axis (a) of the elliptical orbit.
   - Implication: Planets farther from the Sun take a longer time to go around the Sun.
   - Mathematically: $P^2 = \frac{4\pi^2}{G(M+m)} a^3$
     P, period (= time planet takes to complete one orbit) (seconds, s)
     a, semimajor axis (meters, m)
     M, mass of body being orbited (e.g., the Sun) (kilograms, kg)
     m, mass of the orbiting body (e.g., the planet) (kg)
     $G = 6.67 \times 10^{-11}$, universal gravitation constant ($\frac{N \times m^2}{kg^2}$)
     - If $M \gg m$, m can be ignored
   - Mathematically, $\frac{P^2_{planet}}{P^2_{Earth}} = \frac{a^3_{planet}}{a^3_{Earth}}$
     P, period ($P_{Earth} = 1$ in years)
     a, semimajor axis ($a_{Earth} = 1$ in AU, see *Units*)
     - More convenient formula when comparing another planet to Earth.

Newton's **Law of Universal Gravitation:** All objects in the universe attract all other objects with a force dependent upon the mass of the two objects and the distance between them.

- Mathematically: $F = \frac{GM_1M_2}{R^2}$
  F, force (Newtons, N)
  R, distance (m)
  M_1, M_2, mass of bodies (kg)
  G, universal gravitation constant ($\frac{N \times m^2}{kg^2}$)

Circular velocity: Orbital velocity (v_{circ}) when one mass orbits another in a circle.

- Mathematically: $v_{circ} = \sqrt{\frac{GM}{R}}$
  M, mass of body being orbited (kg)
  R, radius of orbit (m)
  G, universal gravitation constant ($\frac{N \times m^2}{kg^2}$)
- **Note:** v_{circ} is independent of the mass of the orbiting body.

Escape velocity: Velocity (v_{esc}) needed to completely escape from the gravitational pull of another object.

- Mathematically: $v_{esc} = \sqrt{\frac{2GM}{R}}$
  M, mass of body being escaped from (kg)
  R, radius of body being escaped from (m)
  G, universal gravitation constant ($\frac{N \times m^2}{kg^2}$)
- **Note:** v_{esc} is independent of the mass of the escaping body.

UNITS

We cannot describe stars and galaxies using human scale units.

ASTRONOMICAL SCALE AND ITS EQUIVALENTS

Quantity	Human Scale	Astronomical Scale
Distance	**Meter,** m **Kilometer,** km	**Solar radius,** $R_\odot$, ($= 7 \times 10^5$ km)
		Astronomical unit, AU ($= 1.5 \times 10^8$ km, distance from Earth to Sun)
		Light year, ly ($= 9.5 \times 10^{12}$ km, distance light travels in one year)
		Parsec, pc ($= 3.1 \times 10^{13}$ km = 3.26 ly)
Mass	**Gram,** g **Kilogram,** kg	**Earth mass,** $M_\oplus$ ($= 6 \times 10^{24}$ kg)
		Solar mass, $M_\odot$ ($= 2 \times 10^{30}$ kg)
Time	**Second,** s **Year,** yr	**Gigayear,** Gyr ($= 10^9$ yr = 1 billion yr)
Luminosity (light power output)	**Watt,** W **Horsepower,** hp (= 746 W)	**Solar luminosity,** $L_\odot$ ($= 3.9 \times 10^{26}$ W)

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“IT IS CLEAR TO EVERYONE THAT ASTRONOMY AT ALL EVENTS COMPELS THE SOUL TO LOOK UPWARDS, AND DRAWS IT FROM THE THINGS OF THIS WORLD TO THE OTHER.” PLATO

THE SOLAR SYSTEM

EARTH-MOON-SUN SYSTEM

EARTH

Composition: Three layers; a solid iron and nickel **core,** a thick layer of **mantle,** and a thin outer **crust**.

- The shape of Earth is an **oblate spheroid** (a slightly squished sphere).

Motions

- **Rotation:** Movement of Earth around its axis once every 24 hours.
  - At any given time, the Sun lights up half of Earth.
  - Day and night begin as a spot on Earth moves into or out of the illuminated half.
- **Revolution:** Earth travels around the Sun once every 365.25 days (one year).

Seasons: Caused by the fixed tilt of Earth's axis (see Figure 3).

- When the North Pole points away from the Sun, it is winter in the Northern Hemisphere. This is because the rays of the Sun are tilted and do not warm the surface efficiently.
- At the same time, it is summer in the Southern Hemisphere. This is because the rays of the Sun strike the surface from almost directly overhead.
- **Note:** The slight variation in the distance from Earth to the Sun, which is caused by Earth's slightly non-circular orbit, is irrelevant to the changes in seasons.

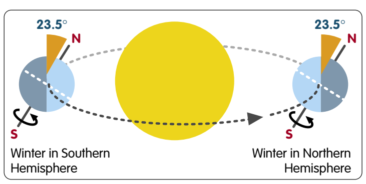


Figure 3

The tilt of the Earth's rotation axis is the cause for the seasons. This diagram is not drawn to scale.

Magnetic field: Generated by the rotational motions of charged particles in the liquid part of the core.

- It emerges from Earth at the North Magnetic Pole (slightly offset from Earth's rotation axis), and returns to the South Magnetic Pole (see Figure 4).
- Magnetic fields interact with moving charged particles and cause them to spiral around magnetic field lines. This leads to 3 important phenomena:

1. **Van Allen Belts:** Charged particles from space get trapped in the magnetic field lines of Earth.
2. **Aurorae** (Northern and Southern lights): Caused by the deexcitation of atoms and molecules that occurs when charged particles trapped by the magnetic field strike the Earth's atmosphere near the poles.
3. **Magnetosphere:** Extension of the Earth's magnetic field hundreds of Earth radii into space (see Figure 4). It traps or deflects the constant flow of charged particles from the Sun. The Van Allen Belts are the inner parts of the magnetosphere.

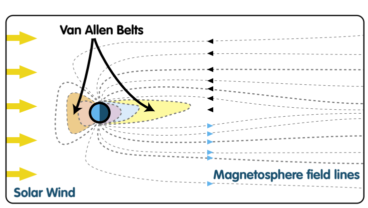


Figure 4: Earth's magnetic field and magnetosphere

THE MOON

Composition: Low-density crust, a silica-rich mantle, and possibly metallic (iron) core.

- **Highlands:** The highly cratered and brighter parts of Moon's surface.
- **Maria** (from the Latin for “sea”): The smoother and darker lowlands on the Moon's surface.
  - Because maria are less cratered, they are thought to have formed later, possibly by volcanic activity.

Phases: Caused by the relative alignment of Earth, the Moon, and the Sun.

- One half of the Moon is always illuminated by the Sun.
- The portion of the illuminated half that we see determines the shape of that particular phase.
- Cycle of phases repeats every $29\frac{1}{2}$ days (see Figure 5).

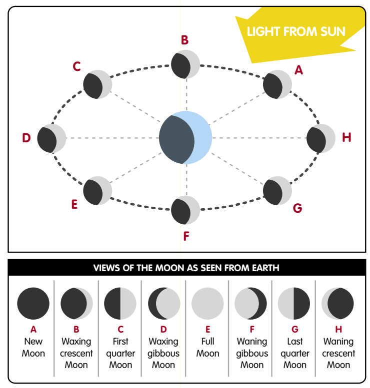


Figure 5: The phases of the moon. Diagram not to scale.

Eclipses (see Figure 6)

- **Solar:** The Moon moves between the Sun and Earth, and casts its shadow on Earth. A total solar eclipse (the Moon completely covers the Sun) can occur even though the Sun's radius is 375 times the Moon's radius because the Earth-Moon distance is much less than the Earth-Sun distance.
- **Lunar:** The Moon moves directly behind the line between the Sun and Earth, and Earth casts its shadow on the Moon.

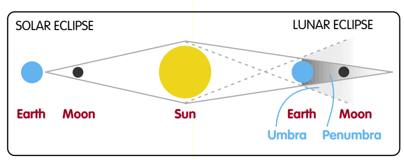


Figure 6: Lunar and solar eclipses. Diagram not to scale.

- Eclipses do not occur once a month because the plane in which the Moon orbits is tilted about 5 degrees from the plane of Earth's orbit around the Sun.

Tides occur on Earth as a result of the gravitational pull of the Sun and the Moon.

- The gravitational pull of any object gets weaker the further you move from the object. Thus, the Moon pulls harder on the water on the side of Earth nearer to it than on the water on the side of Earth farther from it. This creates a bulge in the water on the side of the Earth facing the Moon and another on the opposite side (see Figure 7). The Earth itself is more rigid, so essentially no bulge is created in its crust.

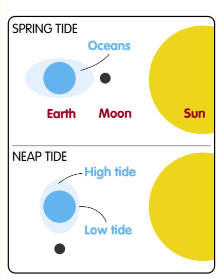


Figure 7: Spring and neap tides. Diagram not to scale.

- A place on the Earth's surface experiences high tide when that place faces toward (or away from) the Moon. Low tide occurs when the Earth has rotated 90 degrees from high tide.
- During a span of approximately 24 hours, every location on Earth passes through 2 high tides and 2 low tides.
- **Spring tides** (unrelated to the season): Strongest tides; occur when the tidal bulges created by the Sun and Moon line up.
- **Neap tides:** Weakest tides; occur when the tidal bulges created by the Sun and Moon are at right angles to each other (see Figure 7).

Impact theory of origin: A Mars-sized object struck Earth off-center, ejecting material that then formed the Moon. This theory is currently favored by geological evidence and computer simulations.

PLANETS

GENERAL TRENDS OF PLANETARY SCIENCE

Active lifetime: The size of a planet determines its active lifetime.

- The internal heat of a planet comes from gravitational contraction during the planet's formation.
- As the internal heat is radiated away into space, changes occur in both the internal structure and surface features of a planet.
- When the heat is gone, the planet can no longer evolve from the inside, and it is considered dead.

Atmosphere: The balance between the force of gravity on a planet and its average surface temperature determines the amount and composition of its atmosphere.

- If the average velocity of gas molecules (determined by surface temperature) is greater than the escape speed of the planet (determined from its mass and size, see *Orbits*), then that molecule will not be present in the planet's atmosphere.
- Lighter molecules like hydrogen and helium are harder for a planet to hold onto because they move faster than heavy molecules at a given temperature.

Internal structure:

- **Differentiation:** If the internal heat is high enough, the materials that make up a planet will melt and the heavier components will sink to the center.
- **Average density:** Total mass of a planet divided by its total volume.
  - High average density implies a mostly rocky planet.
  - Low average density implies a mostly gaseous planet.

Surface features: Four main processes mold the surface of a planet:

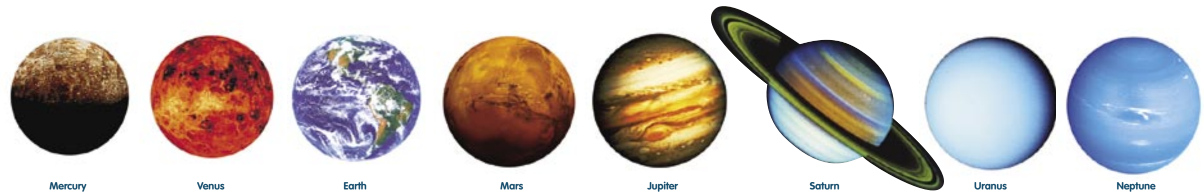
1. **Cratering:** Pits in the crust of planets form because of impacts with other solar system bodies.
2. **Erosion:** Water flows and wind (if an atmosphere is present) wear away a planet's surface features.
3. **Volcanism:** Hot rock and other material rise to the surface of a planet.
4. **Plate tectonics:** A layer of crust is broken into plates and rides on a lower layer of softened rock that is heated by natural radioactivity.
   - This theory explains earthquakes and volcanos by inferring that they are the result of plates being pushed together or driven apart.
   - Plate tectonics occurs only on Earth.

TERRESTRIAL PLANETS

Mercury, Venus, Earth (and its moon), and Mars.

1. **Atmosphere**
   - **Earth and Venus:** Bigger planets can hold onto heavy molecules (such as nitrogen, carbon dioxide, and oxygen), but not hydrogen because the planets' surface temperatures are too high.

THE SOLAR SYSTEM (CONTINUED)



PICTURES NOT TO SCALE

Uranus photo courtesy of NSSDC. Venus © DigitalVision
Mercury, Earth, Mars, Jupiter, Saturn, and Neptune © PhotoDisc, Inc.

- **Greenhouse effect:** Radiation incident on the surface of Venus is re-radiated at longer wavelengths that cannot get back out through the atmosphere. This trapped radiation heats the surface to very high temperatures. The same thing happens inside a closed car on a hot day.
- **Moon and Mercury:** Have almost no atmosphere because of their low surface gravity.
- **Mars:** Has a thin atmosphere of carbon dioxide.

COMPARISON OF THE TERRESTRIAL PLANETS

Planet	Diameter Earth = 1	Mass Earth = 1	Density Water = 1	Surface Pressure Earth = 1
Mercury	0.38	0.055	5.4	10^{-15}
Venus	0.95	0.82	5.2	100
Earth	1.0	1.0	5.5	1.0
Mars	0.53	0.11	3.9	0.01
Moon	0.27	0.012	3.3	10^{-15}

2. **Internal structure:** All terrestrial planets have undergone differentiation (see *Internal structure*). They have high densities because of their rocky interiors.
3. **Surface features**
   - **Earth and Venus:** The most active planets. Erosion, volcanic activity, and plate tectonics (on Earth) constantly renew their surfaces, rapidly wiping away evidence of cratering.
   - **Moon and Mercury:** Because they lack an atmosphere, they retain their craters. Cratering happened long ago, showing that no other surface activity has taken place for a long time.
   - **Mars:** Has huge dormant volcanoes and riverbed-like features that imply there was some volcanic activity and liquid water flow in its recent past.

JOVIAN PLANETS

Jupiter, Saturn, Uranus, and Neptune. Because of their similarities in composition, they are named after the largest of the group, Jupiter.

1. **Atmosphere**
   - Jovian planets are made of gas in their outer layers and have no solid surface.
   - They exhibit **differential rotation** (gas at the equator rotates faster than gas at the poles).
   - Their hot interiors drive hot, dense material from deep in the atmosphere up to the cloud tops.
     - This results in a banded structure, which we can see most clearly in Jupiter and Saturn, and less so in Uranus and Neptune.
     - Small amounts of methane in the atmospheres of Uranus and Neptune give them a greenish and bluish color, respectively.

COMPARISON OF THE JOVIAN PLANETS

Planet	Diameter Earth = 1	Mass Earth = 1	Bulk Density Water = 1
Jupiter	11.0	318	1.3
Saturn	9.5	95	0.7
Uranus	4.1	15	1.2
Neptune	3.9	17	1.7
Pluto	0.17	0.002	2.1

2. **Internal structure:** Two characteristics allow us to constuct models of Jovian planets:
   a. Their sunlike density.
   b. Their ability to radiate more energy into space than they absorb from the Sun.
   - The models show that Jovian planets are active, differentiated worlds composed of:
     - A molecular hydrogen atmosphere
     - A liquid hydrogen (and metallic hydrogen in Jupiter and Saturn) interior
     - A (possibly) rocky core
3. **Surface features:**
   - Jovian worlds do not have a solid surface, so evidence of cratering, erosion, and volcanism are not present.
   - Despite this, there are some stable surface features, including the **Great Red Spot** of Jupiter and the **Great Dark Spot** of Neptune, atmospheric storms of tremendous intensity that will last for many years.
4. **Moons:** All Jovian planets have a large system of moons.
   - **Tidal locking:** Tidal forces have acted over time so that the same half of a moon points toward the parent planet at all times (as seen with Earth's moon).
5. **Rings:** All Jovian planets have rings.
   - **Composition:** Made up of many individual particles averaging one meter in size, all orbiting their parent planet according to Kepler's Laws (see *Orbits*) in a disk about a kilometer thick. There are two types of particles:
     a. **Icy:** Seen as bright rings; found around Saturn.
     b. **Rocky:** Seen as dark rings; found around Jupiter, Neptune, Uranus.
   - **Shepherd moons:** A pair of small moons, one interior to the ring and one exterior to the ring which help to maintain the stability of the ring. The gravitational tugs of the shepherd moons act to herd the ring particles into the same orbit.

- **Pluto:** The outermost planet and its moon, **Charon,** do not fit either of the above categories. Instead, they can be thought of as the largest icy bodies in the **Kuiper Belt** (see *Comets*).

EXTRA-SOLAR PLANETS

- **"Hot Jupiter":** One of dozens of planets, with masses close to that of Jupiter, found orbiting very close to another star.
- **Migration:** The current theory states that hot Jupiters formed further from their star and then migrated inward by some uncertain mechanism.

Detection techniques:

1. **Doppler shift:** A massive orbiting planet causes the position of its parent star to wobble. We can determine some orbital properties of the planet by watching the spectrum of the star shift back and forth because of this wobble.
2. **Transits:** If a planet passes in front of its parent star, we see a dip in the intensity of the light from that star. From the shape of this dip, we can determine some properties of the planet, including its orbital period and size relative to its parent star.

EXTRAS OF THE SOLAR SYSTEM

COMETS

Composition: Comets consist of four parts:

a. **Nucleus:** A dirty snowball a few kilometers wide consisting of water and other organic ices mixed with dust.
b. **Coma:** Region of gas and dust thrown off from the nucleus, measuring up to a million kilometers in diameter.
c. **Gas tail:** Ions blown off the nucleus by the solar wind (see *Solar Activity*).
d. **Dust tail:** Particles released from the melting ice that curve behind the gas tail; up to 150 million kilometers long.
   - **Note**: Tails are only present when a comet is close to the Sun.

Origin:

1. **Kuiper belt:** A collection of comet nuclei that orbit just beyond the orbit of Neptune.
   - Most comets with orbits of less than 200 years originate here.
2. **Oort Cloud:** A collection of comet nuclei in a shell about 1,000 times as far out as Pluto's orbit.
   - Most comets with orbits of longer than 200 years originate here.

METEORITES

- Chunks of matter up to tens of meters across, left behind by passing comets, may burn up as they pass into Earth's atmosphere. They have different names depending on where they are relative to the atmosphere:
  1. **Meteoroid:** A chunk outside the atmosphere.
  2. **Meteor** (shooting star): The flash of light a chunk makes as it burns up in the atmosphere.
  3. **Meteorite:** A chunk that makes it to the ground.
- **Composition:** There are types of meteorite: iron, stony, and stony-iron.

ASTEROIDS

- Minor planets that orbit mostly in a gap between the orbits of Mars and Jupiter.
- **Kirkwood gaps:** Empty orbits in the asteroid belt with an orbital period of exactly $\frac{1}{2}$ or $\frac{1}{3}$ that of Jupiter. They are empty due to orbital resonance.
  - **Orbital resonance:** The repeated tugging between two bodies on orbits with whole number orbital period ratios.
    - An asteroid and Jupiter both orbit the Sun, with the asteroid orbiting faster (from Kepler's Third Law, see *Kepler's Laws*)
    - Because of their period ratios, they are always closest to each other at the same point on their orbits.
    - The repeated gravitational tug the asteroid feels from Jupiter acts to tug it out of that orbit into one that does not have a perfect orbital period ratio.
    - This phenomenon also occurs for moons and rings orbiting a planet.

FORMATION OF THE SOLAR SYSTEM

Any formation scenario must explain the following evidence:

- All planets orbit the Sun in nearly the same plane, in nearly circular orbits.
- All planets travel around the sun in the same direction, which is also the direction of the Sun's rotation.
- Smaller, rocky planets orbit near the Sun, while larger, gaseous planets orbit further away from the Sun.
- In the last ten years, we have found many nearby stars with planetary systems. Therefore, planet formation must be almost as common as star formation.

Nebular theory: The most widely accepted theory of solar system formation (see Figure 8).

a. About 5 billion years ago, a cloud of interstellar dust began to collapse. The trigger for this collapse is still unclear.

CONTINUED ON OTHER SIDE

b. As the cloud of dust continued to collapse under its own gravity, the rotational speed of the particles increased because of **conservation of angular momentum**—the reason why an ice skater spins faster when his or her arms are pulled in—and the cloud became a flattened disk.
c. Energy from the gravitational collapse caused the temperature in the center of the disk to rise until fusion started in the **protosun.** Micrometer-sized bits of dust began to stick together, and after about 10,000 years, they reached a size of tens of kilometers across and were called **planetesimals.**
d. Over tens of millions of years, the planetesimals collided and combined due to gravity, eventually forming planets.

- The planetesimals that did not form planets are thought to be the comets and asteroids in the solar system today.
- Rocky planets formed near the Sun because the heat vaporized most icy components. Most gaseous components escape these planets because the surface temperature is too high and the force of gravity is too low (see *Atmosphere,* under *Trends of Planetary Science*).
- Gas giant planets formed far from the Sun because the cooler gas could not escape their larger gravitational pull.

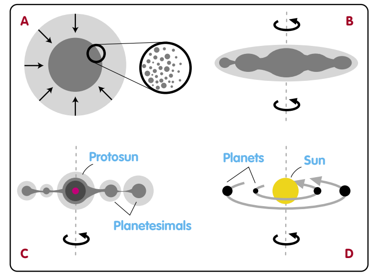


Figure 8: Formation of the solar system from solar nebula

STELLAR ASTRONOMY

OUR SUN

STRUCTURE

Solar interior

- **Core:** Inner 10% of the Sun's radius. The nuclear fusion that powers the Sun takes place in the core at a temperature of 15 million Kelvins.
- **Radiative zone:** Layer of the Sun directly above the core. Energy is transported outward by radiation (the movement of photons).
- **Convective zone:** Layer of the Sun above the radiative zone. Energy is transported outward by convection (hot gas rises and cooler gas falls).

Solar atmosphere

- **Photosphere:** Layer of the Sun we can see (the Sun's surface).
  Temperature: 5800 K
  Composition: 74% hydrogen, 25% helium, and 1% all other elements (same as the rest of the sun).
  Granulation: Lighter and darker regions about 1,000 km across, which cover the photosphere with a pattern that changes on average every 10 minutes. They are created by convection that brings hot material to the Sun's surface and pulls cooler material below the surface.
- **Chromosphere:** Layer of the Sun above the photosphere that shows a pinkish glow during a total solar eclipse.
  Temperature: Rises from 4,200 K to 1 million K; due to radiation from photosphere as well as from magnetic fields extending up from the photosphere into the chromosphere.
  Thickness: 2,000 km
- **Corona:** Layer above the chromosphere that is only visible during a total solar eclipse.
  Temperature: Approximately 2 million K; mechanism which generates this intense heat is unclear, but is related to magnetic activity.
  Composition: Small number of highly ionized atoms (low density) moving at high speeds (high temperature).
  Thickness: Extends from the top of the chromosphere out into the rest of the solar system.

MAGNETIC FIELD

Magnetic dynamo model: Description of how the Sun's magnetic field changes over time. Two motions bring this about:

1. **Differential rotation:** Gas at the equator (25-day period) rotates faster than gas at the poles (31-day period).
   - The Sun's magnetic field lines are locked into the material just beneath the photosphere. Thus, when material at the surface near the equator gets pulled around more quickly than the material near the poles, the magnetic field lines get wound around the Sun (see Figure 9).
2. **Convection at the Sun's surface:** Hot material below the photosphere rises to the surface, as in granulation (see *Photosphere*).
   - Magnetic field lines locked into this material are thus brought up to the surface of the Sun. If the lines are wound tightly enough by differential rotation, they will kink and pop out of the photosphere, causing small regions of magnetic field that are thousands of times stronger than the Sun's average magnetic field (see Figure 9).

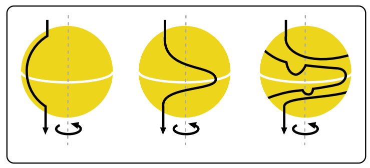


Figure 9: Magnetic dynamo model

SOLAR ACTIVITY

- Most solar activity is thought to be related to the magnetic field of the Sun.
- **Sunspots:** Temporary areas of cooler and darker gas that appear in groups on the photosphere.
  - **Temperature:** 4,200 K (less than 5,800 K average photosphere temperature).
  - **Cause:** Regions of strong magnetic field restrain the convective motion that brings hotter gas to the surface. Thus, sunspots are cooler.
- **Sunspot cycle:** 11-year cycle, beginning with just a few sunspots near the poles that are replaced by more sunspots near the equator as the cycle continues.
- **Solar flares:** Violent solar storms associated with regions of sunspots (and thus strong magnetic fields).
  - **Temperature:** Around 5 million K
  - **Duration:** About 20 minutes
  - **Effect on Earth:** Light reaches Earth in minutes, but energetic charged particles from the flare arrive on Earth days later. If the particles penetrate Earth's **magnetosphere,** they may disrupt radio communication or disable satellites orbiting Earth (see *Magnetic Field* under *Earth*).
- **Solar prominences:** Loops of gas that can rise tens of thousands of kilometers above the surface of the Sun.
  - **Temperature:** Around 10,000 K (this is how they are distinguished from solar flares).
- **Solar wind:** Extension of the charged particles of the corona out into the solar system.
  - **Temperature:** Around 2 million K.

STARS AS SUNS

WHAT ARE THEY?

- **Star:** Enormous, self-sustaining nuclear reactor made of mostly hydrogen gas; only known structures in the universe capable of taking the simple atoms present at the beginning of the universe and fusing them into the heavier elements needed for life.
- **Hydrostatic Equilibrium:** A balance in the **battle of gravity versus pressure** at every point inside a star; a star will not expand, contract, or shift its internal structure.
  - **Pressure:** Outward force resulting from processes of energy generation (usually heat from fusion) or quantum mechanical effects (called degeneracy, see *White Dwarfs*).
  - **Gravity:** Inward force that attracts each bit of gas toward the center of the star.
  - **Note:** Major changes in the star during its lifetime occur when one of these forces temporarily wins out over the other, but the star always settles to a new state of equilibrium.

HOW DO THEY WORK?

- **Fusion:** The combination of lighter atomic nuclei into heavier atomic nuclei. Fusion can only take place at very high temperatures (i.e., fast moving particles) and high pressures (i.e., tightly packed particles) because electrostatic repulsion between two positive nuclei must be overcome before the strong nuclear force causes the nuclei to combine.
- **Hydrogen fusion:** There are two processes:

1. **Proton-proton (PP) chain:** Four hydrogen nuclei fuse into one alpha particle and release high energy photons and neutrinos.
   - **Alpha particle** = helium nucleus
   - Requires chain of 3 separate nuclear reactions to go from initial reactants to final products.
   - Photons take about a million years to reach the surface of the star.
   - Occurs mostly in low mass stars (1.5 $M_\odot$ or less).
2. **Carbon-nitrogen-oxygen (CNO) cycle:** Net reaction is the same as the PP chain: four hydrogen nuclei create one alpha particle.
   - Intermediate reaction steps involve isotopes of carbon, nitrogen, and oxygen as catalysts (they participate in reactions, but do not get used up).
   - More efficient than PP chain = higher yield of energy for same products.
   - Occurs mostly in higher mass stars (greater than 1.5 $M_\odot$).

- **Helium fusion (Triple alpha process):** Three alpha particles fuse into one carbon nucleus.
  - Occurs after all hydrogen in the core has been converted to helium.
  - Requires much higher temperatures, up to 100 million Kelvin.
- **Nucleosynthesis:** Heavier nuclei are created from the products of previous fusing stages.
  - Begins with the production of oxygen from carbon after all helium has been fused into carbon.
  - Iron is the most massive nucleus that can be produced by fusion and still release energy.
  - All heavier elements in the universe are formed in the unusual processes that accompany a **supernova** (see *Stellar Endpoints*).

WHY ARE THEY HERE?

Star Formation: The process of star formation is believed to be similar to the formation of our own Sun (see *Formation of the Solar System*).

- **Site of formation: Giant Molecular Clouds (GMCs)**, a cloud of mostly cool molecular hydrogen with a temperature of 20 K and a total mass of around 1 million solar masses.
- **Process:**

1. **Jeans Mass:** If a region of a GMC of a particular size contains more than this amount of matter, the region will begin to collapse under its own gravity.
2. **Fragmentation:** As a clump of material collapses and becomes more dense, smaller regions begin to collapse inside the larger clump.
3. **Protostar:** The fragmented regions heat up due to the release of gravitational potential energy as they collapse (gravity wins over pressure) until the temperature and pressure become high enough to start hydrogen fusion.

Hertzsprung-Russell (H-R) diagram: Plot of **luminosity** (total power output) versus **surface temperature** on which a star is represented by a point at the position matching its current properties (see Figure 10).

- **Main sequence:** A strip on the H-R diagram where most stars spend the majority of their lives. (see Figure 10).
  - **a.** Cool, low mass, dim stars are points at the lower right end of the main sequence.
  - **b.** Hot, high mass, bright stars are points at the upper left end of the main sequence.
  - **c.** Our Sun's point is approximately in the middle of the main sequence.
- **Evolutionary track:** The line formed by the movement of the star's point on the H-R diagram over its lifetime; caused by changes in composition of the star.

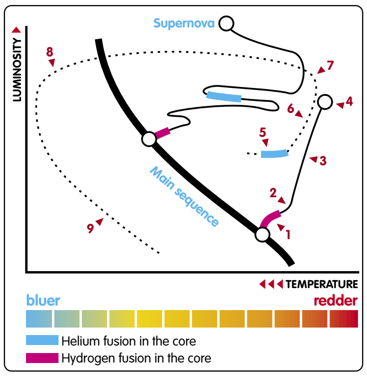


Figure 10

H-R diagram showing the main sequence and the evolutionary tracks of a low mass star and a high mass star

Evolution: The mass (primarily) and composition (secondarily) of a star determine the shape of the evolutionary track a star will follow on the H-R diagram.

- The mass of a star is fixed for the majority of its life, but nuclear fusion changes the internal composition. Thus, changes that occur during the process of fusion are responsible for changes in the star's position on the H-R diagram over its lifetime.
- **Evolution of low mass stars** (less than about 4 solar masses): Stages are numbered in Figure 10.

1. A solar-type star spends 80% of its life on the main sequence.
2. As the star exhausts the supply of hydrogen in its core, it increases slightly in luminosity.
3. When the core runs out of hydrogen, fusion stops and the core begins to collapse (gravity is stronger than pressure). Gravitational potential energy heats the region around the core and a shell of hydrogen just outside the core begins fusion. Due to some complex stability relationships, as the core inside this shell collapses, the rest of the star outside the shell expands and therefore cools, causing the star to become redder. The star has a cooler temperature, but because of the larger surface area, it has an overall increase in luminosity (total energy output). The star is now a **red giant.**
4. The core continues collapsing and heating (as the outer layers expand) until it is hot enough to begin the triple alpha process of fusing helium. This occurs quickly and is called the **helium flash,** although we cannot observe it, since it happens deep in the core of a star.
5. The core expands and the outer layers contract as helium fusion brings stability back to the star. The star gets less luminous, but goes to a higher temperature.
6. When the helium in the core is exhausted, a similar process of core contraction and outer layer expansion occurs—due to helium and hydrogen fusion in shells. This is just like the process in step 3. Once again, the star becomes a **red giant.**
7. Helium fusion is very sensitive to temperature, so bursts of fusion produce thermonuclear explosions in the outer shell called **thermal pulses.**
8. A strong stellar wind begins to blow off the tenuous outer layers of the star. This process takes about 1,000 years. The ejected material expands outward with a speed of 20 km/s, and forms a bright ring called a **planetary nebula** around the (now exposed) hot core of the star.
9. The hot core of the star does not reach the temperatures required to fuse carbon by gravitational contraction (carbon is the product of helium fusion), so it collapses until gravity is balanced by **electron degeneracy pressure.** This is a quantum mechanical effect that results in a constant pressure, regardless of temperature. The core is now called a **white dwarf,** and it continues to cool until its remaining energy has radiated away and it becomes a **black dwarf.**

- **Evolution of high mass stars** (greater than 8 solar masses):
  - **Massive stars live shorter lives:** Essentially, the process of evolution is the same as that of a low mass star until step 6, but the process occurs about 100 times faster.
  - Briefly, the evolution is as follows: hydrogen fusion, core collapse and hydrogen shell fusion to cause the first expansion into a red giant, helium fusion which begins without a helium flash, core collapse and helium shell fusion to cause the second expansion into a red giant, followed by the beginning of thermal pulses.
  - **Type II supernova:** Although the cutoff depends on the star's composition, a star more massive than about 8 solar masses will come to a much more violent end. The core can get hot enough to fuse carbon and then heavier elements. These processes generate energy so quickly that the star may blow itself apart.

STELLAR ENDPOINTS

The final product of stellar evolution is strongly dependent on the mass of the star after it has shed its outer layers. The following are final products:

1. **White dwarf:** For stars with 0.1 to 1.4 solar masses at the end of evolution, the **electron degeneracy pressure** of the material is enough to counteract gravity and hold the object in hydrostatic equilibrium. No fusion occurs in a white dwarf.
   - **Nova:** If a white dwarf has a companion red giant star, fresh hydrogen from the loosely bound outer layers of the red giant fall onto the surface of the white dwarf, igniting a brief thermonuclear explosion until the new hydrogen has been fused.
2. **Neutron star:** If the post-ejection core is greater than 1.4 solar masses (called the **Chandrasekhar limit**), the electron degeneracy pressure is not enough to balance gravity. The resulting gravitational collapse causes free electrons to combine with protons to form neutrons, and it is **neutron degeneracy pressure** that eventually halts the collapse. No fusion occurs in a neutron star.
   - **Type I supernova:** The explosion that occurs when a red giant companion dumps enough mass onto its white dwarf companion to push it over the Chandrasekhar limit. In contrast to a Nova, there is probably nothing left after the explosion.
   - A neutron star could also be the remnant of a **type II supernova** explosion (see *Evolution of high mass stars*).
   - **Pulsar:** A rapidly rotating neutron star.
     - **Lighthouse effect:** The magnetic field axis of the neutron star is offset from its rotation axis. The magnetic field accelerates charged particles that then give off radiation in the direction of the magnetic poles. As the neutron star rotates, we see this light in pulses (see Figure 11).

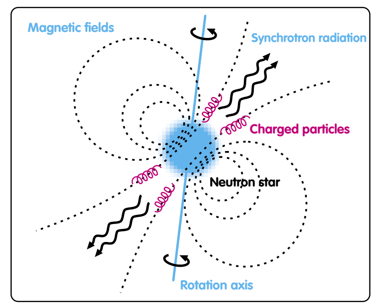


Figure 11: The lighthouse model of a pulsar

3. **Black hole:** A massive star (greater than 3 solar masses after shedding its outer layers) that even neutron degeneracy cannot support.
   - The force of gravity at the star's surface will increase to the point where the escape velocity (see *Orbits* above) will be equal to the speed of light. No light escapes, so the object appears black.
   - Observed by their gravitational effect on other objects (a partner star or surrounding gas), as well as by the intense x-ray radiation any ionized infalling material emits as it is accelerated toward the black hole.

MAIN SEQUENCE MASS RANGES FOR DIFFERENT STELLAR ENDPOINTS

Mass while on the main sequence (in solar masses)	Resulting stellar endpoint
0.1 – 0.5	White dwarf
0.5 – 8	Planetary nebula, leaving a white dwarf
8 – 20	Supernova, leaving a neutron star or black hole
Greater than 20	Supernova, leaving a black hole

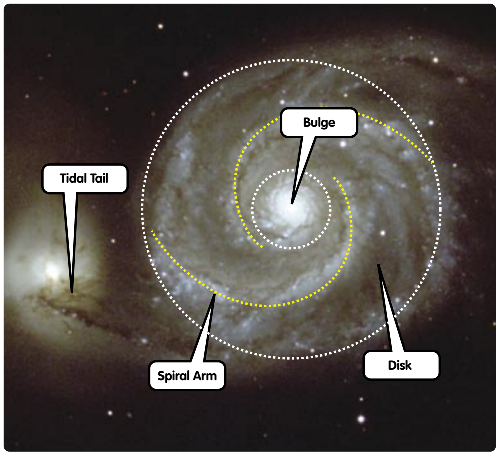
EXTRAGALACTIC ASTRONOMY

GALAXIES AND COSMOLOGY

GALAXIES

Spiral galaxies: The galaxy we inhabit, the **Milky Way,** is an example of a **spiral galaxy** (see Figure 12). Most spiral galaxies are composed of three parts:

1. **Disk:**
   - **Thin:** Diameter is usually 100 times larger than thickness.
   - **Dusty:** Home of the GMCs, the places where starbirth occurs (see *Star Formation*). Thus, the stars in the disk are typically younger.
   - **Spiral arms:** Two or more twisted regions of increased density seen in most disks; they are not unchanging structures. Thought to be density waves.
     - **Density waves:** Stars are slowed down by gravitational effects at certain places along their orbits and thus get bunched up like cars in the bottleneck of a traffic jam.
   - Classified according to how tightly their two or more spiral arms are wound.
2. **Halo:** Spherical region that extends up to ten times farther in radius than the luminous disk.
   - Majority of matter in this component does not emit light (e.g., is **dark matter**), but we know it is present because of gravitational effects.
   - **Globular clusters:** groups of (usually older) stars that orbit in the halo together.



Todd Boroson (NOAO), AURA, NOAO, NSF

Figure 12: M51—The whirlpool galaxy (note: this is also an interacting galaxy)

3. **Bulge:** The thickening of stars and gas at the center of a spiral galaxy.
   - **Supermassive black hole:** The rapid motion of stars and gas very close to the galactic center implies the existence of one of these at the center of most spiral galaxies, including our own.

Elliptical galaxies: The other fundamental type of galaxy.
- Much less dust than spiral galaxies; the absence of dusty GMCs in most ellipticals means there is much less star formation than in spiral galaxies. Thus, most ellipticals are composed of older stars than their spiral counterparts.
- Football-shaped and classified according to how squished that football shape is (see Figure 13).

Interacting galaxies: Although individual stars in a galaxy are so distant from one another that a collision is unlikely, certain places in the universe have a high density of galaxies, so the chance of a galaxy collision is much greater. One theory states that elliptical galaxies are the leftovers from galaxy interactions between spiral galaxies.
- When two spiral galaxies collide, the difference in gravitational force from one side of a galaxy to the other, called the **tidal force,** disrupts the orbits of the stars in the galaxy, causing its spiral shape to be distorted.
- Models predict that streamers of gas and stars, called **tidal tails,** may be the product of such an interaction.

Distances to galaxies: A majority of extragalactic astronomy involves finding the distances to objects. Two of the most useful ways to measure distance are the following:
1. **Standard candles:** If we can predict the theoretical luminosity (total power generated) of an astrophysical event, then we can determine the distance to that phenomenon by comparing the theoretical luminosity to how luminous that event appears in the sky, (e.g., if two friends run away from you in the darkness with identical flashlights, you know the dimmer flashlight is farther away). Examples:
   - **Cepheid variable stars:** Unstable, pulsating stars whose period of pulsation is related to its luminosity.
   - **Supernovae:** Explosions that always have the same peak luminosity (see *Stellar Endpoints*).
2. **Hubble's Law:** Objects that are farther from us move away faster.
   - Expansion of the universe discovered by Hubble in 1924.
   - Mathematically: $v = H_0 \times d$
     v, velocity of receding galaxy (km/s)
     d, distance to galaxy (megaparsecs, Mpc)
     $H_0 \approx 70$, Hubble constant (km/s/Mpc)
   - If the spectrum of a galaxy is redshifted (see *Doppler shift*), we can calculate how fast it is moving away and, from the Hubble Law, calculate its distance.

Galaxy clustering: Galaxies are not uniformly distributed when their three-dimensional positions relative to Earth are plotted. Astronomers have found:
1. **Voids:** Regions with few galaxies.
2. **Clusters:** Regions with many galaxies.
3. **Filaments:** Strings of galaxies connecting the voids and clusters (see Figure 14).

COSMOLOGY

The study of the nature and evolution of the universe as a whole. Assumptions:
1. **The universality of physics:** Physics must be the same everywhere in the universe, otherwise we could not describe it.
2. **The universe is homogeneous:** Matter and radiation are spread out evenly; any clumps (e.g., people, stars, or galaxies) are small compared to the size of the universe.
3. **The universe is isotropic:** Space looks the same regardless of what direction you look.
   Big Bang theory: The universe (and thus, all matter and energy in it) was once compressed into a hot, dense point at some finite time in the past and has expanded ever since. The big bang did not expand *into* anything, but rather space itself expanded. Evidence:
1. **Current expansion of the universe:** Today's expansion implies that all matter and energy were once squished to a hot, dense point.

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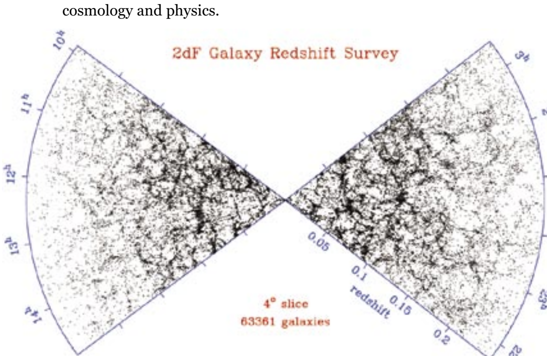
Figure 13: M87—An elliptical galaxy

2. **Abundance of Helium:** Theoretical predictions of this quantity based on the conditions directly after the Big Bang match the abundance of helium found in the oldest stars.
3. **Cosmic Microwave Background Radiation (CMBR):** There should be a leftover glow from the dense, hot conditions of the early universe. The temperature of this "background radiation" has been measured (see *Spectroscopy*) and found to agree exactly with the prediction of a blackbody spectrum at 2.7 K.

Critical Density ($\approx 1.88 \times 10^{-26} \frac{\text{kg}}{\text{cm}^3}$): The future of the universe is determined by comparing its actual density to the critical density. There are three possibilities:
1. **Closed universe:** Average density is greater than critical density.
   - Eventually, the gravitational attraction between all matter will stop the cosmic expansion, reverse it, and the universe will end in a **Big Crunch**.
2. **Flat universe:** Average density is equal to critical density.
   - The gravitational attraction between all matter will slow the cosmic expansion, but will take an infinite amount of time to stop it.
3. **Open universe:** Average density is less than critical density.
   - The gravitational attraction between all matter will slow the cosmic expansion, but expansion will never stop.

Current density estimates:
1. **Visible matter:** Stars and gas that emit light; approximately 0.5% of critical density.
2. **Dark baryons:** Materials made of protons, neutrons, and electrons that do not emit light; approximately 4% of critical density.
2. **Non-baryonic dark matter:** Exotic material that is not the normal matter we are used to (protons, neutrons, and electrons), whose existence is proved by its gravitational effect; approximately 25% of critical density.
3. **Dark energy:** 70% of critical density.
   - Recent observations using type I supernovae as standard candles (see *Distances to galaxies*) have found that the expansion of the universe is not slowing down (as in all models mentioned above), but instead speeding up.
   - **Dark Energy:** A repulsive force introduced by theorists to explain the accelerating expansion of the universe.
     - Represented in equations by Λ, the **cosmological constant.**
     - Its true nature remains one of the most important problems in modern cosmology and physics.



Graphic courtesy Matthew Colless and the 2dF Galaxy Redshift Survey team

Figure 14: A redshift survey showing voids and clusters in the large-scale structure of the universe

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