# Chapter 14 - Light Part II: Interaction with Matter

*But the most remarkable discovery in all of astronomy is that stars are made of atoms of the same kind as those on the earth.*
– Richard P. Feynman

*The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.... Our future discoveries must be looked for in the sixth place of decimals."*
- Albert. A. Michelson, 1894

**Chapter Preview**

Most of astronomy is based on observations dependent on the interaction between light and matter. By spreading light into its component colors, perhaps by means of a prism, one can obtain a great deal of information about the conditions of the object that emitted the light: what it is made of, how hot it is, and so on. This applies to stars as well as laboratory light sources. It is one of the fundamental assumptions of astronomy that the laws of physics are the same everywhere in the Universe as they are in our laboratories here on Earth. In this chapter we will look at the laboratory end of the relationship. In order to examine the interactions between light and matter that are essential in understanding stars, planets, and the Universe in general, we will find that the wave model of light is inadequate. It is necessary to introduce an alternate model or means to describe the interaction between light and atomic matter. The particle, or photon, model of light is introduced in this chapter.

**Key Physical Concepts to Understand:** *particle model of light, Bohr model of the atom, the origin of emission and absorption lines, Kirchoff's laws*

## I. Introduction

By the end of the 19$^{th}$ century, it was a generally held view that all of the major problems of physics had been solved. In 1900, the renowned British physicist, Lord Kelvin, stated *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."* It was thought that if Newtonian mechanics, electromagnetic theory based on the wave nature of light, and **thermodynamics** (the study of heat and energy) were applied in sufficient detail, any physical phenomena could be explained. It wasn't until the 20$^{th}$ century that physicists found fundamental flaws in physics that needed to be repaired with new theories. In particular it was discovered by Max Planck in 1899 that the wave nature of light was not adequate to explain the interaction of light with matter. This is of particular importance to astronomers who investigate the nature of matter in cosmic objects, e.g. stars and planets, by studying light that has interacted with the material in them.

## II. The Photoelectric Effect – The Particle Nature of Light

One of the first indications that light doesn't always behave as a wave appeared in experiments in the latter part of the 19th century with the **photoelectric effect**. The photoelectric effect is the ejection of electrons from a surface when it is illuminated by light. This effect is used in to detect light beams in burglar alarms, door openers, and in movie sound tracks. In a **photocell,** light hitting a photoelectric surface will liberate electrons, which can produce an electric current. Without light the photocell generates insignificant current.

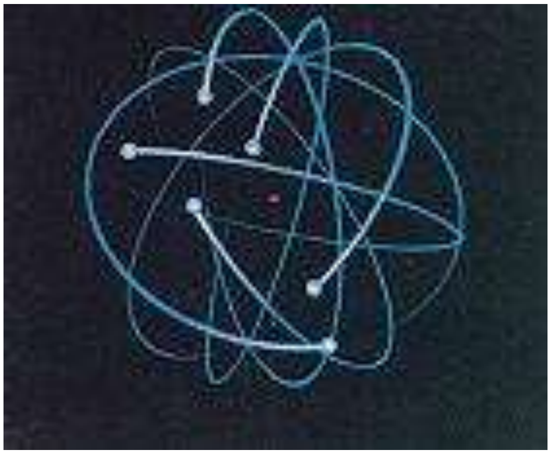


**Figure 1.** *Rutherford's model of the atom. In the Rutherford model, electrons orbit the nucleus in a swarm. This model is not to scale and does not illustrate the vast distances between the electrons and the nucleus compared to their sizes, nor does it show that the electrons are much smaller than the nucleus.* ***Modified KW 528-22-12.***

The gross properties of the photoelectric effect can be explained by the classical wave theory of light. Waves of light impact the photoelectric surface, depositing their energy there. Atoms that make up the surface absorb this wave energy. The surface atoms consist of negatively charged electrons orbiting positively charged atomic nuclei (Figure 1). As the waves of light crash against the surface the electrons are set into vibrations at larger and larger amplitudes (energies) until they acquire enough energy to break free of the surface. At this point they are ejected into space.

This classical wave picture has problems with results seen by experimenters in the laboratory:

1. When light shines on a photoelectric surface there is no measurable time lag between the light being turned on and the photoelectric electrons being expelled, regardless of how weak the beam intensity is.
2. Light of the "wrong color", or below a certain threshold frequency, will not free photons no matter what the intensity of the light beam. Some surfaces, for example,

will eject electrons when they are illuminated by blue visible light, even at low intensity, but will not liberate electrons when illuminated by yellow light no matter what the intensity.
3. The number of electrons ejected is proportional to the intensity of the illumination.
4. The maximum energy of the freed photons is not dependent on the illumination intensity but is dependent on the frequency, or color, of the light.

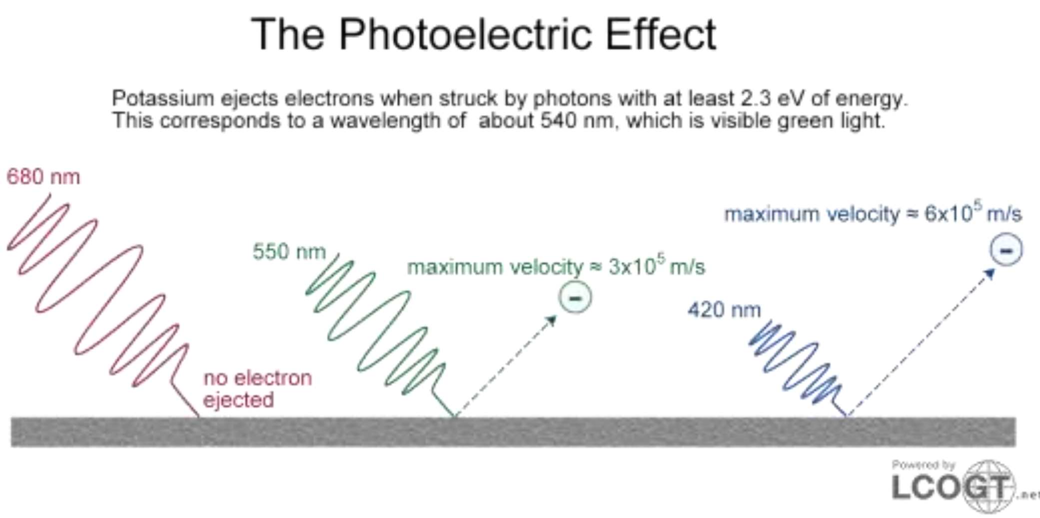



**Figure 2.** *A schematic of the photoelectric effect.* ***From lcogt.net***

In 1905 Einstein proposed another model of the photoelectric effect, based on the particle nature of light. (Einstein received the Nobel prize in 1921 for his theory of the photoelectric effect, not for his theory of relativity.) If light behaves as a particle, called a **photon**, with its energy proportional to its frequency, then the observed properties of the photoelectric effect can be explained in a straightforward manner (Figure 2):

1. When photons strike a photoelectric surface each photon either has enough energy to liberate an electron or it doesn't. In general the energy deposited by light striking the surface will either immediately eject an electron or be dissipated by the surface; it is not be stored by the electrons. As a result, there is no time lag between photons striking the photoelectric surface and electrons being ejected.
2. Electrons in a photoelectric surface require some minimum energy to be ejected. If light is composed of individual photons with energy proportional to frequency, **or $E = hf$**, where h is a constant of proportionality, then when each individual photon strikes the photoelectric surface, either it has sufficient energy to liberate an electron or it doesn't. There will be some threshold frequency below which photons will not have sufficient energy to free an electron, above which photons will carry enough energy to eject a single electron.
3. If light of a specific frequency is able to free electrons from a photoelectric surface then the number of electrons liberated will be proportional to light intensity, or equivalently, the number of photons striking the surface. However, if the frequency of the incident light is such that each photon has inadequate energy to liberate any

photons, then no electrons will be expelled, no matter what the intensity of light striking the surface.

One illustration of the photon (or particle) nature of light is the manner in which photographic film is exposed (Figure 3). Photographic film consists of a dense array of silver halide grains suspended in a gel or **emulsion**. When each grain has been struck by a photon it becomes exposed and completely darkens. If a picture is taken using film in a camera in a dark room, an underexposed image containing a random-looking distribution of dots, each due to a single photon, will appear. As the exposure time is increased an overall pattern becomes evident. As the proper exposure time is reached a clear picture appears. The image is built up piece by piece as each photon strikes the photographic film and darkens it.

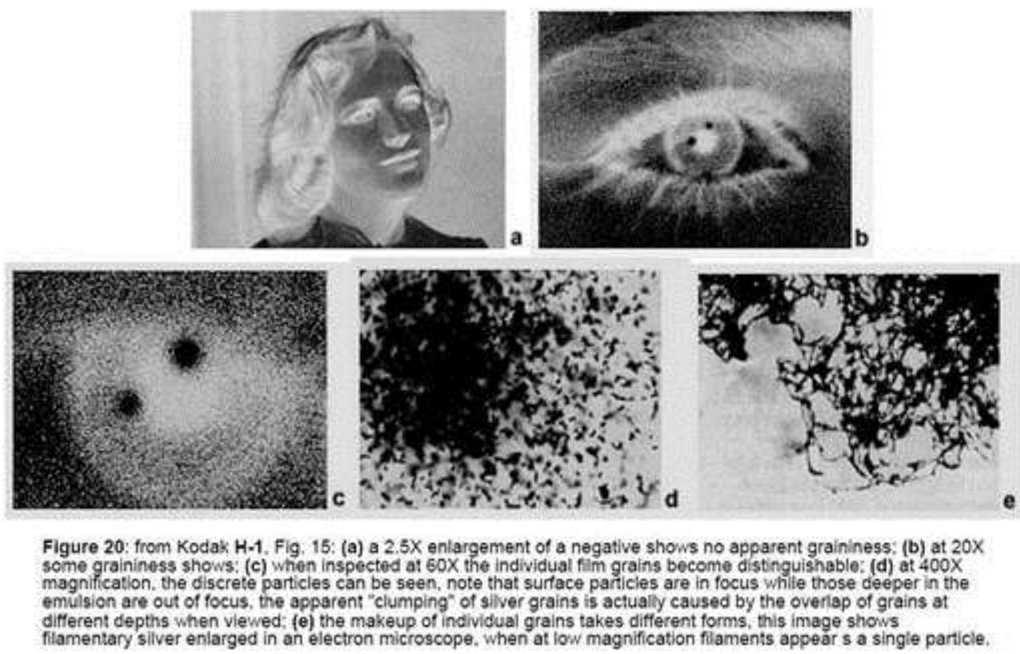



**Figure 3.** *Exposed photographic film. This figure shows a single photograph seen at magnifications of 2.5, 200, and 400, the latter showing individual grains which turn dark on exposure to light. From digitalartform.com*

### III. The Wave-Particle Paradox and the Quantum Nature of Light

Now we have two **models**, or ways that the behavior of light can be described mathematically. The wave model of light describes most optical phenomena well, such as the reflection and bending of light, as does the particle model. **But a particle model must be used to explain the photoelectric effect; the wave model must be used to explain interference effects (Chapter 5, Section III), such as the colors seen in light reflected from a soap bubble or in light passing through a double slit.** We have a physical paradox here: light behaves like a wave in some experiments, and like particles in others. Surely the light itself can't change its properties depending on the experiment performed. The problem is the inadequacy of the two models; light is more complicated than previously thought.

The German physicist Max Planck proposed the basic ideas for the modern **quantum theory of light** in 1900. It was known that the observed blackbody spectra of solids were not consistent with a wave model of light so he proposed a theory of light whereby it consists of bundles or "**quanta**" of energy. Modern quantum physics is the bridge that unites the particle and wave properties of light. In essence, light behaves as a wave packet (Figure 4), a localized wave of finite length, a bundle of energy.

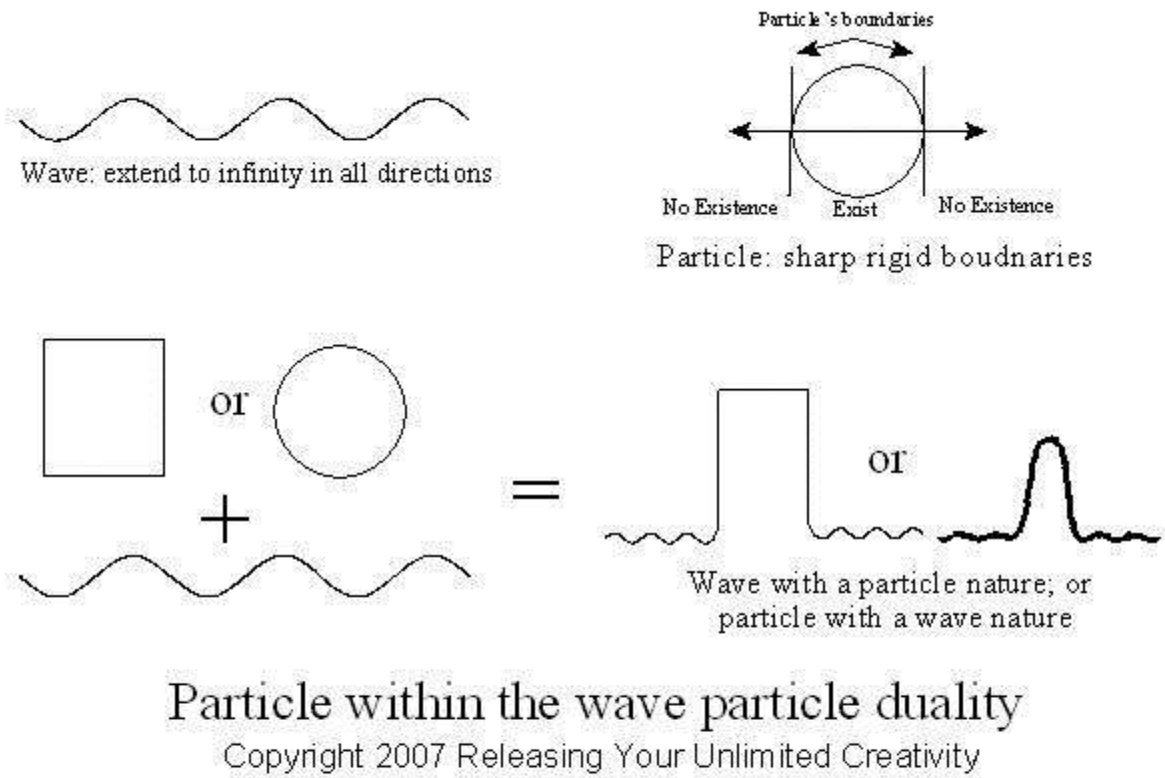



**Figure 4.** *Schematic of showing wave, particle, and wave-particle models of light.*

If light can be modeled as a particle, can electrons, protons, and neutrons be modeled as waves? The French physicist Louis de Broglie examined this question in his Ph.D. thesis in 1924, for which he later won the Nobel prize in physics. De Broglie developed a theory in which particles were attributed wave properties, which depend on their energy and mass. He predicted that all bodies have wavelike properties (with large bodies, like you and me having wavelengths that are so short as to be immeasurable). Subsequent measurements verified this theory by showing that electrons, neutrons, and protons exhibit interference effects as does light.

**WebVideo: Neutrons as Particles and/or Waves**
**http://www.toutestquantique.fr/#dualite**

**IV. Pre-Quantum Models of the Atom**

"The first concept that matter is composed from basic building blocks, which we call the atom, came from the **early Greek philosophers Leucippus and Democritus 2500 years ago. The Greeks considered that if one cut matter apart into smaller and smaller pieces, eventually a limit would be reached when the pieces were no longer divisible but had reached some limiting size: the atom. The Greeks conceived of only four elements, or kinds of atom: earth, air, fire, and water. When combined in various ways these would explain all of the objects in nature."**

**"In 1808 the British chemist John Dalton proposed that matter consists of a number of different elements with different properties, having something to do with their different shapes, which somehow connected to form molecules. These combinations would explain the different properties that different materials have. Dalton's theory was based on his observations that different materials seem to react together in well-defined proportions. An actual measurement of the size of an atom, typically a few $10^{-10}$ meters in diameter, did not occur until the $19^{th}$ century."**

One of first indications that atoms had internal structure was the observation in the $19^{th}$ century that atoms of each element produced a unique emission spectrum. It was seen that any material would give off light when heated. If this light passed through a spectrometer it could be analyzed and used to determine chemical composition.

At the beginning of the $20^{th}$ century and end of the $19^{th}$ century experiments were beginning to show the internal structure of the atom. A New Zealand physicist working in Britain, Ernest Rutherford, began probing the internal structure of the atom by firing particles from radioactively decaying material into gold foil. A small fraction of the particles hitting the gold rebounded, reversed direction, and came flying directly backwards. This result was possible only if almost all of the mass of the gold atom were concentrated in a tiny positively charged nucleus with vast space between nuclei (Figure 5). Rutherford proposed that the negatively charged electrons were orbiting the atomic nucleus in a three-dimensional swarm of Keplerian elliptical orbits, like planets in a miniscule solar system.

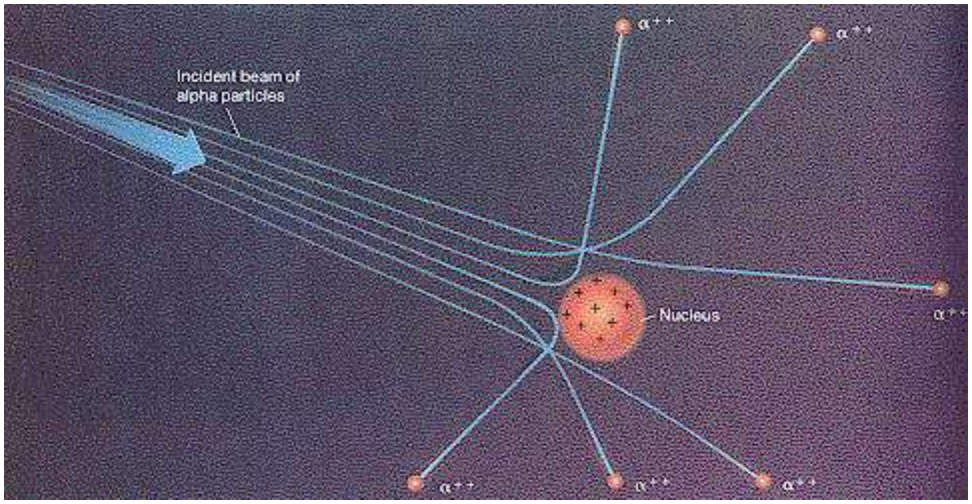



**Figure 5.** *Physicist Ernest Rutherford, began probing the internal structure of the atom by firing particles from radioactively decaying material into gold foil. The manner in which particles were scattered by the nucleus, allowed Rutherford to model the physical properties of the nucleus.*

However there was a serious problem with this model, the stability of an electron's orbit. Electrons orbiting a nucleus act like oscillating currents in an antenna, they give off electrical energy as they orbit, eventually spiraling into the nucleus in a short time interval, roughly $10^{-8}$ seconds, as they give off light. This light would have a continuous spectrum, not a spectrum with emission or absorption lines, as is observed for atomic gas lamps.

## V. The Bohr Atom

In 1913 the Danish physicist Niels Bohr used the quantum theory of Planck and Einstein to model the atom. The **Bohr model** of the atom is a *planetary* model, that is relatively low-mass electrons orbit the high-mass nucleus in circular orbits, bound to the nucleus by the electrical force between the positively charged nucleus and the negatively charged electron(s). In the hydrogen atom, for example, the nucleus consists of a single proton, which is orbited by an individual electron (Figure 6). The electrical force between electron and proton falls off with the inverse square of the separation distance, as it does for gravity.

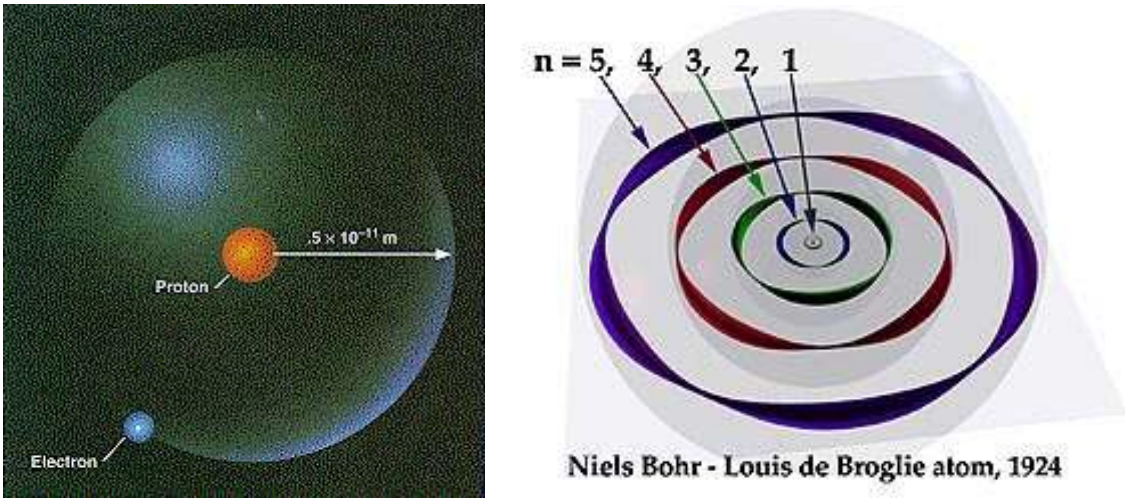



**Figure 6.** *The Bohr model of the atom. Left Panel*: *A schematic diagram of the Bohr model of a hydrogen atom in its lowest energy state. The electron is held in a circular orbit about the nucleus by the electrical attraction between oppositely charge particles.* ***FMW 96-4.13.*** *Right Panel: Each energy state in the atom corresponds to an electron orbit with a circumference corresponding to an integer number of wavelengths. From* ***kennethsnelson.net***

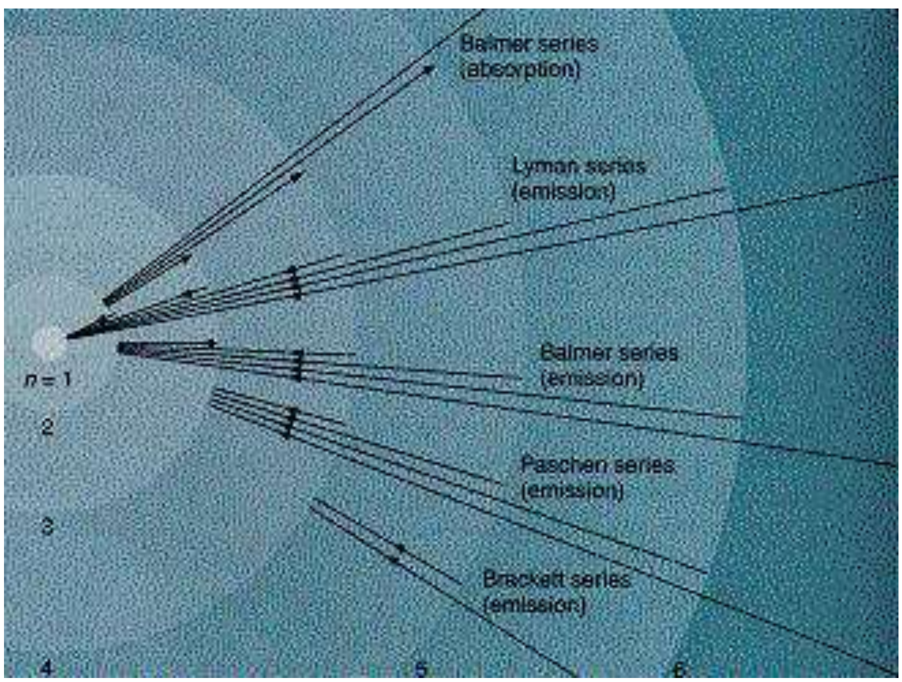



**Figure 7.** *Emission and absorption lines in the Bohr model of the hydrogen atom. Each concentric circle represents a possible orbit for an electron. Arrows drawn inward indicate electrons falling in energy, producing an emitted photon. Arrows drawn outward represent an electron gaining in energy after absorbing a photon. Each series of lines represents transitions in and out of a single energy level, and is named after the prominent scientist who discovered it.* **FMW 98-4.16.**

Electrons are not allowed orbits of arbitrary radius. In the Bohr model, electrons can be thought of as waves, and orbits are only allowed that have an integer number of wavelengths in circumference (Figure 7). We will refer to these radii as $r_n$, where n = 1,2,3 …, and the corresponding electron energies as $E_n$. Although the hydrogen atom normally has a single electron, it has an infinite number of potential orbits. When the electron is in the closest orbit to the nucleus, corresponding to $r_1$ it is in its lowest energy level, or state, called the **ground state**. The atom is then said to be unexcited. If the electron gains energy, by collision with another atom or the absorption of a photon, the electron can use this energy to jump to an orbit further from the nucleus which corresponds to an orbit of greater energy. The electron is then said to be in an **excited state**. Roughly, this corresponds to a satellite orbiting the Earth. If one wants to put it in an orbit of higher altitude, then a rocket engine burn must expend energy to push the satellite into a higher orbit against the force of gravity. In the case of the atom, the energy is expended in pushing the electron against the attractive electrical force from protons in the nucleus.

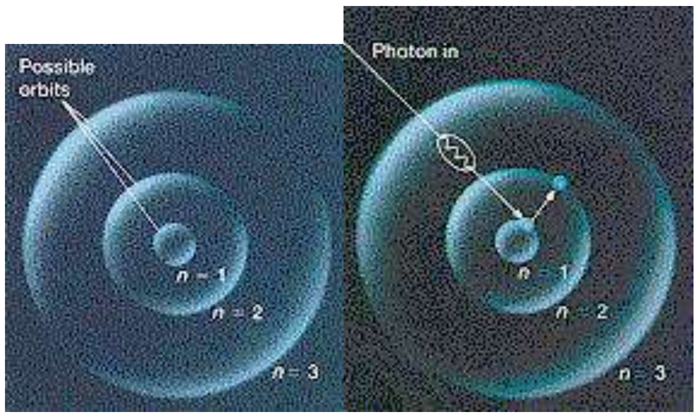



**Figure 8.** *The interaction between light and matter.* ***Panel A:*** *If a photon striking an atom has the correct frequency it will be absorbed and boost an electron from a lower energy level to a high one, the energy difference between the levels corresponding precisely to the energy of the photon.* ***Modified KW 535 22.18. Panel B:*** *If an electron orbiting an atomic nucleus falls from one orbit to one of lower energy, a photon will be emitted with an energy equal to the energy difference between the two orbits.* ***Modified KW 535 22.19.***

**How do light and matter interact?** That depends on the energy of the photons; since **E = hf**, it also depends on the frequency or color of the light. (Blue photons have a higher frequency and therefore carry more energy than red light. Chapter 5 - Section III.) When light strikes an atom it can pass through the atom or it can be absorbed. If light is absorbed its energy goes into moving an electron from one energy state to one of higher energy (Figure 8). But an atom cannot absorb any photon that strikes it. The incident photon must have precisely the right amount of energy to boost an electron from its current orbit into an *allowed* excited state of higher energy. If the electron in a hydrogen atom is in a state corresponding to $r_n$, it may absorb only photons of energy $E_{n+1} – E_n$, $E_{n+2} – E_n$, $E_{n+3} – E_n$, etc. Atoms will remain transparent to light at other wavelengths.

This process of exciting atoms can be reversed, causing the emission of a photon by an excited atom (Figure 8). Electrons in an excited state will eventually spontaneously fall to a lower energy state. When this happens, the energy that is generated by the electron dropping to a lower energy orbit goes into creating a photon, which immediately zips off at the speed of light. The energy of the photon is the energy difference between the two orbits, $E_m – E_n$, where the two energy levels are m and n.

**VI. Spectral Lines**

The Bohr model of the atom correctly predicts the behavior of light interacting with atoms in a gas. Figure 9 shows the spectrum of visible light from the Sun. In 1815 the German physicist Joseph Fraunhofer discovered that a forest of absorption lines breaks up the white light spectrum of the Sun; these absorption lines are frequencies in the spectrum where the light intensity is relatively low. Figure 10 shows the *emission* from hydrogen, argon, and xenon gas lamps. Notice the difference among the spectra of each of these elements. The nucleus of each element is characterized by a different number of protons, giving rise to different electrical forces imparted to its electrons and different electron energy levels. The result is that each element has its own characteristic spectrum, hence each element has its own unique spectrum, its fingerprint. Helium (from the Greek word *helios* for Sun) was discovered in 1868, not from its detection on Earth, but from its appearance as an unidentified element in the solar spectrum. This is just one illustration of the importance of the use **spectroscopy** in astronomy, for the detection of elements and their abundances in stars.

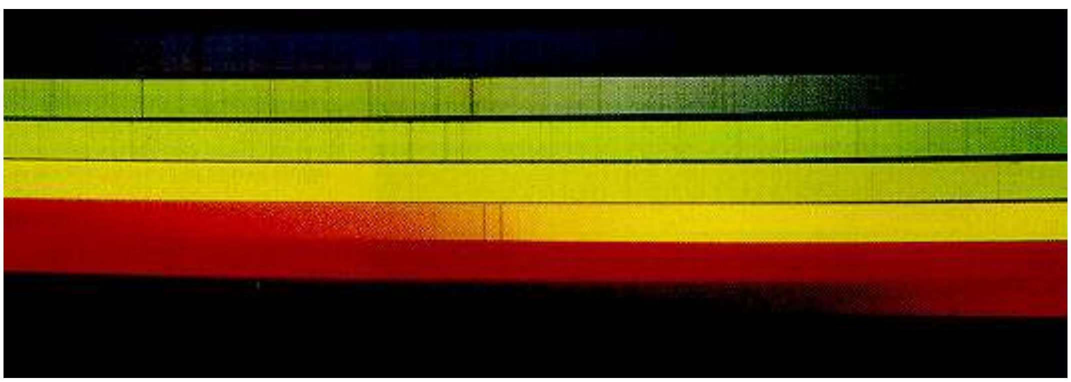


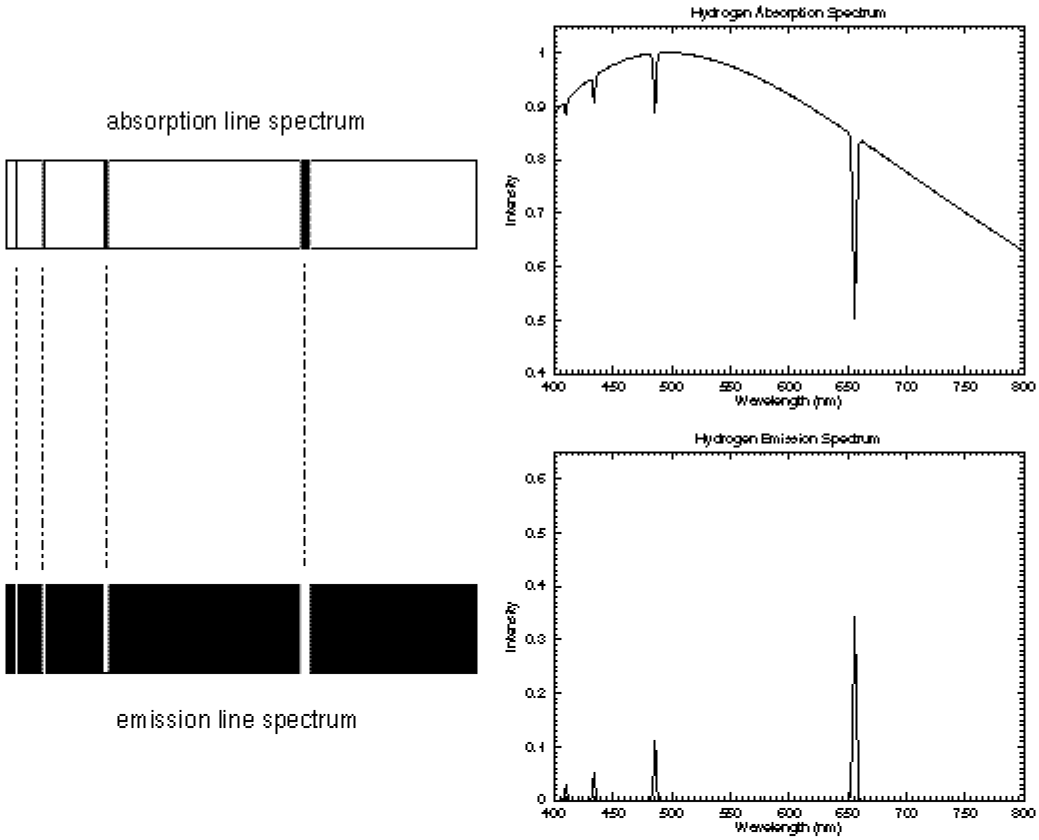
**Figure 9.** *The visible solar spectrum. The dark lines in the spectrum are absorption lines produced in the outer atmosphere of the Sun and serve as "fingerprints" of the atomic species found there.* ***FMW 93-4.10.***

**When does one see emission lines and when does one detect absorption lines?** An empirical set of rules for the manner in which light interacts with matter was developed in 1860 by the German physicist Gustav Kirchoff, and are called **Kirchoff's laws** (Figure 10):

1. A hot tenuous gas gives off an emission line spectrum.

2. A hot solid, liquid, or dense gas emits a continuous spectrum with no lines (nearly a blackbody spectrum in the case of a solid or liquid, which are close to being ideal radiators). (Chapter 5, Section VII).)
3. A continuous spectrum that passes through a relatively cool gas results in an absorption spectrum superimposed on the continuous spectrum.

Examples of emission spectra are the spectra from the atomic gas lamps shown in Figure 11. Other examples are mercury vapor street lamps and the common household florescent lamp in which an electric current is passed through mercury vapor. Atoms in each of these gases are excited using an electric current. When an atom is excited, one of its electrons is kicked into an orbit higher in energy. Later this electron will spontaneously fall to an orbit of lower energy; then a photon is emitted. The end result is that electrical energy is expended and light is given off.




Two ways of showing the same spectra: on the **left** are pictures of the dispersed light and on the **right** are plots of the intensity vs. wavelength. Notice that the pattern of spectral lines in the absorption and emission line spectra are the **same** since the gas is the same.

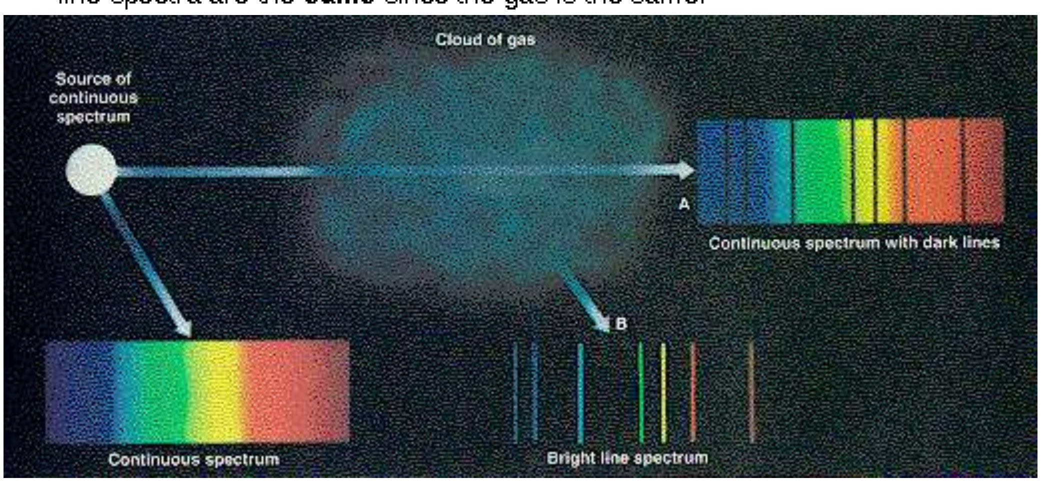



**Figure 10**. *The production of a continuous spectrum, emission lines, and absorption lines according to Kirchoff's laws. A hot solid, liquid, or dense gas generates a continuous spectrum. If a continuous spectrum is passed directly through a cooler cloud of gas, discrete absorption lines will be produced. A hot diffuse gas produces an emission line spectrum.* ***Modified FMW 99-4.18.***

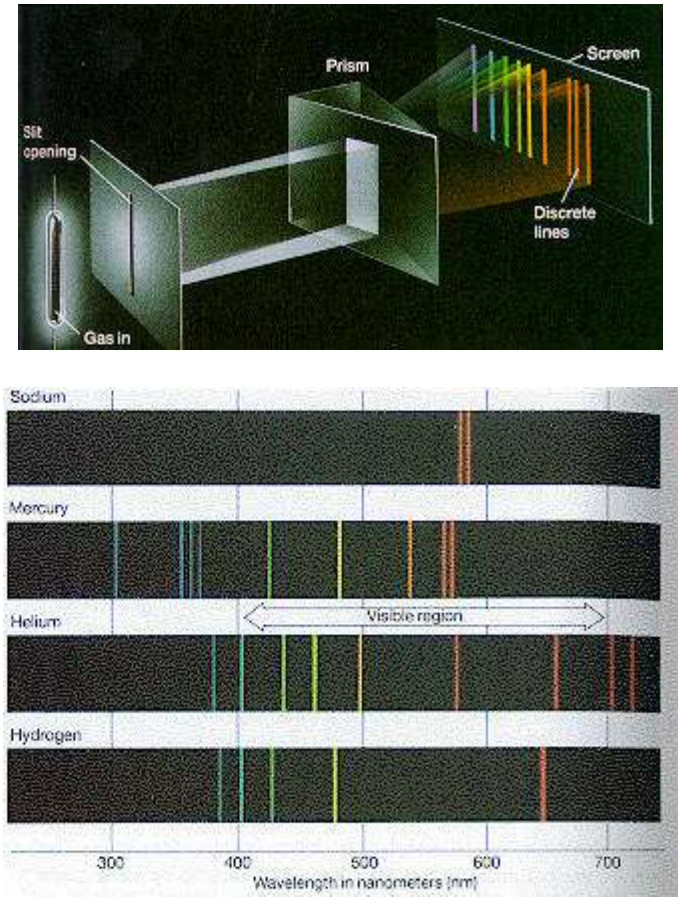



**Figure 11**. *The emission spectrum of a glowing gas.* ***Panel A:*** *The spectrum of a hot gas consists of a series of discrete emission lines. These lines can be seen when the light is spread into a spectrum by passing it through a prism.* ***KW 520-22.2. Panel B:*** *A schematic of the emission line spectral "fingerprints" for sodium, mercury, helium, and hydrogen gases.* ***KW 521-22.3.***

An example of a continuous spectrum is the approximate blackbody spectrum given off from an ordinary incandescent light bulb when the filament is heated by the passage of electric current through it.

An example of an absorption spectrum is the solar spectrum (Figure 9). Light with a continuous spectrum is emitted by hot dense gas in the Sun's interior. As it passes through the (relatively) cooler gas in the Sun's outer atmosphere the atmospheric gases absorb photons at those wavelengths matching allowed transitions for atoms that occupy the solar atmosphere. The result is the forest of hundreds of absorption lines in the visible solar spectrum.

**WebVideo: Identification of Spectral Lines**
**http://www.youtube.com/watch?v=g5ESplRCTdA**

## Summary

The wave model of light is inadequate in explaining the photoelectric effect, the ejection of electrons from a surface struck by light. The particle, or photon model, successfully models the interaction between light and matter. Light can be modeled as photons where each photon has energy proportional to its frequency. In turn, particles of matter, such as electrons and protons, can successfully be modeled as waves. The quantum theory of light is a combination of the wave and particle models, in which light and atomic particles are modeled as wave packets. The Bohr model of the atom describes an atom as a nucleus of neutrons and protons enveloped by electrons in discrete circular orbits, where each allowed orbit is an integer number of wavelengths in circumference. Atoms can absorb light having precisely the right amount of energy to boost an electron from one allowed orbit to a higher orbit. This process can be reversed; atoms can emit light having the same wavelength or energy if it moves from this higher state back to its former low energy state.

An empirical set of rules for the manner in which light interacts with matter are called Kirchoff's laws:

1. A hot tenuous gas gives off an emission line spectrum.
2. A hot solid, liquid, or dense gas emits a continuous spectrum with no lines (nearly a blackbody spectrum in the case of a solid or liquid, which are close to being ideal radiators).
3. A continuous spectrum that passes through relatively cool gas results in an absorption spectrum superimposed on the continuous spectrum.

## Key Words & Phrases

1. **Bohr model -** a model of the atom in which electrons orbit the nucleus in circular orbits, bound by the electrical force between the positively charged nucleus and the negatively charged electron(s).
2. Emulsion **-**
3. **Excited –** when an electron in an atom is in an orbit about the nucleus of greater radius and higher energy than the ground state
4. **Ground state –** the lowest energy state of an electron in an atom, corresponding to the closest orbit to the nucleus
5. Photocell **-**
6. **Photoelectric effect –** the phenomenon in which a photon hitting a material surface liberates one or more electrons from the atoms composing the surface
7. Photon – a particle of light
8. **Quantum** – the smallest unit of energy

9. **Quantum Theory of Light -** a dual wave/particle theory in which light, as well as atomic particles, are modeled as waves of short length or wave packets
10. **Thermodynamics -**

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**Review for Understanding**

1. Summarize, in your own words, Kirchoff's laws.
2. Describe the photoelectric effect in your own words.
3. Describe a property of light that can only be satisfactorily explained by a wave model. A particle model.
4. Why does hydrogen absorb only light having specific wavelengths?

**Essay Questions**

1. In quantum theory, how do the models for light and atomic particles differ? How are they the same?
2. Give examples of light sources that give rise to emission lines, absorption lines, and continuous radiation.
3. How are emission lines, absorption lines, and continuum formed?

# Chapter 15 - The Sun: Our Nearest Star

*The test of all knowledge is experiment. Experiment is the sole judge of scientific truth.* – Richard P. Feynman

**Chapter Figure.** *A 1973 Skylab image of the Sun showing a solar prominence.* **NASA.**

**Chapter Preview**

Most of the observable Universe is filled with stars and stars are its most visible component. When astronomers look for extrasolar planets, they look for the effect of such a planet on its mother star. Galaxies, including our own Milky Way, appear to be assemblages of stars in one form or another and galaxies are used as probes of the structure of the Universe. Stars are literally and figuratively the most visible building block in our Universe. But the only star that can be studied at high resolution and in detail is our own Sun; only a handful of stars can be resolved into anything other than a pinpoint of light. The result is that the Sun is fundamental in our understanding of stars in general and plays an important role in understanding the Universe as a whole.

**Key Physical Concepts to Understand:** *the structure of the Sun's atmosphere, the relationship between solar activity and the Sun's magnetic field, the relationship between solar activity and the Earth's climate*

## I. Introduction

To us as humans the Sun represents one of the two most important celestial bodies in the Solar System. The Sun is the ultimate source of power for the Earth providing the light and warmth necessary for life. It is obviously the brightest star in the sky. The Sun is a garden-variety star with near-average mass and diameter, usual in every respect save one; it is the closest star to us.

**Table 15.1:** *Bulk Properties of the Sun*

| Property | Value |
|---|---|
| Radius | 696,000 km |
| Mass | $1.99 \times 10^{30}$kg |
| Photospheric Temperature | 5,800 K |
| Core Temperature | 15 million K |
| Mean Density | 1400 kg/$m^3$ |
| Rotation Period | 26 days – equator |
| | 31 days - poles |

The Sun is an enormous glowing ball of hot gas, roughly 100 times the diameter of the Earth and 300,000 times its mass. Spectra tell us that 60% of the mass of the Sun is hydrogen (80% of the atoms by number), and approximately 39% is helium. Roughly 1% is heavier elements such as carbon, nitrogen, and oxygen. The luminosity of the Sun is enormous, it emits approximately 3.9 x 1026 watts, and has been for about 4.6 billion years. What powers the Sun? The Sun is powered by thermonuclear fusion deep in its interior, exquisitely regulated by the simplest thermonuclear thermostat, gravity. We will study the Sun's power generation in Chapter 16.

## II. The Solar Atmosphere

The outer part of the Sun that we can see from Earth can be divided into three parts, the **photosphere**, **chromosphere**, and **corona** (Figure 1). Using our knowledge of the physics of gases and the way atoms absorb and emit light, we can calculate how the gas temperature, density and pressure varies with altitude in the solar atmosphere.

*Photosphere*

The solar **photosphere**, meaning "sphere of light", is the opaque outer "surface" layer of the Sun that we see when we look at the Sun. The chromosphere and corona are transparent, so they aren't normally observed. The photosphere emits like a blackbody with a temperature of 5,800 K. The gas pressure in the photosphere is a few percent of the Earth's atmospheric pressure (at its surface) while the density is 10,000 times less than that of the Earth's atmosphere.

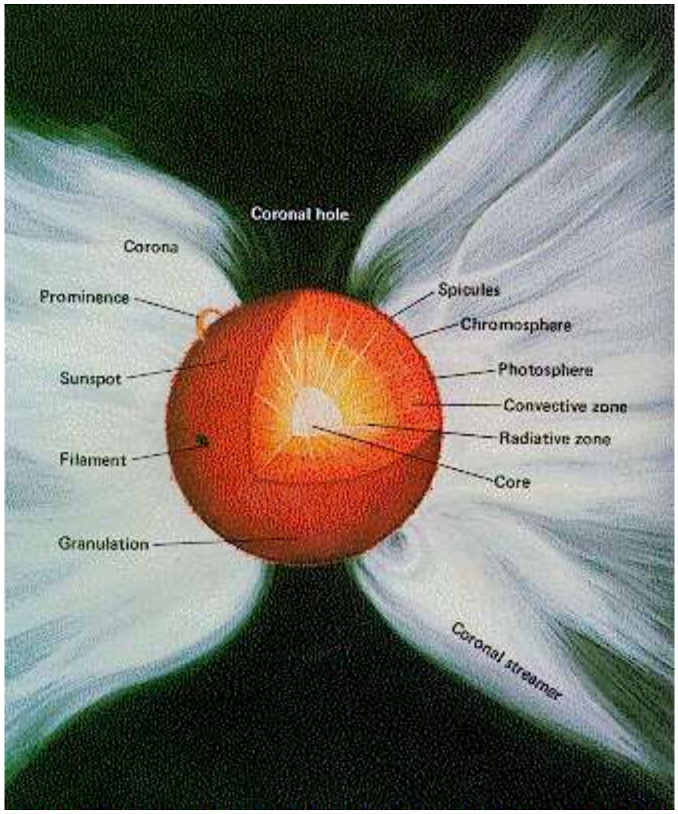


**Figure 1.** *The structure of the Sun. The light that we see originates in the solar photosphere. Above the photosphere are the thin chromosphere and the hot, extended corona. The Sun is approximately 1.3 million kilometers in diameter.* ***P 388-23.2.***

*Chromosphere*

Above the photosphere is a tenuous layer normally only seen by the unaided eye during an eclipse as a red fringe encircling the Sun (Figure 2). The color of the **chromosphere,** or "sphere of color" is produced by red emission lines from hot hydrogen gas. Helium was first discovered, by the French astronomer Pierre Janssen in 1868, in the Sun's chromosphere from its emission lines. The chromosphere is 2,000 to 3,000 km thick with a temperature of about 10,000K. It is not uniform, but contains a forest of flame-shaped jets of gas, called **spicules**, pushing 10,000 km into the upper atmosphere above it with typical velocities of 70,000 km/h (Figure 3). Each spicule has a lifetime of only minutes.

**Figure 2.** *The chromosphere seen during an eclipse. The red color is due to emission from the hydrogen alpha line.* ***P Chapter 23 Cover.***

**Figure 3.** *A forest of solar spicules, jets of gas poking into the solar chromosphere.* ***FMW 291-14.3.***

*Corona*

The uppermost layer of the solar atmosphere is the Sun's corona; like the chromosphere it is only visible to the unaided eye during a solar eclipse (Figure 4). The **corona** extends millions of kilometers above the photosphere, emitting half as much light as the full moon, but a million times fainter than the solar photosphere. The corona has a density of only $10^{-10}$ Earth atmospheres but has a temperature 1-2 million K. This temperature is hot enough that the extremely fast moving atoms in the corona become stripped of many of their electrons in high velocity collisions between atoms. Spectra of the corona show emission lines from iron that has been stripped of 13 of its outer electrons. **Why does the temperature of the Sun's atmosphere increase with increasing altitude, farther away from the thermonuclear furnace powering the Sun?** The high temperature of the corona is produced by the supersonic outflow of matter from the photosphere, carried through the solar atmosphere by convection. Although the coronal temperature is extremely high, because its gas density is extremely low it removes little heat energy from the sun.


**Figure 4.** *The total solar eclipse of 1980. With emission from the Sun's photosphere blocked by the Moon, the corona becomes visible. The out-flowing coronal gas becomes the solar wind.* ***High Altitude Observatory Archives.***

*Granulation*

Convection cells covering the solar photosphere, called **granules**, give the solar photosphere the granular appearance of oatmeal (Figure 5). Individual granules are 300-1000 km in diameter with a temperature contrast of 50 to 100 K from center to edge. The interior portion of the granules is flowing upward at 2 to 3 kilometers per second (Figure 6). They form and disappear over a period lasting several minutes, convectively transporting gas to the surface, which then radiates energy into space. Subsequently the cooler, denser material sinks back toward the Sun's interior along the outer edge of the granule. Larger convection cells, called **supergranulation**, are 30,000 kilometers in diameter (larger than the Earth's diameter) and flow from center to edge (Figure 7). Each supergranule contains about 1000 granules.

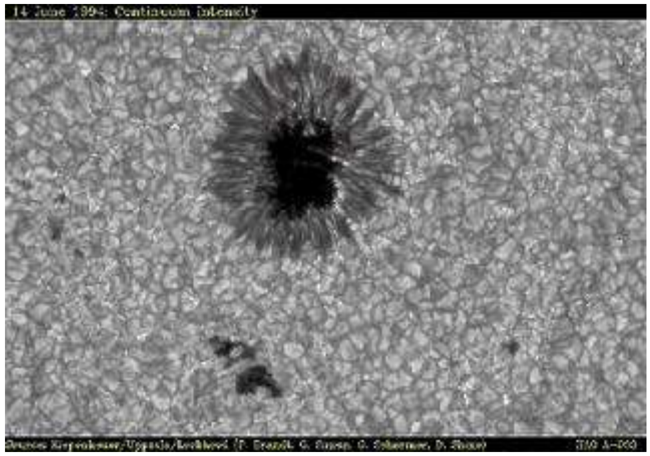

**Figure 5.** *A high-resolution photograph of a sunspot and the surrounding solar granulation. The field of view is 60,000 km by 38,000 km. The darkest portion of the sunspot has approximately the same diameter as the Earth. The mottled granulation is the pattern associated with rising and falling convection cells, transporting energy from the Sun's interior to the photosphere. The brighter columns of the granulation pattern are hotter rising gas cells, roughly 1000 km across, the darker areas between are cooler sinking gas cells.* ***AOPD or FMW 295-14.9.***

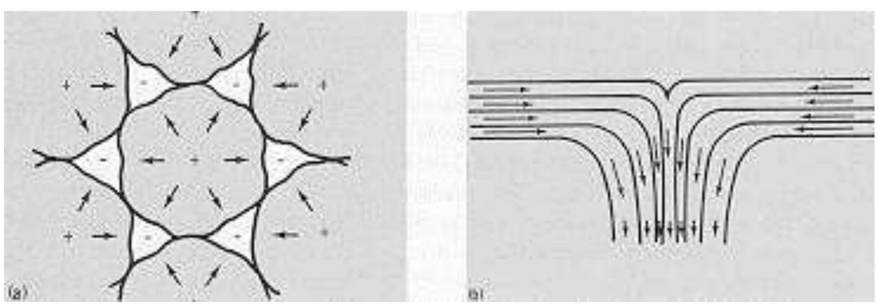


**Figure 6.** *Flow of gas within a solar granulation cell. + indicates upward motion, - downward motion.* ***The Quiet Sun. p. 165, Figure 5-8, Modified.***

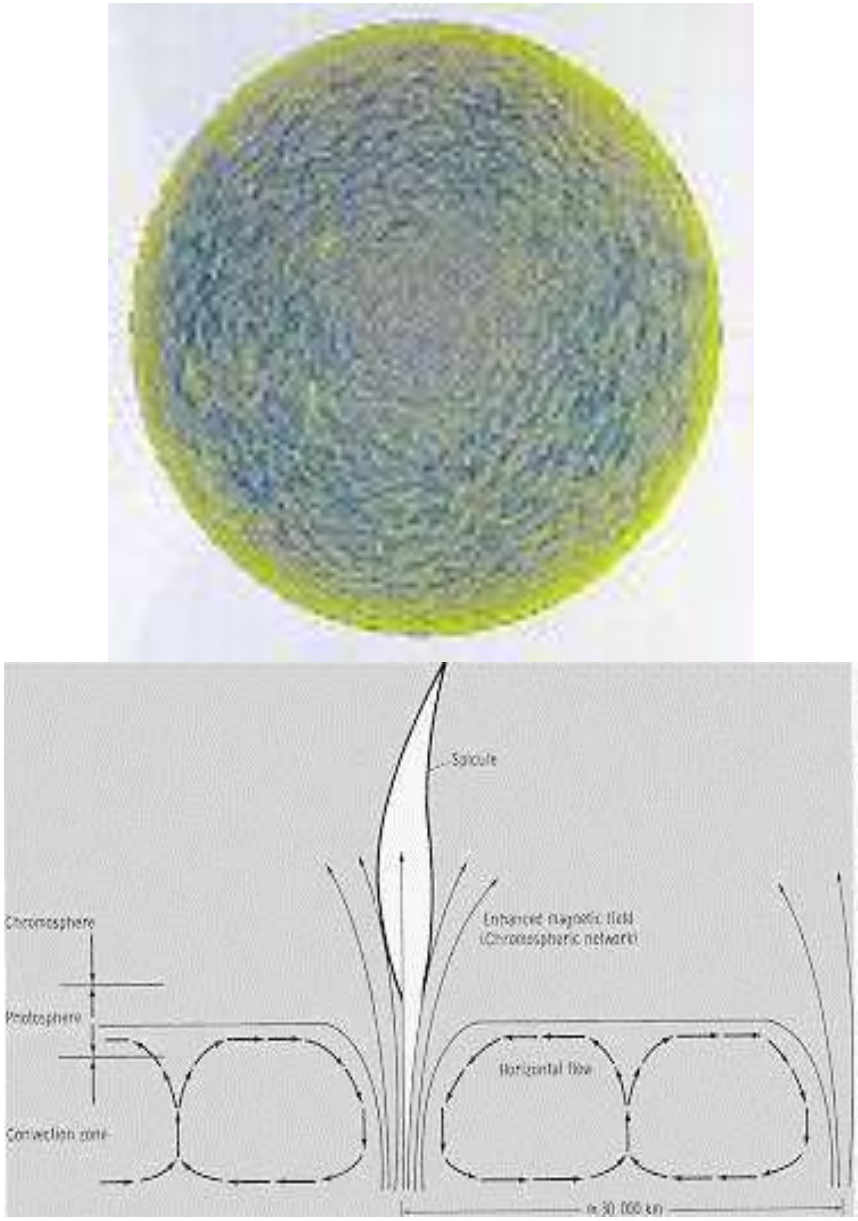


**Figure 7.** *Solar supergranulation.* ***Panel A:*** *Supergranulation is seen here in a velocity image of the Sun. Dark regions represent gas flowing toward us, light areas represent gas flowing away.* ***P 392-23-10. Panel B:*** *A schematic of supergranulation convection cells**.** Spicules are found at supergranulation boundaries, coinciding with a locally enhanced magnetic field.* ***The Quiet Sun, p. 19, Figure 2-12, Modified.***

### III. The Active Sun

We think of the Sun as a brilliant but quiet source of light, when in fact the Sun’s atmosphere can be an extremely violent, rapidly changing region. The Sun does have periods of quiescence, but these are interrupted by periods where magnetic storms blow hot blobs of gas larger than our Earth into its corona. Such solar activity is often correlated with the number of dark sunspots covering the solar disk.

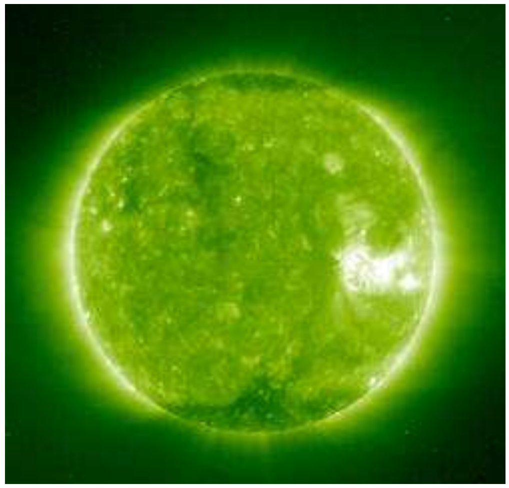

**Figure 8.** *The Sun imaged in ultraviolet light from the SOHO (Solar and Heliospheric Observatory) spacecraft. The light that created this image was emitted from iron atoms in the Sun's corona, stripped of 11 electrons by the extreme temperature, over 2 million K.* ***NASA. APOD.***

*Sunspots*

**Sunspots** are actually bright regions, but they look like dark blotches on the Sun's surface in contrast with the surrounding photosphere because they are 1,500 K cooler (Figure 9). Sunspots are up to 80,000 kilometers in diameter and have lifetimes ranging from hours to months.

Naked-eye sightings of sunspots were first recorded by the Chinese, nearly 2,000 years ago. In 1612, Galileo was the first to observe sunspots through the telescope, and used them to determine that the Sun rotates once each month. They show that the gaseous Sun exhibits differential rotation, with its equator rotating more quickly (about 25 days) than its poles (as long as 35 days near the poles). A large sunspot group was observable to the unaided eye in 1979.

**CAUTION: The Sun should never be viewed through binoculars, a telescope, or lenses, as this can cause blindness.**

In 1908, the American astronomer George Ellery Hale linked sunspots to magnetic fields on the Sun (Figures 9 and 10). Sunspots appear in groups composed of two principal spots in an East-West orientation, with as many as hundreds of spots in a group. One principal spot is found where the magnetic field exits the Sun's surface; the other appears where it re-enters the surface. Sunspots can be observed to drift slowly across the Sun's surface with respect to the Sun's rotation.

The Sun's magnetic field controls the motion of the charged atoms, called **ions**, that have been stripped of one or more electrons in the hot atmosphere of the Sun. These ions are held captive by the Sun's strong magnetic field, particularly in the vicinity of sunspots, where they are constrained to move by spiraling around the direction of the magnetic field, flowing from one magnetic pole to another, from one sunspot to another. Masses of gas larger than the Earth can erupt from a region of sunspots and move along the Sun's magnetic field, sometimes hanging suspended for hours.

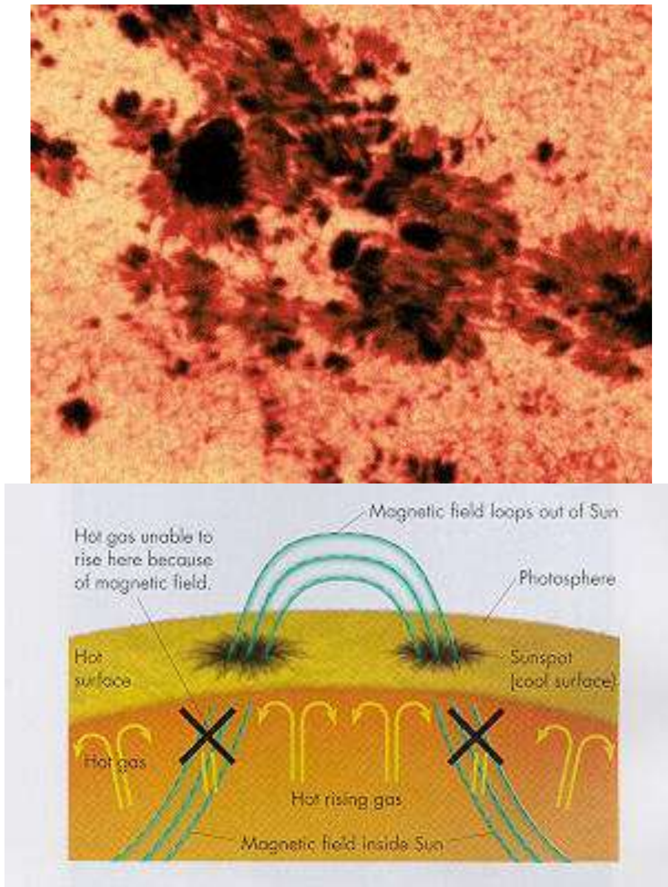


**Figure 9.** *A solar sunspot group.* ***Panel A.*** *Although sunspots appear darker than the surrounding photosphere, they are actually quite bright. Sunspots represent regions where the solar magnetic field pokes through the Sun's atmosphere****. APOD. National Solar Observatory. Panel B.*** *Sunspots occur in pairs, located where the magnetic field exits and enters the solar interior.* ***Arny.***

*Sunspot Cycle and the Earth's Climate*

In 1960 the American astronomer Horace Babcock developed a magnetic dynamo model for the Sun's magnetic field. In this model current from the flow of hot ionized gases in the Sun's interior produces a magnetic field, similar to the model for the Earth's magnetic field. The solar magnetic field normally lies just under the photosphere until convection brings it to the surface. Convection of the atmosphere produces tangles and kinks in the magnetic field, while differential rotation stretches the magnetic field around the surface of the Sun in an East-West direction (Figure 11). Sunspots are loops of magnetic field that have broken through the solar surface. Over a period of years the magnetic field becomes more and more twisted and tangled. At some point the complex magnetic field above the surface breaks, releasing a great deal of energy, and disappears, leaving only the subsurface field and the cycle begins again, but with the field reversed. This magnetic field reversal also occurs in the Earth, which reverses its North and South magnetic poles every few hundred thousand to few million years. Our understanding of sunspots is far from complete. Scientists still don't know what holds them together over a period of months or why there are long periods with no sunspots.

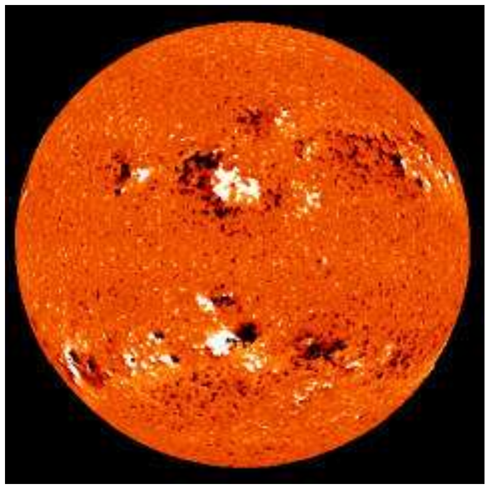

**Figure 10.** *An National Solar Observatory image of the solar magnetic field near sunspot maximum. One magnetic polarity is colored white, the other black. Note that the highest magnetic fields are found in sunspot groups and that sunspots are seen in pairs of opposite polarity, corresponding to spots where the Sun's magnetic field exits and reenters the interior of the Sun.* ***National Solar Observatory.***

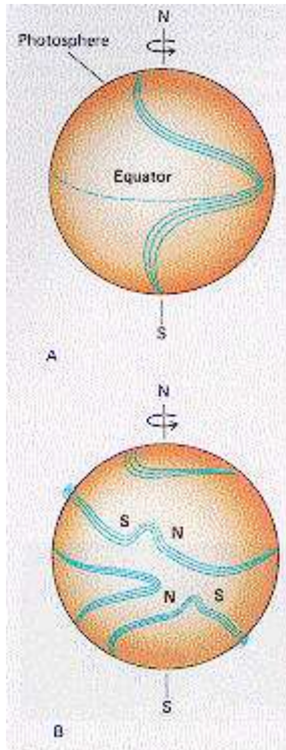


**Figure 11.** *A schematic showing the winding of the Sun's magnetic field as the Sun differentially rotates. First, the magnetic field is stretched at the Sun's equator, eventually becoming tangled and kinked. Finally, kinks in the Sun's magnetic field pierce the atmosphere, forming sunspot pairs.* ***P 402-23.29.***

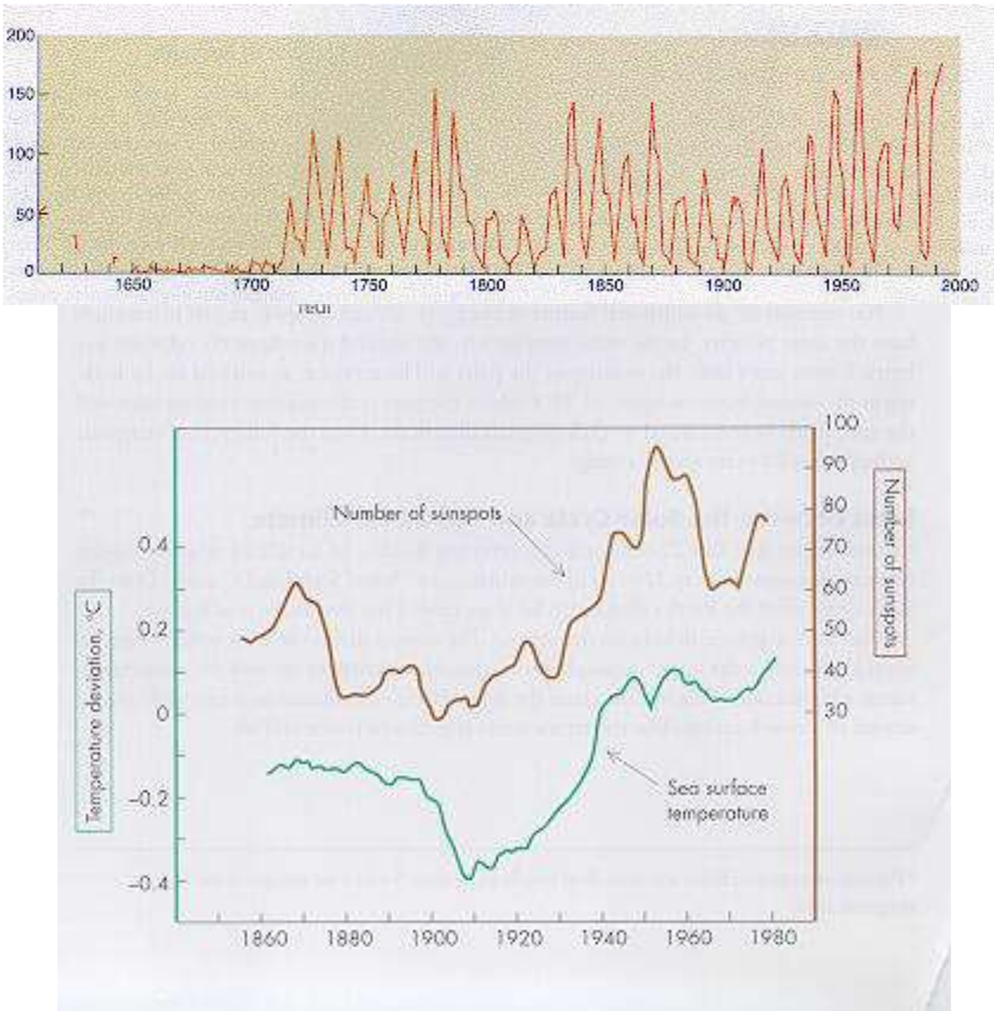


**Figure 12.** *The sunspot cycle.* ***Panel A.*** *The number of sunspots seen on the Sun's "surface" varies on an 11-year cycle. No sunspots were seen from 1645 to 1715, a period known as the Maunder minimum, marked by extremely cold winters.* ***FMW 302-14.2. Panel B.*** *There is a close correspondence between the Earth's climate and solar activity. The mean global ocean temperature tracks the number of sunspots.* ***Arny.***

Maximum and minimum numbers of sunspots appear with an 11.1-year period (with more than 100 sunspots typically seen at maximum) (Figure 12). The leading spot will have a N/S polarity (N when entering the Sun's surface, S when exiting) in the southern solar hemisphere, and S/N polarity in the northern solar hemisphere. This pattern reverses polarity with each 11-year cycle, so that the real solar cycle is a 22-year cycle. A sunspot minimum occurred in 1997 and will reoccur in 2008. A sunspot maximum was observed in 1990 and will be seen again in 2001.

In the period from 1640-1715, called the **Maunder minimum**, no sunspots were seen on the Sun's surface. This period coincided with the "little" ice age in Europe. Temperature indicators (e.g. tree-ring growth patterns) indicate a correlation between climate and sunspot frequency over the last 1000 years (http://en.wikipedia.org/wiki/File:2000_Year_Temperature_Comparison.png).

The luminosity of the Sun is relatively constant. During a solar flare (Figure 13), when a magnetic storm causes the temporary brightening of a portion of the Sun's surface, the total energy output of the Sun changes by less than 1%, although X-ray radiation from the Sun may vary 100-fold. Over the 22-year sunspot cycle the number of flares also changes. Although these changes in solar output are low, it should be kept in mind that a one or two-degree change in global temperature can produce drastic changes in local climate, such as drought, over the Earth. Climate changes are made more complicated by the addition of carbon dioxide into the Earth's atmosphere causing a greenhouse effect.

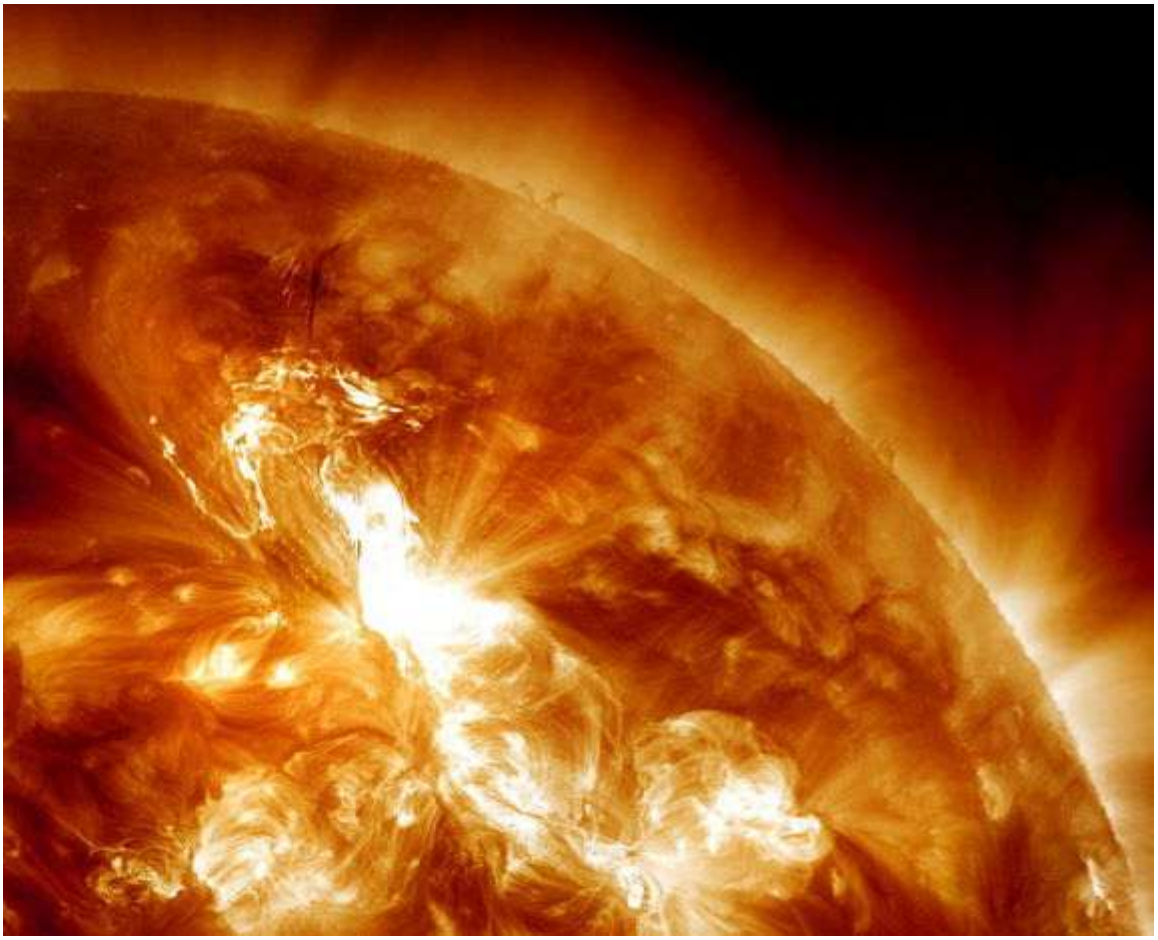

**Figure 13.** *The solar flare of January 23, 2012.* ***NASA/SDO.***

*Flares*

**Flares** are temporary but violent magnetic storms on the Sun's surface seen in sunspot groups, associated with an observed increase in the Sun's magnetic field (Figure 13). Flares have lifetimes of seconds to hours. Flares send streams of gas 10s to 1000s of km into the corona at temperatures of 3 to 5 million Kelvins. Flares are accompanied by an increase in the solar wind often causing intense aurorae (Figure 14) and disrupting radio communications.

Figure 14. Aurora.
From **http://www.geo.mtu.edu/weather/aurora/images/aurora/jan.curtis/**

*Filaments, Prominences, and Aurorae*

**Filaments and prominences** are loops and streamers of hot gas, 1000s of kilometers long, reaching temperatures as high as 50,000 K and releasing energy into the photosphere (Figures 15 and 16). They are both the same phenomenon, but seen from different perspectives. A streamer seen in the middle of the Sun's disk appears as a bright linear feature, called a filament. A streamer seen emanating from the edge, or limb, of the Sun is called a prominence. As a streamer rotates from the center of the Sun to the edge, it is first seen as a filament, then as a prominence. They are almost always associated with sunspots and last from hours to months. Flares and prominences vary with the same 11-year cycle as sunspots.

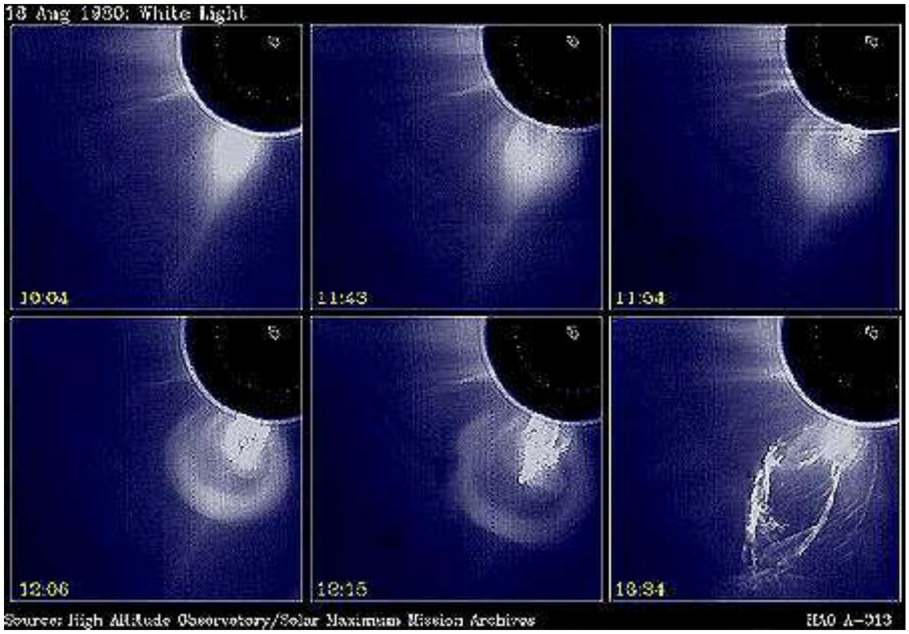


**Figure 15.** *One of the most dramatic aspects of solar activity is the coronal mass ejection, when up to $10^{13}$ kg of gas is injected into the solar wind at velocities of up to 1,000 km/s.* ***APOD.***

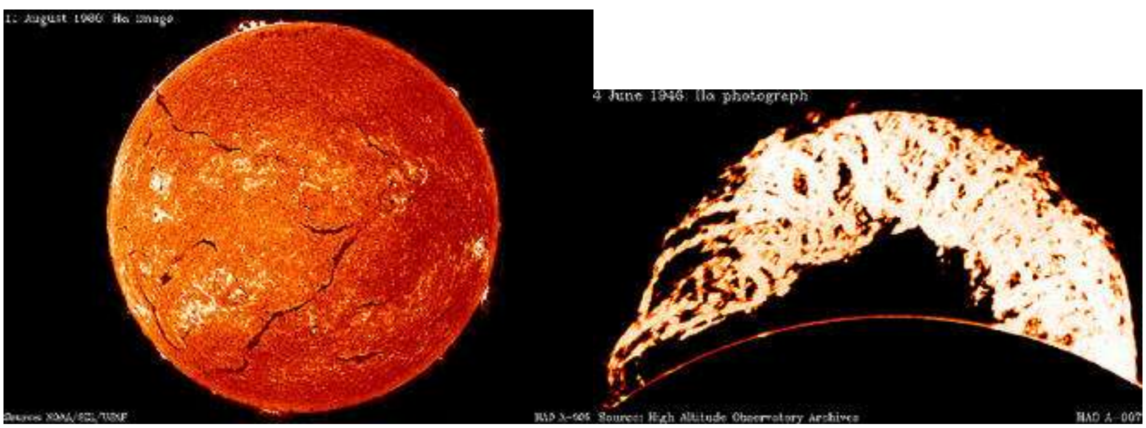


**Figure 16.** *Filaments and prominences are the same physical phenomenon seen with two differing viewing geometries. They are both condensations of cooler gas high in the Sun's atmosphere.* ***Panel A:*** *When seen against the Sun's disk these condensations appear as bright linear features.* ***APOD***. ***Panel B:*** *When viewed on the edge, or limb of the Sun, they are seen towering above the Sun's photosphere.* ***APOD.***

The Sun effectively holds its mass in with its gravity. However, the gas in the corona is moving at velocities in excess of 2 million km/h, exceeding the Sun's escape velocity. As a result coronal gas escapes the gravitational hold of the Sun, becoming the **solar wind,** mainly protons and electrons that flow out of the Solar System in all directions, past the Earth and the other planets (Figure 17). At the position of the Earth the solar wind travels at velocities ranging from 400-1,000 km/s and random motions corresponding to a temperature of 200,000 K. The gas is so thin that the amount of heat transmitted to the Earth from the solar wind is insignificant. This wind, along with sunlight, does push comet tails away from the Sun. The Sun will lose a relatively tiny fraction of its mass from the solar wind during its lifetime.

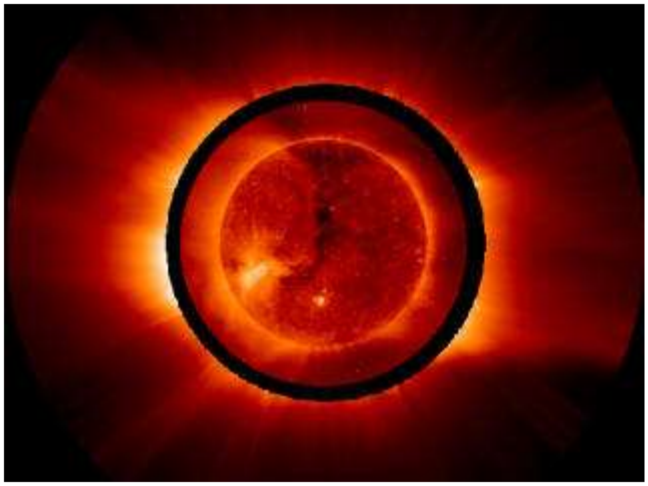

**Figure 17.** *The solar wind is the electrons and ions streaming off the solar corona. This image is a composite of two ultraviolet images of the Sun taken by the SOHO (Solar and Heliospheric Observatory) spacecraft showing the intense emission from the over 2 million K corona.* ***NASA.***

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**Summary**

The Sun represents the closest garden-variety star to the Earth. The part of the Sun's atmosphere that we see is the photosphere, a 5,800 K layer of gas emitting photons mainly in the visible part of the spectrum. Above the photosphere are two layers that are normally invisible to us: the chromosphere and the corona. The chromosphere is a thin layer with a temperature of roughly 10,000 K. The corona is a tenuous envelope of gas extending millions of kilometers outwards from the solar surface with temperatures of 1-2 million K.

The Sun's surface is in constant motion. Convection cells bubble energy to the surface of the Sun from the deep interior. Sunspots are dark, cool blemishes on the solar surface where the Sun's magnetic field has twisted and popped through the surface. The number of sunspots correlates with periods of extreme climate on the Earth; when the sunspot number is abnormally low, the global climate is colder than normal. When the sunspot number is high, the global climate is warmer than average. The Sun's magnetic field activity is related to flares, magnetic storms accompanied by streams of hot gas ejected into the corona, and prominences, loops of hot gas sent high into the corona. The solar wind, high-energy matter boiled off the Sun's surface, strikes the Earth's surface and results in aurorae and communications interference.

## Key Words & Phrases

1. **chromosphere** – the layer in the Sun's atmosphere immediately above the photosphere. A tenuous layer normally only seen by the unaided eye during an eclipse as a red fringe around the Sun.
2. **corona** - the uppermost layer of the solar atmosphere, extending millions of kilometers above the photosphere.
3. **filaments -** loops and streamers of hot gas, 1000s of kilometers long, releasing energy into the photosphere. A streamer seen in the middle of the Sun's disk appears as a bright linear feature, called a filament.
4. **Flares** - temporary but violent magnetic storms on the Sun's surface seen in sunspot groups, associated with an observed increase in the Sun's magnetic field
5. **Granules** - convection cells covering the solar photosphere
6. **ions** – charged atoms, which have been stripped of one or more electrons, leaving them with a net positive charge or which have acquired an extra electron(s) leaving them with a net negative charge
7. **Maunder minimum** - the period from 1640-1715 in which no sunspots were seen
8. **Photosphere** – the opaque layer of the Sun's atmosphere that emits the light that we see
9. **Prominences** - are loops and streamers of hot gas, 1000s of kilometers long, releasing energy into the photosphere. A streamer seen emanating from the edge, or limb, of the Sun is called a prominence.
10. Solar wind –
11. **Spicules** - flame-shaped jets of gas in the solar chromosphere
12. **Sunspots** – dark blotches in the solar photosphere. Sunspots are regions of lower temperature and higher magnetic field than the surrounding photosphere.
13. **supergranulation** - large convection cells, roughly 30,000 kilometers in diameter. Each supergranule contains approximately 1000 granules.

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## Review for Understanding

1. Sketch and label the outer parts of the Sun.
2. What are sunspots and what causes them?

## Essay Questions

1. What are some practical reasons for studying solar activity?
2. Discuss the similarities in the origin of the Sun's magnetic field and the Earth's magnetic field. How are they different?
3. If the outermost layer of the Sun, the corona, has a range of temperatures in the millions of Kelvins, then why does the intensity distribution of visible sunlight approximate a 5,800 K blackbody?
3. How does solar activity correlate with the Earth's climate? Why?

# Chapter 16 - The Sun: a Thermonuclear Furnace

*Analogies are useful for analysis in unexplored fields. By means of analogies an unfamiliar system may be compared with one that is better known. The relations and actions are more easily visualized, the mathematics more readily applied, and the analytical solutions more readily obtained in the familiar system.*
-- Harry F. Olson

**Chapter Photo.** *The detonation of a thermonuclear bomb in the Earth's atmosphere and sunlight both represent the effects of the fusion of hydrogen into helium.* ***National Nuclear Security Administration.***

**Chapter Preview**

One of the biggest scientific and technological achievements of the 20th century was the development of nuclear energy. One of the biggest scientific milestones in 20th century astronomy was the discovery that the Sun has been generating its energy for 5 billion years by converting hydrogen to helium in a self-regulating thermonuclear reactor. This is the same process that powers almost all of the stars that glow in the night sky. In this chapter we will study in some detail the elegant thermonuclear furnace that powers the Sun and other stars.

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**Key Physical Concepts to Understand:** *thermonuclear fusion, hydrostatic equilibrium, the Sun as a self-regulating reactor, how energy is transported through the Sun, potential and kinetic energy*

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## I. Historical Perspective: the Energy Problem

In order for a star to shine for billions of years, as most stars do, it requires an ongoing production of enormous amounts of energy. The source of energy is the conversion of mass to energy via controlled nuclear reactions. In the $19^{th}$ century, before radioactive dating of rocks suggested that both the Earth and Sun were billions of years old, it was supposed that the Sun's luminosity was produced by chemical burning, such as the burning of coal, or from the impacts of comets into the Sun. When theories began to attribute an age of billions of years to the Sun, understanding how the Sun sustains its luminosity over its lifetime became a difficult problem. As shown in Table 16.1, chemical burning is not even remotely a viable energy source for the Sun. In the late $19^{th}$ century two renowned scientists, Lord Kelvin of England and Heinrich Helmholtz of Germany proposed that the luminous energy of the Sun could be attributed to its slow gravitational collapse. Indeed, such a slow collapse could power the Sun for a very long time, 200 million years if the Sun shank to one-quarter of its original size. However even this energy source is inadequate to power the Sun over its estimated life of 4.6 billion years. In the 1930s Arthur Eddington calculated that the Sun's core temperature should be in the millions of Kelvins. American physicist Hans Bethe and German physicist Carl von Weisacre were the first to propose that the conditions in the core of the Sun were sufficient for its production of energy by thermonuclear **fusion**, in which nuclear particles combine and release tremendous amounts of energy. Fusion could sustain the Sun's current energy output for at least 10 billion years.

**Table 16.1:** *Potential Solar Energy Sources*

| Candidate Energy Source | Lifetime of Solar Energy at Sun's Current Luminosity |
|---|---|
| Accretion of Comets | Insignificant |
| Chemical Burning | 5000 years |
| Stored Heat, Cooling Off | $2 \times 10^7$ years |
| Gravitational Collapse | $2 \times 10^8$ years |
| Nuclear Fusion | $1 \times 10^{10}$ years |

## II. Nuclear Fusion and Stellar Structure

A star is simply a hot, glowing sphere of gas, powered by thermonuclear fusion, usually of hydrogen into helium. The interior structure of the Sun, or for any star, is determined by the balance in the gas between gravity which tries to collapse the gas and the energy source at the center of the star, which heats it and attempts to expand the gas.

Consider the cross-section of the Sun in Figure 1. A small volume at or near the surface of the Sun is attracted to the center of the Sun by all the matter lying below it. It pushes down on the gas below it with the force of its weight. The gas at any arbitrary point inside the Sun is supporting the weight of a column of gas above it. Burrowing deeper inside the Sun's interior, the mass of overlying material becomes greater as does its weight. This is analogous to a diver in the ocean (Figure 2). The deeper one dives the greater the water pressure that one feels (particularly on their eardrums). Pressure is the amount of force distributed over a unit of surface area. This can be measured in pounds per square foot, in English units, or in **Newtons** per square meter, in metric units (a Newton is the amount of force necessary to accelerate a one kilogram object at 1.0 $m/s^2$).

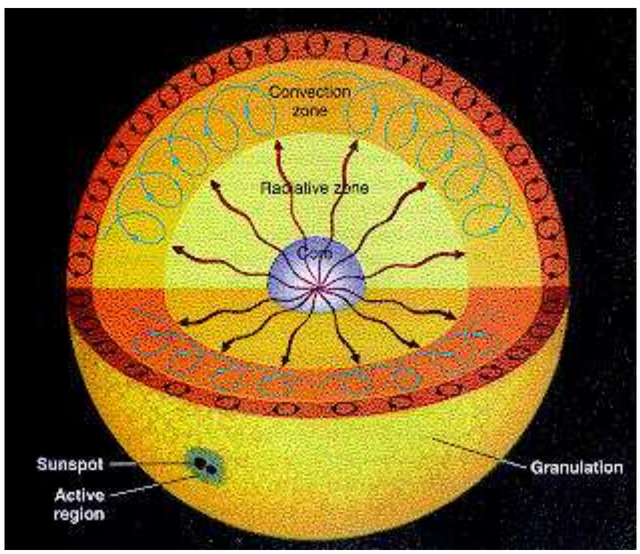


**Figure 1.** *A schematic of the Sun's interior. The Sun generates most of its energy in a hot, dense gaseous core, fusing hydrogen into helium. Energy is transported through the Sun's interior first radiatively by the flow of light, then chiefly by convection.* ***FMW 310-15.10 modified.***

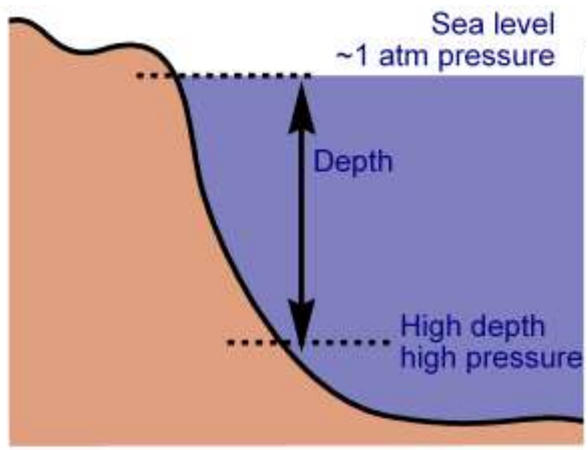


**Figure 2**. *The increasing pressure of water with depth in the ocean is an example of hydrostatic equilibrium, the balance between gravity and water pressure. The weight of water in a column above a diver must be balanced by the pressure of water at that depth.* **From calctool.org.**

III. Math Box: Calculation of pressure at the bottom of a swimming pool.

**What is the pressure, in kilograms per square meter (kg/m$^2$) at the bottom of a four-meter deep swimming pool?** The force at any point in the water is simply the weight of water resting on top of it. Imagine placing a 1 meter square of cardboard underwater, oriented so that its surface is parallel to the surface of the water. The cardboard will be pressed on by a 1-meter cross section of water. If the cardboard were 1 meter under water the force on it would be equal to the weight of 1 cubic meter of water, the mass of water lying above it. 1 cubic meter of water has a mass of 1000 kg. The weight of a 1000 kg mass at the Earth's surface can be calculated by multiplying this mass by the acceleration of gravity, 9.8 m/s$^2$. The result is 9,800 kg-m/s$^2$, or 9,800 Newtons (abbreviated N). This force is spread over the 1 square meter of cardboard, so that the pressure on the cardboard is 9,800 N/m$^2$. This same pressure is exerted on any object of any size at a depth of 1 meter under water. At a depth of two meters the cardboard would have twice as much water resting on top of it, giving rise to a pressure of twice 9,800 N/m$^2$ or 19,600 N/m$^2$. At the bottom of the pool, at a depth of 12 meters, the water pressure is 28,400 N/m$^2$. Deep in the ocean, at a depth of 1000 meters the pressure is a crushing ten million N/m$^2$.

**Does this pressure always push down?** No, if one holds cardboard underwater in a pool, it isn't pushed in any direction, it just sits there. Water pressure pushes in all directions. If we swim to the bottom of the pool, water pressure pushes us on all sides. We feel it pushing on our eardrums in particular, because they are sensitive to pressure.

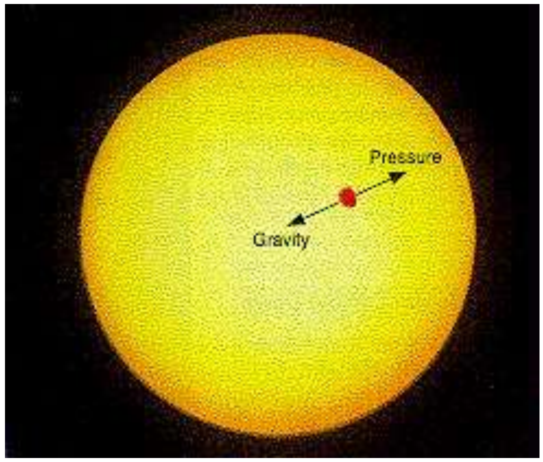


**Figure 3.** *Hydrostatic equilibrium. The Sun is in hydrostatic equilibrium when the force of gravity is balanced by gas pressure everywhere in the Sun's interior.* ***FMW 317-15.7.***

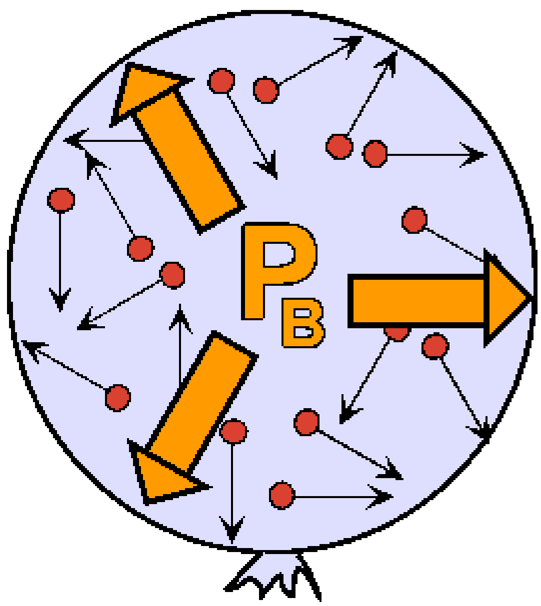


***Figure 4.*** *Gas pressure is caused by the sum of impacts of fast-moving molecules in a gas; as the temperature of the gas is increased, the molecular velocities increase, and the impacts carry more force. As air is blown into a balloon it expands until air pressure inside the balloon, from impacting molecules, must balance air pressure on the outside plus the force from the balloon elasticity. If the temperature of the air in the balloon is increased, it will expand, if it is decreased it will expand – until hydrostatic equilibrium is achieved again. From* ***www.indiana.edu***

This weight of solar gas (remember weight equals gravitational force) must be counterbalanced by an equal an opposite force or this mass will begin to move (Figure 3). In this case the opposite force is the pressure within this volume of gas (Figure 4). If the gas pressure of a volume of gas is less than the weight of the overlying material, then the gas collapses. If the gas pressure is greater than the weight of the overlying material, then the gas expands. The pressure near the center of the star must support the weight of the entire star**. The pressure at the center of the Sun is about 20 billion pounds per square inch. How does the Sun generate that much pressure?**

## IV. Balloon Model of the Sun

**The pressure in a gas is proportional to Density × Temperature.** A rubber balloon has a balance between the elastic tension in the plastic or rubber out of which the balloon is made, along with the gas pressure of the outside air, and the outward pressure of the gas filling the balloon (Figure 4). If the temperature and density of the balloon remain constant, the size of the balloon will remain constant. If the balloon is warmed the gas pressure in the balloon will increase and it will expand. If the balloon is immersed in ice water (try it!) the interior gas pressure will decrease and the balloon will shrink. The very same phenomenon occurs in any gas.

In order to provide the pressure near the center of the Sun to support the weight above, the temperature at the center must be 10 to 15 million K and the density 100,000 $kg/m^3$ This a gas with a density over 10 times greater than steel, possible because of the enormously high temperature which keeps the constituent atoms moving at extremely high velocity, too high for any rigid solid to exist. At the solar "surface" the temperature is about 5,800 K and the density is 10,000 less than the Earth's atmosphere at sea level.

A star of 10 to 20 solar masses has a more extensive mass problem than the Sun, so it requires an even greater central pressure and internal temperature. In order for a star to remain stable the central pressure must always balance the weight of the star. Pressure and gravitational force must always balance in the long term. If for any reason pressure and gravity aren't balanced, the star will adjust its size and temperature until balance is achieved. **What happens if the pressure force exceeds the force of gravity?** The star will expand. When a gas expands its density and temperature drop. Since the pressure of a gas is simply proportional to density times temperature, the gas pressure will also drop. The pressure will continue to drop until the gas pressure force equals the gravitational force. This balance in a star between gas pressure and gravity is known as **hydrostatic equilibrium**.

## V. The Potato Model of a Star

To examine how energy flows through a star, we can use the same hot potato model that we used in Chapter 9, Section III. Imagine a hot potato, cooling after having been taken out of the oven (Figure 5). The surface cools by radiating thermal energy into space, like a blackbody, and by convection from the surface of the potato into the air. As the surface cools it becomes cooler than the center of the potato and energy starts to flow from the hotter center to the cooler outside. This latter process occurs by **conduction**, the flow of heat in a body from a hot region to a cooler region. **Heat** is simply the fast atomic motion in matter, which can be vibration of molecules in a solid or straight-line motion of molecules in a gas. As a molecule starts to vibrate or move more rapidly, we say that its temperature has gone up. In a potato, the hot, fast vibrating molecules in the inside set into more rapid vibration their cooler, more slowly vibrating neighbors. As this happens heat flows to the cooler molecules and their temperature begins to rise.

One of the main qualitative differences between a star and a potato is that the star is gaseous and the potato is solid. Another difference is that the star is powered by thermonuclear energy; the potato is not. The Sun loses energy from its photosphere by radiating light into space like a blackbody. It also pumps a little energy into its corona by convection. The net effect of this energy loss is that the photosphere (at 5800 K) has become a lot cooler than the center of the Sun (10 to 15 million K) like the potato. Since energy is flowing out of the Sun, if it were not replenished by a central energy source the temperature of the Sun would drop as it cooled off. If the temperature of the gaseous Sun were to drop, its pressure would also drop (unlike the solid potato). The Sun could find a new equilibrium by gravitationally contracting, which would heat up the Sun's interior and restore the internal gas pressure. Without a central heat engine, the Sun, as any other star, would steadily contract, generating the necessary energy for sunlight by a continuous gravitational contraction.

**Figure 5.** *Cooling potatoes.* From **blessedveganlife.blogspot.com**

## I. What Powers the Sun?

The source of energy from the Sun is explained by Einstein's famous equation from his theory of special relativity:

**Equation 16.1: $E = mc^2$**

The proceeding equation mathematically describes the allowed conversion of mass into energy, where $c^2$ is the speed of light squared. Prior to the Special Theory of Relativity it was thought that mass was always conserved in any physical reaction and that energy, although it could be changed from one form to another was also always conserved.

An example of energy conservation during conversion is the dropping of a mass from a height to the ground (Figure 6). It takes a certain amount of energy to lift a book from the floor to the upper shelf of a bookshelf, for example. The amount of energy is simply equal to the force used to lift the book, i.e. the book's weight, times the distance through which it is moved. The energy used in lifting the book is not destroyed, but is stored in the book and is available when the book is dropped. This stored energy is called **potential energy**. When the book is dropped the potential energy is used up to move the book, which is accelerated to some velocity before it hits the floor. The energy of motion of the book is called **kinetic energy**. When the book is dropped potential energy is converted to kinetic energy. Finally, the book slams into the floor. The kinetic energy in the gross motion of the book causes the molecules in the floor to speed up; i.e. their temperature rises. The kinetic energy of the book is converted to the random kinetic energy of motion of molecules in the book, floor, and air. We say that the kinetic energy of the book has been converted to heat energy in the book and floor and to acoustic or sound energy.

In Einstein's special theory of relativity, neither energy nor mass by itself is conserved, but energy *plus* mass is conserved. Energy can be converted into mass and mass into energy. The conversion is described by $E = mc^2$; if an amount of mass, m, is destroyed, it is converted to an equivalent energy E. The amount of energy wrapped up in a small amount of mass is enormous. If one *gram* of matter could be completely converted into energy it would produce an amount of enough equivalent to burning 2.5 million *kilograms* of coal. Conversion of mass to energy can easily supply the Sun with the energy it needs to satisfy its current luminosity for billions of years.

Mass is converted into energy, and vice versa, in ordinary chemical reactions. In the chemical burning of hydrogen in oxygen, for example, which produces water, the following occurs: *Two molecules of Hydrogen ($H_2$) combine with one molecule of $O_2$ to form two molecules of water ($H_2O$).*

The special theory of relativity can be used to describe the conversion of mass to energy in ordinary chemical reactions. The mass of the water molecule produced is actually less than the sum of the individual particles used to produce the water molecule. The lost mass is converted into the energy produced in this chemical reaction. The tiny amount of mass lost in a chemical reaction like this is too small to be measurable. In reactions that require energy, the mass of the products is greater than the mass of the reacting atoms/molecules.

The energy produced in a nuclear reaction is much greater than that produced in an ordinary chemical reaction and the conversion of mass into energy can be measured. An example is the thermonuclear fusion of hydrogen nuclei into a helium nucleus.

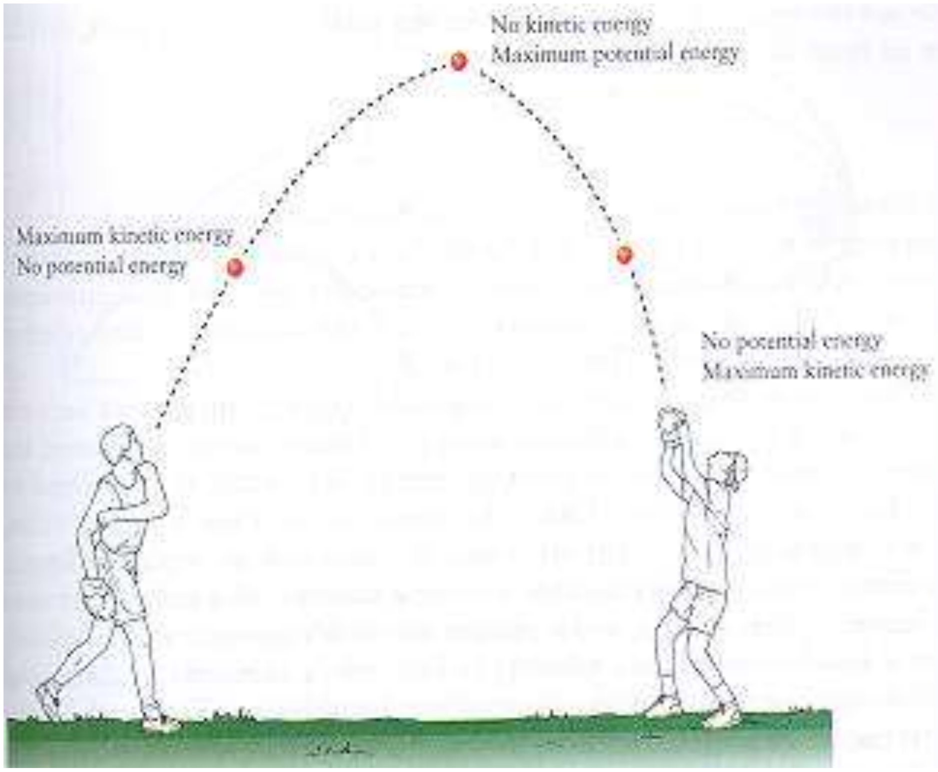


**Figure 6.** *Illustration of potential and kinetic energy.* **Silk.**

Two hydrogen nuclei and two neutrons can fuse together to liberate 0.7% of their mass as energy (Figure 6). Is hydrogen fusion sufficient for powering the Sun? If all of the hydrogen in the Sun were fused into helium the Sun could appear at its current luminosity for 100 billion years (about 20 times its estimated lifetime). The process that powers the Sun and most other stars with the conversion of hydrogen to helium is called the **proton-proton chain** (Figure 7).

**WebAnimation: the Proton-Proton reaction.**
http://www.youtube.com/watch?v=LpUB8iMbNw0

Energy is produced mainly in the form of gamma ray photons in each step of the proton-proton chain. The other way of forming helium from hydrogen in the cores of stars is the **CNO cycle** (named for the carbon, nitrogen, and oxygen nuclei involved in the process), another energy-producing fusion process. The CNO cycle works only at temperatures that are higher than those produced in the Sun, so it only takes place in stars with mass greater than 1 solar mass.

## VII. Fusion in the Sun and in Reactors

**What is required for fusion to occur?** Fusion is difficult to control. Although thermonuclear (hydrogen) bombs have been developed and detonated on Earth, we have yet to see a practical fusion reactor that can steadily convert hydrogen into helium, producing energy. The fuel would be cheap and practically limitless, since the hydrogen in water could be used as a fuel source. However fusion requires high temperatures (~10 million degrees) and a method of containing and regulating the thermonuclear reaction. What is difficult on Earth, happens quite naturally in stars. The tremendous gravitational forces in stars allows them to be held together at these incredible temperatures without evaporating themselves.

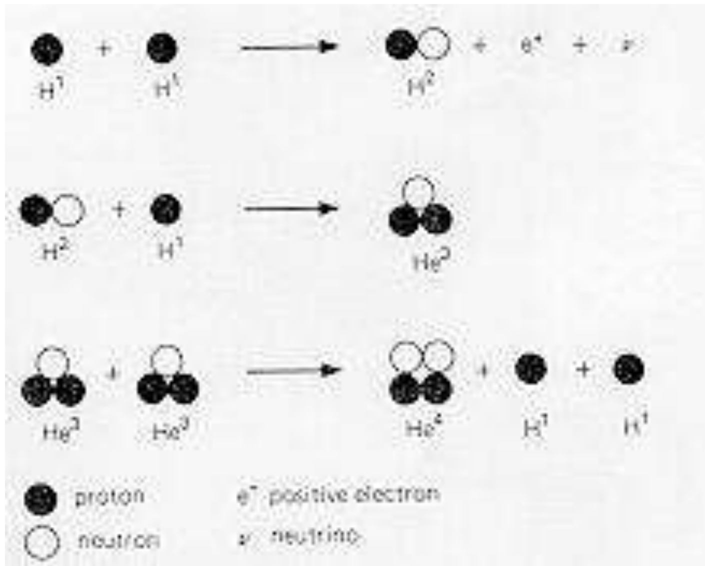


**Figure 7.** *Energy is generated in the Sun in a three-step reaction called the proton-proton chain: 1. Two hydrogen nuclei (protons) fuse into a deuterium (heavy hydrogen) nucleus, a positron (essentially a positively charged electron) and a neutrino. 2. A deuterium nucleus and a hydrogen nucleus fuse to a helium-3 nucleus. 3. Two helium-3 nuclei merge to form a helium-4 nucleus and two protons.* ***Harrison, Cosmology, 2.9. Modify.***

In jump-starting fusion in a gas, high temperatures and densities are required. The fusion of hydrogen into helium gets started when two hydrogen nuclei bang together and stick, forming a more massive nucleus. Once placed together, the nuclear strong force, which holds protons and neutrons together in an atomic nucleus. However the strong force has a short range and is only significant over a very short range, $10^{-15}$ m. Over larger distances electrical attraction and repulsion of charged particles are much more potent. Hydrogen nuclei are single protons, which have positive electrical charges. It is impossible for hydrogen nuclei at room temperature to simply bang together close enough for the strong force to take hold and fuse two protons together. Their positive charges cause them to successfully repel each other under normal conditions. However, in gases at millions of Kelvins, nuclei are stripped of their electrons and bang together at such high velocities that they can get close enough for the strong force to take over and hold protons together in a combined nucleus. High temperatures mean *hard* collisions.

When this happens, the resulting nucleus is often more massive than the individual components; as a result, energy is created from mass.

In the Sun, energy is produced in a self-sustained **chain reaction** (Figure 8). In a nuclear chain reaction, the energy produced by an individual fusion reaction producing a single nucleus is enough to keep the temperature high enough in its neighborhood to produce multiple nuclear fusions nearby. High gas densities are required for a chain reaction for there to be enough reactions per unit volume in order to sustain a high temperature. In this way, once the center of the Sun has reached a temperature and density great enough for high-velocity particles to fuse frequently, the energy produced by this fusion will maintain the high temperature of the solar core, and ensure that thermonuclear fusion will continue.

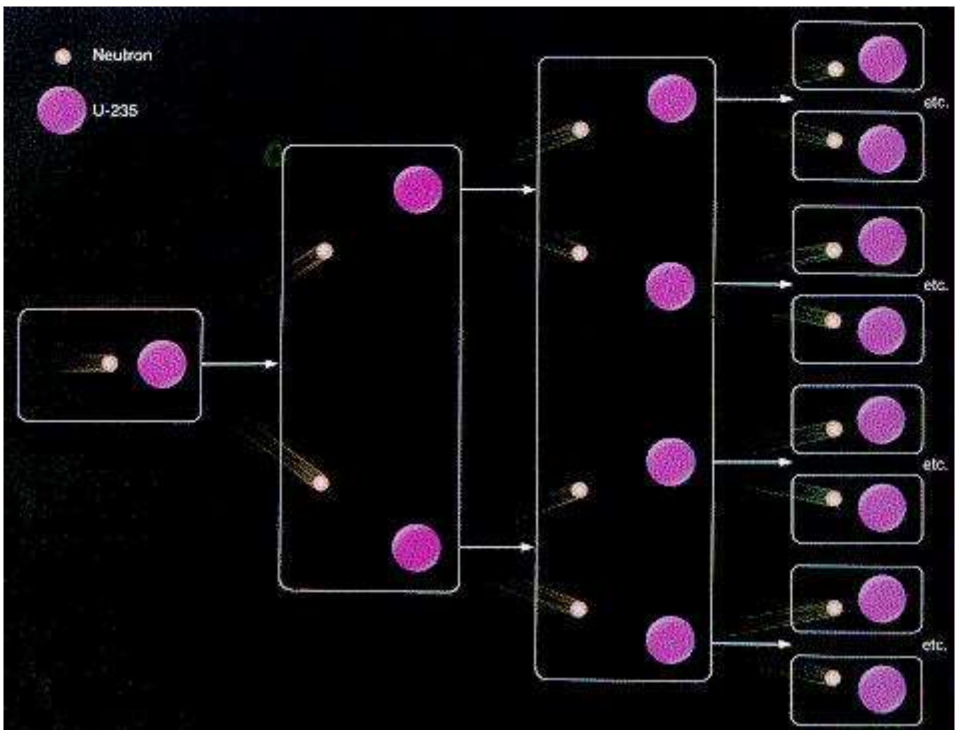


**Figure 8.** *A nuclear chain reaction. A chain reaction occurs when each reaction releases two or more high-energy particles that produce additional reactions. Modify **KW 619-25.10.***

**Why doesn't the Sun simply explode like a gigantic hydrogen bomb?** The Sun has its own natural thermostat for regulating nuclear fusion. This thermostat **is hydrostatic equilibrium**, the balance between gravity a rise in gas pressure. If nuclear fusion were to begin to runaway with a dramatic increase in the rate of fusion, the core temperature of the Sun would quickly rise, followed by an increase in gas pressure. The core pressure would then exceed the gravitational force of overlying layers of gas and the core would expand. An expanding gas cools and this would cause an immediate drop in the rate of nuclear reactions. Conversely, if the fusion rate in the core were to drop dramatically, the core temperature would decrease, followed by a decrease in pressure, causing the solar core to compress. A compressing gas is heated and this increase in temperature would immediately increase the fusion rate. Thus, the Sun's hydrostatic equilibrium holds its thermonuclear fusion rate, its size, and its energy output steady. This has, in turn, provided life on Earth with a constant source of sunlight and a stable temperature for a supportive environment.

Most of the mass of a star is in the form of hydrogen 75% by mass (90% by number) and helium (10% by number, 25% by mass). 1% of the stellar mass is made up of heavier elements. Hydrogen and helium become ionized (lose their electrons). Protons provide the energy source.

~~WebModel: an Interactive Model of a Star.~~

**IIX. The Size of the Energy-Producing Core**

The Sun's temperature decreases from 10-15 million K at the center to 5800 K in the photosphere. Since the rate of thermonuclear fusion in the Sun is temperature sensitive, it follows that the conversion of hydrogen to helium in the Sun takes place in a rather small core volume. The result is that only a relatively small fraction of the Sun's hydrogen will be converted to helium in its lifetime. Only about 10% of the Sun's hydrogen is available for fusion. This still provides the Sun with enough hydrogen to hold it at its present luminosity for another 5 billion years. Since the Earth and Sun are estimated to be 4.6 billion years old, the Sun will have a total lifetime of about 10 billion years. During this time the Sun will produce $10^{38}$ helium nuclei per second.

Since the volume of a sphere is proportional to its radius cubed (the volume of a sphere is $4/3\pi r^3$), one-thousandth of the volume of the Sun lies within the inner 10% of the Sun's radius. Because the Sun's core is highly compressed, more than half of the Sun's energy is generated in this small volume. This energy is mainly released in the form of gamma ray photons. We don't see these photons directly, however, as they are absorbed by the Sun's hydrogen and helium before they have traveled very far. When a gamma ray photon is absorbed by another volume of gas the energy goes into heating this gas. The gas then re-emits photons with a near-blackbody spectrum, according to its temperature. The energy works its way from the Sun's core to its photosphere by a long series of such absorptions and re-emissions. As the photons get closer to the surface the gas temperature decreases and the re-emissions occur at longer and longer wavelengths, until the energy of a single gamma ray photon is re-emitted as many visible wavelength photons near the Sun's surface. (Energy near the surface of the Sun is primarily transported by convection.) It can take as long as 1 million years for the energy generated by a nuclear reaction in the Sun's core to leave the energy as visible light.

**IX. The Solar Neutrino Enigma**

For every helium nucleus that is produce in solar nuclear fusion, two **neutrinos** are produced. Neutrinos are elementary nuclear particles with no charge and no measurable mass that travel nearly at the speed of light. The neutrino is produced whenever a proton in a nucleus changes into a neutron.

Neutrinos are extremely hard to detect because of their extremely weak interaction with matter. A neutrino can easily pass through the entire Earth without being absorbed or scattered. The Sun is also transparent to neutrinos allowing them to leave the core where they are produced and travel through the entire Sun unimpeded. The Sun produces about $10^{38}$ neutrinos per second. Approximately 100 billion neutrinos pass through each square centimeter of the Earth's surface per second; roughly 10 trillion go through your body each second. If one could build a neutrino telescope they could use it to image the solar core and directly measure its physical properties, such as temperature and density.

Rarely does a neutrino strike a neutron in an atomic nucleus and convert it into a proton. Because the number of protons in an atomic nucleus defines what element it is, when a neutrino transforms a neutron into a proton, it also transforms the nucleus from one element into another. This phenomenon is used to detect the neutrino.

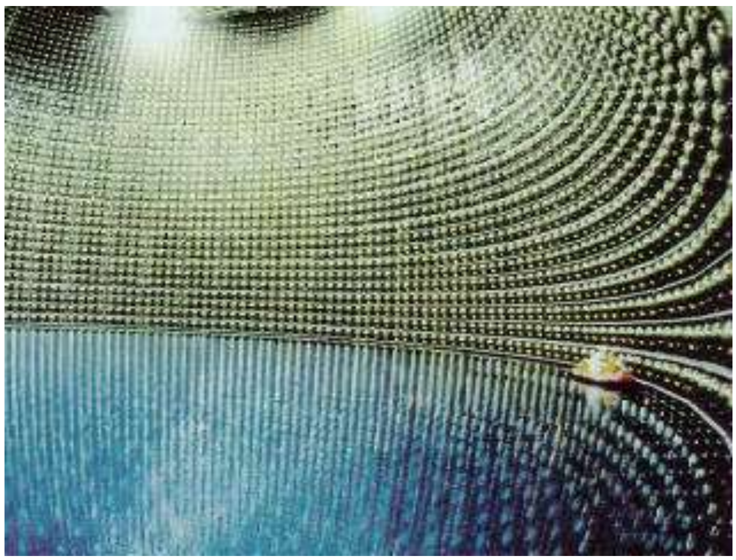

**Figure 9.** *The Super-Kamiokande solar neutrino experiment is buried inside the Mozumi mine in Japan. This 12.5 million gallon pool of purified water serves as the neutrino detector. Scientists in a rubber raft are examining the wall of photodetectors used to detect photons given off from nuclei in the water when struck by neutrinos.* ***Super-K. APOD.***

In the 1970s Raymond Davis of the Brookhaven National Laboratory built a neutrino detector using 100,000 gallons of perchloroethylene cleaning fluid (Figure 9). The tank of cleaning fluid is 1,500 meters underground in the Homestake Gold Mine in South Dakota. Whenever a neutrino strikes a chlorine nucleus in the cleaning fluid it can potentially convert it to radioactive argon. The radioactive argon will decay, which can easily be detected. The cleaning fluid is placed deep underground to prevent the detection of other high energy particles which could confuse the results.

The Davis experiment detects one solar neutrino every three days, on average. This is only one-third of the rate predicted by nuclear physicists and astronomers. This experiment has been repeated several times over the last several decades, always with the same result, a discrepancy between theory and observations.

There are two possible explanations for the solar neutrino problem, either the nuclear physics of solar fusion are poorly understood or the models of the structure of the Sun are in error. One possibility is that there is a transformation of the neutrino from the time that it is produced in the solar core until the time that it is detected. It could decay from a detectable neutrino to a more hard-to-detect neutrino. The other unlikely possibility is that the Sun's core temperature is about 10% cooler than models predict, making the neutrino emission rate from the core less frequent. However, this would bring the solar temperature and size out of line with observations. This phenomenon remains one of the interesting puzzles of modern astrophysics.

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**Summary**

The Sun is a natural thermonuclear furnace, producing energy in its core by the fusion of hydrogen nuclei into helium nuclei. Einstein's special theory of relativity predicts the amount of energy generated in a nuclear reaction from the equation $E = mc^2$, where E is the energy produced, m is the amount of mass that disappears in the process, and c is the speed of light.

The structure of the Sun can be modeled from the balance between gas pressure and gravity. The closer one gets to the center of the Sun, the greater the pressure that is needed to balance the weight of the overlying layers of gas, requiring a higher gas temperature to produce this pressure. The Sun must be roughly 10-15 million K at its center in order to support its weight. This is also the temperature that is required to sustain thermonuclear fusion. Thermonuclear fusion in the Sun is self-regulating, if its rate becomes too high it expands and cools; if the rate of thermonuclear fusion becomes too low, it contracts and heats up. Because the center of the Sun is much hotter than the photosphere, energy is transported from the Sun's center to its photosphere, where it is radiated away as light.

The only way of directly "seeing" into the Sun's core is by detecting neutrinos. The neutrino detection rate and the predicted rate of detection differ, leading both astronomers and particle physicists to question their models.

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**Key Words & Phrases**

1. **Chain reaction** - In a nuclear chain reaction, the energy produced by a fusion reaction producing a single nucleus is enough to keep the temperature high enough in its neighborhood to produce multiple nuclear fusions nearby.
2. CNO cycle -
3. **Conduction** - the flow of heat in a body from a hot region to a cooler region
4. **Fusion** – the combination of two smaller atomic nuclei into one larger nucleus

5. **Heat** - the fast atomic motion in matter, which can be vibration of molecules in a solid or straight-line motion of molecules in a gas
6. **Hydrostatic equilibrium** – the balance in a star between gas pressure and gravity
7. **Kinetic energy** – energy of motion
8. **Neutrino** – a type of elementary nuclear particle with no charge and no measurable mass that travels nearly at the speed of light
9. **Newtons** - the amount of force necessary to accelerate a one kilogram object at 1.0 $m/s^2$
10. **Potential energy** – stored energy, due to the position or configuration of a body, for example, its position in a gravitation field
11. **Proton-proton chain reaction** - a process whereby protons (nydrogen nuclei) fuse to form helium

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**Review for Understanding**

1. Describe how the Sun generates energy.
2. Explain how the Sun supports itself against gravitational collapse.
3. Summarize the solar neutrino controversy.
4. What is the estimated longevity of the Sun?
5. Where does the Sun's energy originate?
6. Why doesn't the Sun simply explode like a gigantic hydrogen bomb, in a runaway thermonuclear chain reaction?
7. What is the difference between kinetic energy and potential energy? Explain using an example.

**Essay Questions**

1. How do we know that the Sun is hotter and denser at its core than in its photosphere?
2. Discuss what evidence we have for believing that the Sun generates energy by the thermonuclear fusion of hydrogen to helium.
3. When you are blowing air into a balloon, is the balloon in hydrostatic equilibrium? Is it in hydrostatic equilibrium after the balloon has been filled and tied? Explain.
4. Why do you think that controlled thermonuclear fusion is so difficult to produce and contain in a man-made reactor on Earth, yet occurs naturally in the Sun's interior?

**Figure Captions**

Figure 12. Light working its way out of the Sun. Fusion in the Sun's core produces high-energy photons. Each photon only travels a short distance before it is absorbed and re-emitted in another direction. It randomly works its way out of the Sun, on a journey taking roughly one million years.

# Chapter 17 – Measuring Stellar Properties & the H-R Diagram

*It is sound judgment to hope that in the not too distant future we shall be competent to understand so simple a thing as a star.*
-- Sir Arthur Eddington

### Chapter Preview

What makes a star tick? How are they born? How do they die? Why do stars have different properties? In order to answer these and other difficult but fundamental astronomical questions astronomers first must put stars "under the telescope" and carefully measure and compare their fundamental properties, such as mass, size, and color. In correlating these properties it is then possible to deduce the answers to the broader questions of origin and evolution. Astronomers usually make these correlations graphically, using the powerful method pioneered in the early 20$^{th}$ century, the Hertzsprung-Russell diagram.

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**Key Physical Concepts to Understand:** *the measurement of the distance, luminosity, temperature, diameter, and mass of stars, the Stefan-Boltzmann relation, the H-R diagram, estimation of a stars lifetime from its mass and luminosity*

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### I. Introduction

In this chapter and the following three we will learn how astronomers came to realize that stars are born, live according to their physical properties, and die. How can astronomers learn of the origin and evolution of objects that are so far away that it takes years if not centuries for their light to arrive at the Earth, so small that they appear only as pinpoints of light, and so slow to age that they can live for 10s of billions of years? Obviously, the fact that astronomers have successful theories of the origin and evolution of stars is a testament to their cleverness and perseverance over many generations. But how was this accomplished? Astronomers pieced together this puzzle from the measurement of the fundamental properties of stars and then began to tie these properties together with a consistent physical model.

The basic properties of stars that can be measured directly or indirectly from the Earth include distance, luminosity, temperature, mass, composition, diameter, and age. (Age is not actually measured but estimated using computer models of stellar evolution.)

Other important, but less fundamental properties of stars that can be measured from the Earth include magnetic field strength, rotation, velocity, and turbulence.

## II. Distance

**What units of distance do we use when measuring how far away stars are?** The two most common units for measuring the distances to stars are the light-year and the parsec.

The **light-year** is a measure of distance, not time. It is the distance that light travels in one year, approximately 6 trillion miles. The Sun is 8 light-minutes from Earth, as it takes sunlight approximately eight minutes to make a one-way trip from the Sun to the Earth. Proxima Centauri, the nearest star to the Earth, other than the Sun, is 4.3 light years away or $4 \times 10^{13}$ kilometers. The North Star, Polaris, is 650 light years distant.

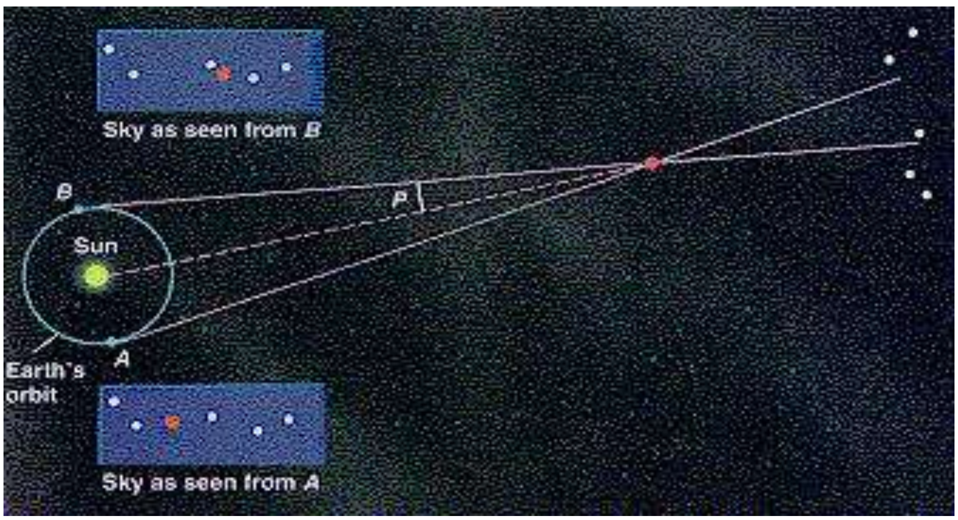


**Figure 1.** *Stellar parallax. As the Earth orbits the Sun, nearby stars appear to shift their positions relative to distant background stars. The parallax angle P, is one-half of the maximum annual angular shift as a result of the Earth's revolution about the Sun.* ***FMW 365-18.3.***

How do astronomers know these distances? Astronomers use measurements of stellar **parallax** (Figure 1). As the Earth orbits the Sun nearby stars appear to move back and forth against the background sky in inverse proportion to their distance (Chapter 3, Section IV). Parallax is the same method that we all unconsciously use to judge the distances to objects when driving, playing sports, or in any other human endeavor that depends on distance estimation. Since most people have two functioning eyes they have binocular (literally "two eyes") vision. Binocular vision allows for distance estimation by parallax for nearby objects. You can explore this yourself in several ways. Hold a pencil at arm's length. Look at it with your left eye closed and then your right. Compare the position of the pencil with respect to background objects and see how the position of the pencil shifts with respect to its background as you alternate the eye with which you view it.

The distance of an object, whether a star or a pencil, is proportional to 1/parallax angle. If the parallax angle is 1 arcsecond (1/3600 of a degree, see Chapter 2, Section IV), then by definition the distance is 1 parsec (close to the typical distance between stars in our Milky Way galaxy).

The parallax of Proxima Centauri is 0.77 arcsecond. So we can calculate its distance using the following equation:

**Equation 17.1: distance in parsecs = 1 / (parallax angle in arcseconds)**

or distance = 1/0.77 parsecs = 1.30 parsecs. This is comparable to a dime viewed at a distance of a mile.

The first parallax measurement was made by Friedrich Bessel, the German astronomer and mathematician in 1838 Bessel measured the distance to 61 Cygni, 3 pc away.

Parallax measurements are only useful out to distances of 100 parsecs. Outside this distance parallax is smaller than the blur of a star caused by the Earth's atmosphere. To overcome this limitation, the European Space Agency launched the satellite Hipparcos (named after the early Greek Astronomer Hipparchus) in 1989 to measure the parallax of the 20,000 stars within 500 parsecs of the Sun.

## III. Stellar Brightness

Magnitudes. When Hipparchus catalogued 1,000 stars in 130 BC by eye, he ranked their **apparent magnitude** or **brightness** on a scale of 1 to 6, with "1$^{st}$ magnitude" stars the brightest and "6$^{th}$ magnitude" the faintest (Figure 2). A difference of 5 magnitudes is now defined as a factor of 100 in brightness. Any given star is about 2.5 times brighter than a star of the next fainter magnitude. The apparent brightness of a star depends not only on its intrinsic brightness but also on its distance from us, just as the apparent brightness of a candle depends on its distance from us.

More precisely, if a one magnitude difference in brightness between two stars corresponds to a 2.512 ratio in brightness. It follows that a 5 magnitude difference in brightness corresponds to a brightness ratio of $2.512^5$ = 2.512 x 2.512 x 2.512 x 2.512 x 2.512 = 100.

A small number of stars in the sky, some of the planets, the Moon, and the Sun are brighter than 1$^{st}$ magnitude. For this reason, the magnitude scale was extended to include negative magnitudes for extremely bright objects. The Sun has an apparent magnitude of -26.8. For stars that cannot be seen with the unaided eye, but can be detected telescopically, we use postive magnitudes greater than 6. The Hubble Space Telescope can detect stars nearly as faint as 30th magnitude.

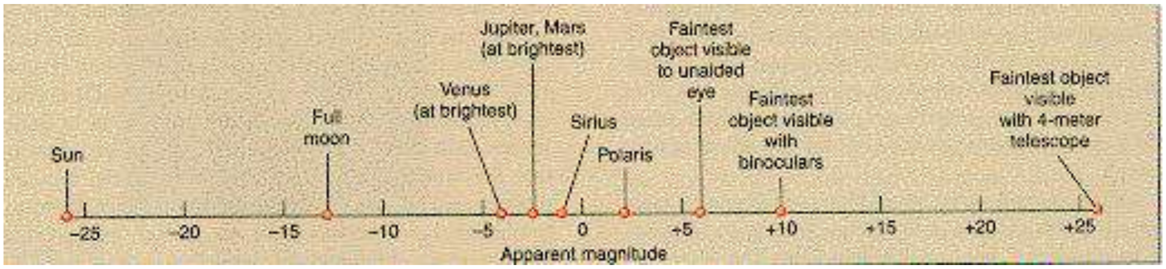


**Figure 2.** *The apparent magnitude scale. There is a difference of more than 50 magnitudes in apparent magnitude between the Sun and the faintest objects seen by the largest telescopes. This corresponds to a factor of approximately $10^{20}$ in brightness.* **FMW 329-16.2.**

**How does brightness change with distance?** The brightness of an object changes according to the inverse square law for light (Chapter 5, Section VI). If we view two stars of equal intrinsic brightness, but Star A is twice as distant as Star B, Star A will appear $(1/2)^2$ as bright, or ¼ as bright, by the inverse square law. Although the Sun is a star of average energy output and size, it overwhelms the other stars in the sky in its apparent brightness to the inhabitants of Earth simply because it is the closest star to us. It follows that apparent magnitude is not any intrinsic proper of stars, but depends mainly on their distance from us.

In order to compare the total energy output of stars, we need to compare their apparent magnitude as if they were all moved to the same distance from us. If we move all the stars in the galaxy to an equal distance we can see the more fundamental differences in their total energy output per unit time or **luminosity**. Astronomers measure luminosity in units of solar luminosity, where the luminosity of the Sun is $4 \times 10^{26}$ watts. Another way of describing the luminosity of a star is by using **absolute magnitude**. Absolute magnitude is the magnitude a star would have if moved to a distance of 10 parsecs. Magnitudes depend on the color to which the measurements refer (usually the color sensitivity of the human eye – or visual magnitude). One can measure magnitude in filters of differing color: blue magnitude, red magnitude, yellow magnitude, etc.

## IV. Temperature

One of the most fundamental properties of a star is its temperature. A star cannot be characterized by a single temperature since the temperature changes as a function of distance from the center of a star. Since we see near-blackbody emission from the photosphere when we view a star, we commonly use the photospheric temperature of a star to characterize it. The Sun's photosphere is approximately 5800 K, so it radiates energy with a spectrum that is nearly that expected for at 5800 K blackbody (Chapter 5, Section VII). The photospheric temperature of a star can be measured in two ways, from its color and its spectrum.

*Colors*

We observe stars to have different colors. The Sun appears yellow, Rigel is blue, and Betelgeuse is red. The color of a star follows Wien's law for blackbodies (Chapter 5, Section VII), the hotter the body the bluer it is (Figure 3).

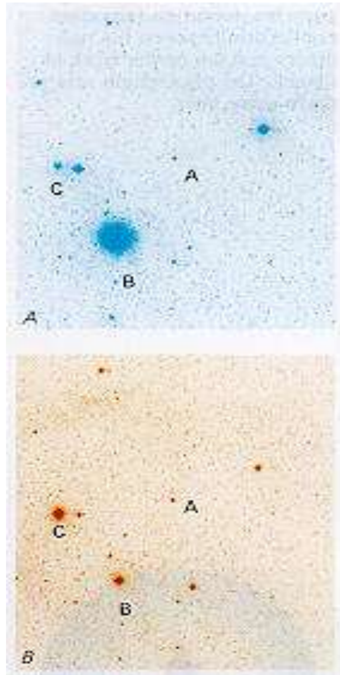


**Figure 3.** *Filter photometry can be used to measure the photospheric temperature of a star. The upper image is a photograph of a star field taken through a blue filter. The lower image was taken with a red filter. Star A appears to have roughly the same brightness in both colors. Star B appears brighter in blue light than in red light, indicating that it is hotter than Star A. Conversely, star C appears brighter in red light than in blue light, indicating that it is cooler than Star A or Star B.* ***P 333-20.2.***

The color of a star can be used to estimate its photospheric temperature. Blue stars are 10,000 to 25,000 K, yellow stars about 6,000 K, and red stars 2,000 to 5,000 K. This is essentially the same method used by metallurgists to estimate the temperature of molten metal in a blast furnace. Astronomers can make a more precise measurement with **filter photometry**. **Photoelectric photometry** is a precise way of measuring the brightness of an object such as a star. A photometer is an electronic instrument that measures the brightness of light by converting photons to an electric current. One way of performing photoelectric photometry is to use the photoelectric photocell (Chapter 14, Section II) and measuring the current that flows through the photocell circuit when light falls on the photocell. This current is in direct proportion to the brightness of the light falling on it. When used with a telescope, the photoelectric photometer enables an astronomer to precisely measure the apparent brightness (or magnitude) of a star. When filters are inserted in front of the photometer, one at a time, the color of a star can be precisely quantified. By comparison with the colors of blackbody spectra representing different temperatures, the measured star color can be used to determine its photospheric temperature.

*Spectra*

Stellar **spectroscopy** is the technique of determining stellar composition and photospheric temperature, among other things, using a telescope to collect light, and optics, such as a prism, to separate light into a rainbow of its component colors, prior to the spectrum being recorded by film or a video camera. Stellar spectra show absorption lines of hydrogen, as well as calcium, iron, and various molecules (Figure 4). **Spectra are related to both stellar composition and temperature.**

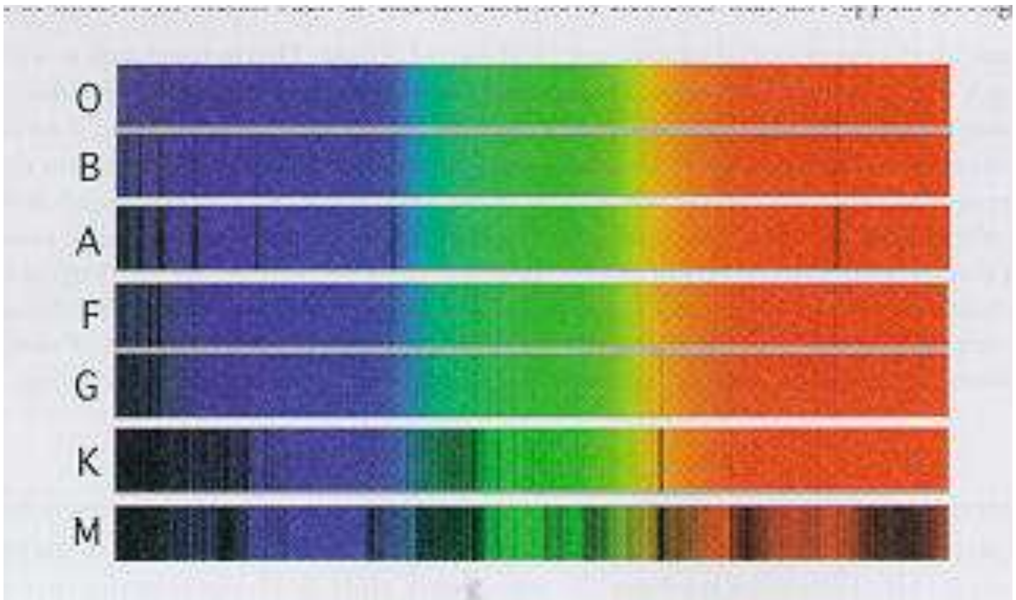


**Figure 5.** *Stellar spectra are determined mainly by photospheric temperatures. All of the spectra in this panel contain dark absorption lines. Stellar photospheric temperature increases from the uppermost spectrum to the lowest. The letters on the left indicate the stellar spectral classification, characterizing photospheric temperature. Many of the absorption lines are labeled by element.* ***Modification Arny.***

Consider absorption spectra from the hydrogen atom (Figure 6). The absorption lines produced by electrons moving from energy level 1 to a higher energy level are called the **Lyman** series. The absorption lines produced by electrons moving from energy level 2 to a higher level are called the **Balmer** series. The Balmer hydrogen lines produce a regular accordion-like spacing in visible-wavelength stellar spectra of medium-temperature stars (Figure 6).

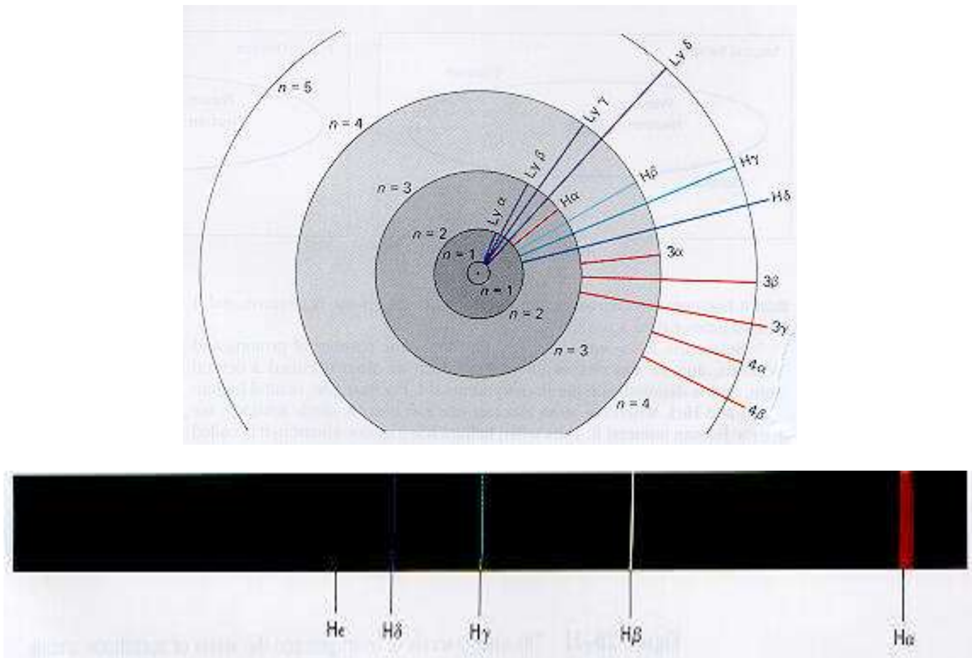


**Figure 6. Panel A.** *A schematic of a hydrogen spectrum showing the Balmer series, spectral lines occurring from electron transitions into or out of the second energy level of hydrogen***. *P 338-2.10* Panel B.** *A hydrogen emission spectrum showing the Balmer series.* ***P 337-20.8.***

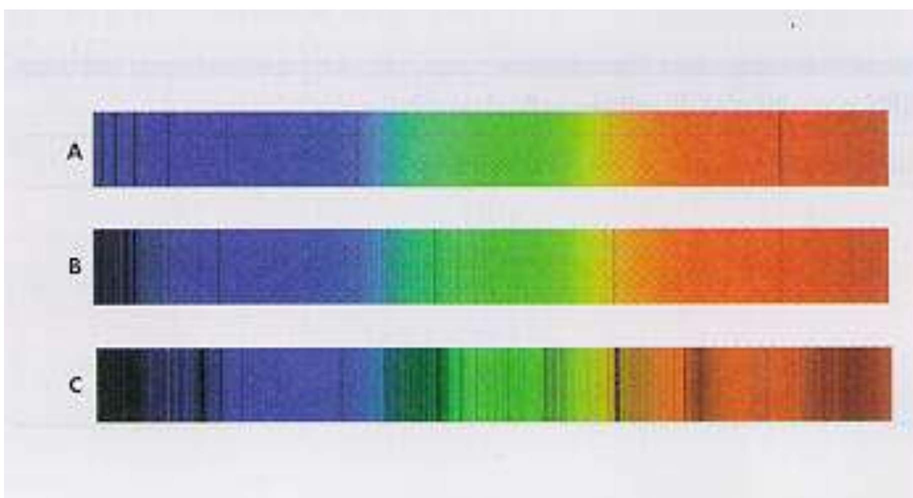


**Figure 7.** *Spectrum B is a low resolution solar spectrum. Spectrum A is the spectrum of a star hotter than the Sun; C is the spectrum of a star cooler than the Sun.* ***Arny.***

Hydrogen is the primary constituent of the Sun. **Why don't we see hydrogen more prominently in the solar spectrum (Figure 7)?** Stellar spectra are very sensitive to the temperature of the photosphere. The reason that hydrogen Balmer lines are more prominent in the spectra of other stars, with no greater percentage of hydrogen than the Sun is a result of the following:

1. In cooler stars, like the Sun, most of the hydrogen electrons are in their lowest energy state. This means that absorption, when it occurs, occurs in the Lyman (energy level 1) series from the lowest energy state of the hydrogen atom. Since the electrons have a long way to go to be lifted to higher energy states, the Lyman series only absorbs high-energy photons from ultraviolet (UV) part of the spectrum, blocked by the Earth's UV-absorbing atmosphere.
2. Balmer series (energy level 2) lines are not seen because of the low temperature of the solar photosphere. Hotter stars (~10,000 K) show Blamer lines, because the hotter photospheric temperature raises electrons from energy level 1 to energy level 2. Visible light can be absorbed by energy level 2 electrons, because this energy level is closer to the higher energy levels than energy level 1 is, and therefore requires photons of less energy for absorption. Balmer lines are seen in the visible part of the spectrum in stars of moderate temperature (4,000 to 10,000 K).
3. At higher temperatures (11,000 – 25,000 K) hydrogen is stripped of electrons (ionized) and the most prominent lines are formed from helium, a more tightly bound atom. Balmer lines and Lyman lines are weaker in stars in this temperature range.
4. At very high temperatures (greater than 25,000 K) the photosphere is almost completely ionized and the spectrum is basically continuous.
5. At low temperatures (less than 3,000 K) molecules can form in the atmosphere and can be detected from their absorption lines.

## V. Diameter

Almost all stars are too far away to directly measure their diameter. The Sun is a prime exception. **How can one determine the diameter of a distant star?** A star's diameter can be calculated from the Stefan-Boltzmann relation (Chapter 5, Section VII):

$$\textbf{Equation 17.2: } L = A\sigma T^4,$$

$$\text{Or rearranging, } A = L/\sigma T^4.$$

Where L is the luminosity or total energy output from a star, A is its surface area, $\sigma$ is the Stefan-Boltzmann constant of proportionality, and T is the star's photospheric temperature. A star's luminosity is determined from its measured brightness and its distance. If the apparent magnitude or brightness of a star has been measured by photoelectric photometry and its distance has been determined from stellar parallax, its luminosity can be calculated from the inverse square law. That gives us L. The colors of a star can also be measured using photoelectric photometry (with filters), allowing the astronomer to calculate the T, the photospheric temperature. Now, the surface area, A of the star can be calculated from **Equation 17.2**. But the surface area of a sphere is $4\pi R^3$, where R is its radius. Knowing A, the astronomer now also knows R.

## VI. Stellar Mass and Binary Stars

We can't directly measure the mass of any star from the Earth. However, using Newtonian mechanics it is possible to derive the masses of stars from the period that a satellite takes to orbit a star. From Newtonian mechanics, a relationship akin to Kepler's laws can be derived (Chapter 3, Section XI):

**The sum of the masses of a star and its satellite times the square of the orbital period = cube of the semi-major axis.**

While we can't easily put a satellite into orbit about a star, there are stars being orbited by companion stars that are easily seen from Earth with the aid of a telescope. By measuring the changing separation between one star and its companion over time, it is possible to calculate the sum of the masses of the star and its companion. For binaries with companions having masses much lower than the central star, it is really the mass of the central star that is being calculated.

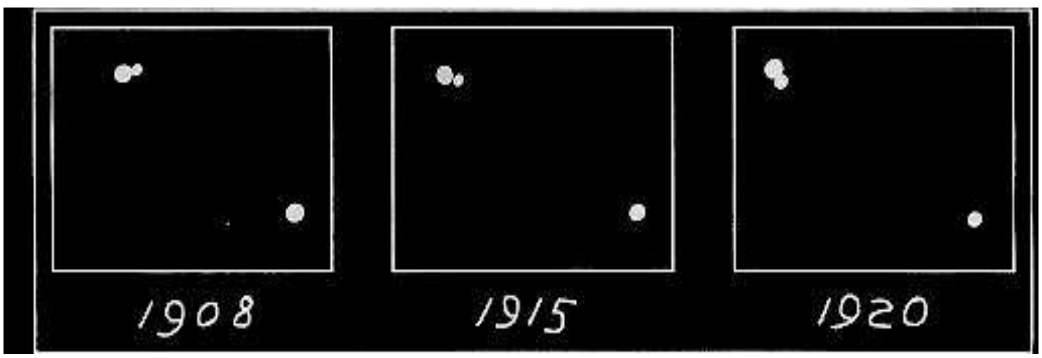


**Figure 8.** *Kruger 60, a nearby true binary system. Three photographs taken from 1908 to 1920 show the revolution of both stars about their center of mass.* ***FMW 345-17.4.***

Two-thirds of nearby stars are members of **multiple star systems**, stars that are seen to be close to each other on the sky. One-half of the stars in the sky are thought to be **binary stars (Figure 8)**. Some of these **double stars** are **optical doubles**, two stars that appear to be close together on the sky, by are widely separated in three dimensions, so that they are not gravitational bound. Others are **true binaries**, with both stars orbiting a common center of mass (Chapter 13, Section IV).

In **visual binaries** the stars can be spatially resolved, that is, their separation can be seen and measured. By tracking the separation of a visual binary over time (Figure 8), the masses of the stars can be determined. Measurements of binaries yield a range in stellar masses from $1/10^{th}$ solar mass to 100 solar masses.

## IIX. The H-R diagram

**What makes stars tick? How can we determine the structure of stars, how they formed, and how their properties change as they age from studying their fundamental properties?**

If we examine four fundamental properties of stars (Table 17.1), their luminosity, photospheric temperature, radius, and mass we see that stars vary greatly in luminosity (by a factor of $10^8$), moderately in radius (by a factor of 5,000), and only by a relatively small amounts in mass and photospheric temperature. Why do luminosity and radius vary so much in stars, while photospheric temperature and mass stay in a relatively narrow range? If we examine the luminosity, photospheric temperature, radius, and masses of a random sample of stars will we see patterns that tell us something about the way stars behave?

**Table 17.1:** *Normal Range of Stellar Properties*

| Property | Range of Values |
|---|---|
| Luminosity | $10^{-4}$ L to $10^{4}$ L |
| Photospheric Temperature | 2000 K to 20,000 K |
| Radius | 0.01 R to 500 R |
| Mass | 0.1 M to 50 M |

*Fundamental Properties of People: Height and Weight*

In this section we will graphically examine two of the fundamental physical properties of people, their height and weight, to see if they can tell us something fundamental about the structure of the human body. Subsequently, we will use the same technique to examine the fundamental properties of stars to see what they say about stellar structure and evolution.

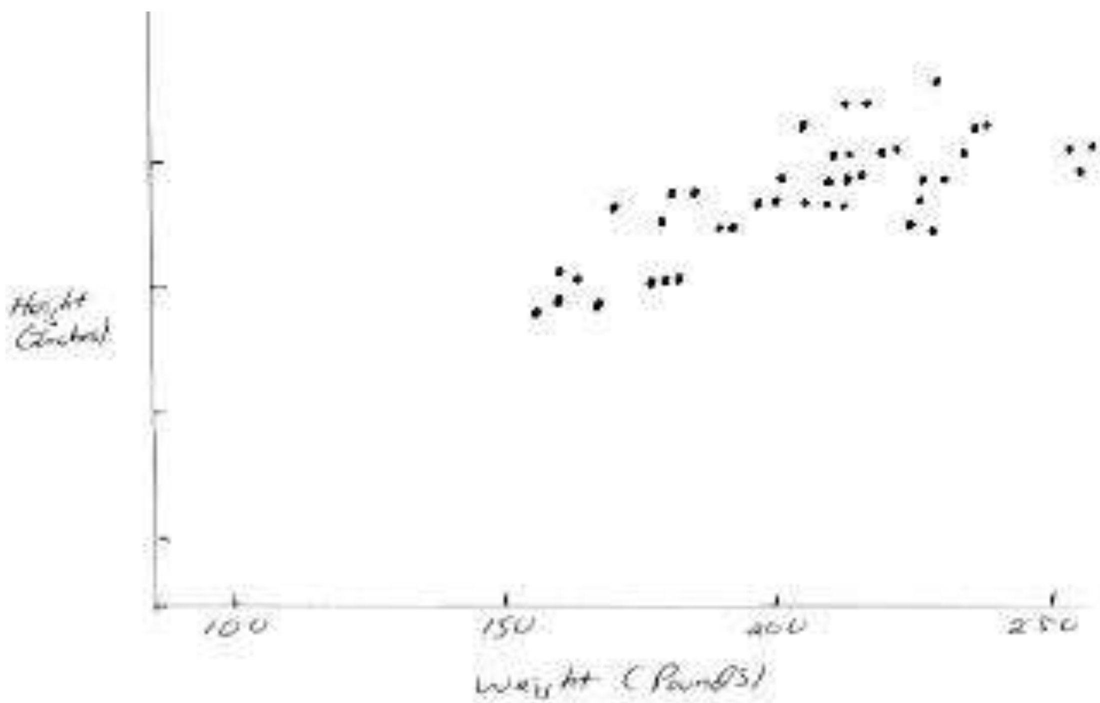


**Figure 9.** *Heights and weights of the University of Wyoming football team.* ***Original.***

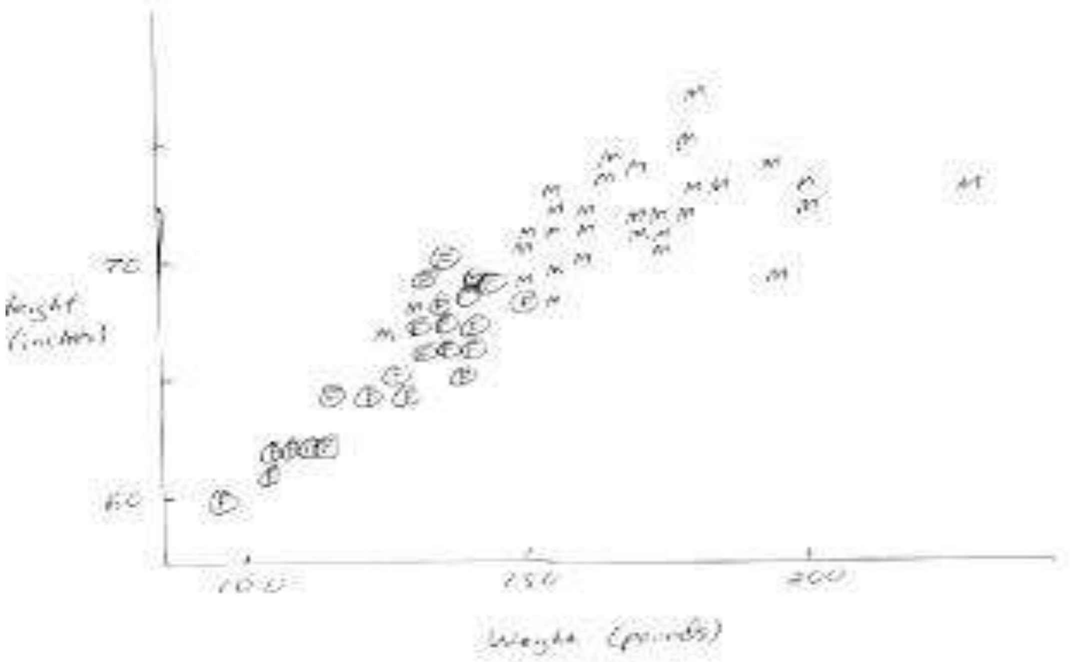


**Figure 10.** *Heights and weights of college students. Women are represented with an "F" enclosed in an open circle; men are designated with an "M."* ***Original.***

Figure 9 shows the heights and weights for the defensive squad of the University of Wyoming football team. A smooth line has been drawn through the data points, each one of which represents the height and weight of a football player. This line represents a possible relationship or correlation between height and weight, ignoring deviations caused by atypical individuals.

In Figure 10 are shown the heights and weights of college students from an introductory astronomy class at the University of Wyoming. A smooth line has been drawn through this data set, representing a possible relationship between height and weight. Notice that women and men fall on the same height/weight relationship trend, although women tend to be shorter and weigh less than men, at least for this particular group of college students. Why do most men and women in this sample fall near the same trend line? If humans all have similar shapes (in a gross sense) and mass densities, then taller people will weigh more and shorter people will weigh less. People whose shape is atypical will show a deviation from the trend line.

Now let’s look at the Wyoming Cowboys’ heights and weights on the same graph with the college students (Figure 11). Only the smallest of these professional football players fall on the same trend line previously drawn through the college students. The football player trend line seems to level off at 75” (6 foot 3 inches) height, the height for a 200-pound college student, but 6 foot 3 inch football players can significantly exceed 200 pounds. This is not too surprising, since professional football players intentionally increase their bulk through diet and exercise. We don’t expect them to follow the same trend as typical college students.

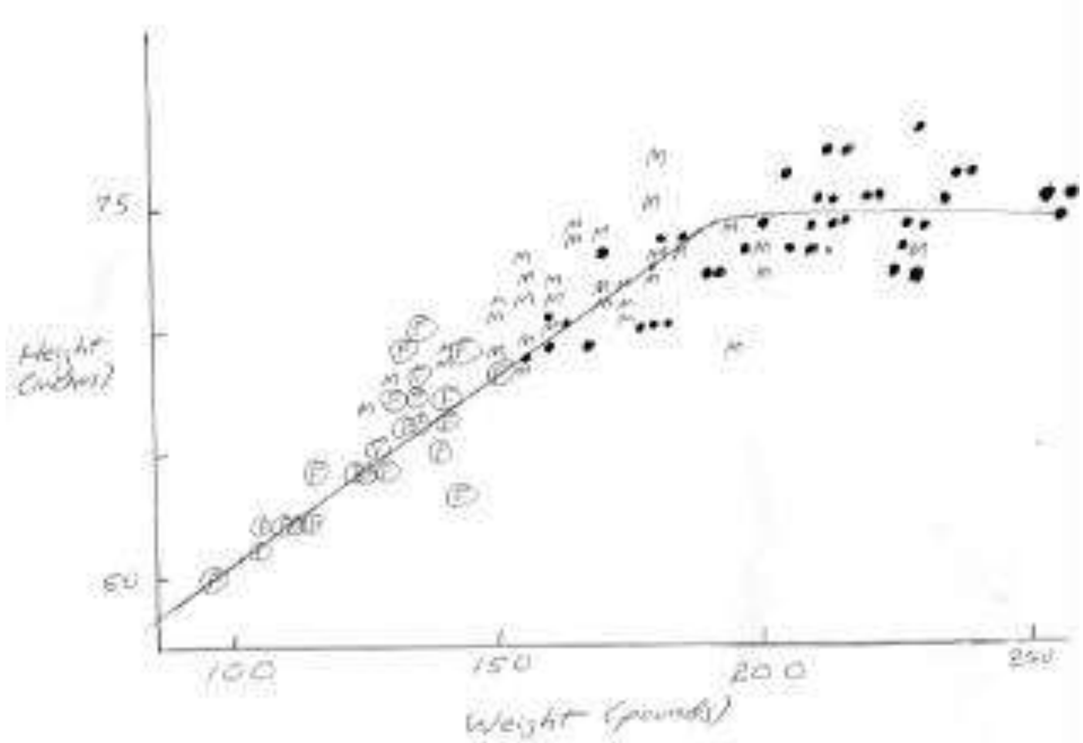


**Figure 11.** *Heights and weights of college students and football players combined. The solid line represents a suggested trend line drawn through the data.* ***Original.***

We can use this same graphical method for the analysis of the fundamental properties of stars, to see what we can learn about them, their sub-populations, and to separate the typical from the atypical.

*Fundamental Properties of Stars: Temperature and Luminosity*

To learn something about the structure of stars we will plot their luminosity against their photospheric temperatures for a group of typical stars and then for a group of the brightest stars, similar to the exercise that we performed above for typical college students and then for professional football players.

*The Nearest Stars*

Figure 12 shows a graph of photospheric temperature versus luminosity for the 37 stars nearest to the Sun, a sampling of stars that just happens to be within 5 parsecs of the Sun, and therefore easy to measure, but which should be expected to be typical in their properties with respect to other stars in our galaxy.

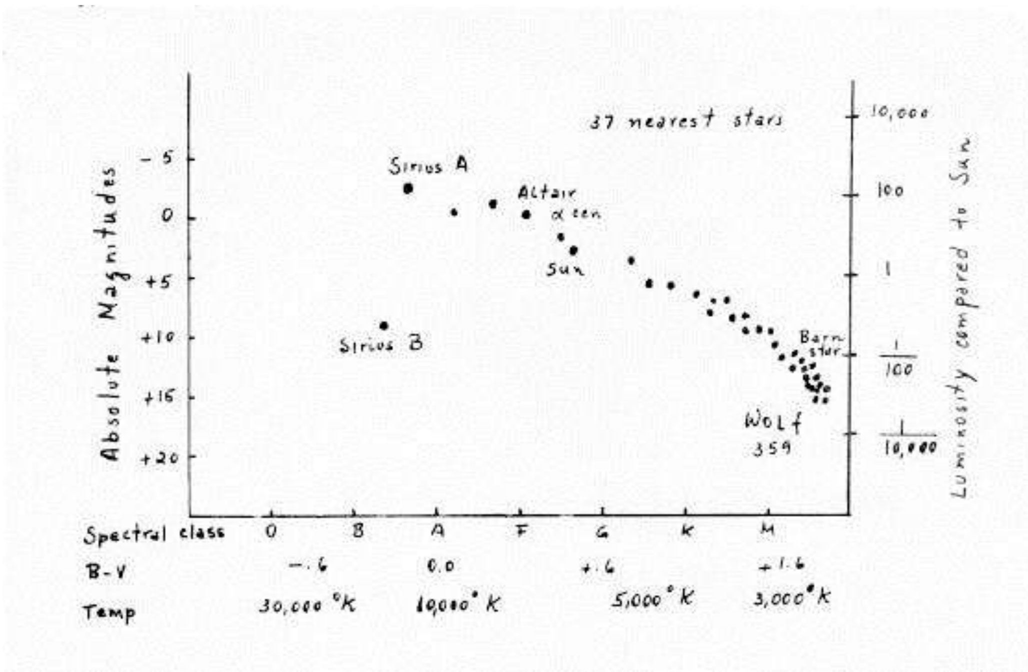


**Figure 12.** *The H-R diagram for the 37 nearest stars. These stars are within 17 light years. The diameters of the open circles correspond to the diameters of stars on the main sequence. White dwarfs are represented by dots.* ***Original.***

In 1911, the Danish astronomer Ejnar Hertzsprung was the first to plot such a diagram. In 1913, the American astronomer Henry Norris Russell independently made a similar analysis. We call these diagrams **Hertzsprung-Russell diagrams** or **H-R diagrams**. Today they are one of the most powerful tools in astronomy and astrophysics. For historical reasons the temperature scale on an H-R diagram is always plotted backwards, from high photospheric temperature on the left to low photospheric temperature on the right.

Notice that all of the nearest 37 stars to the Sun in Figure 12, except for Sirius B (the binary companion to Sirius A), fall on a trend line, which astronomers call the **main sequence**. Sirius B has nearly the same temperature as Sirius A but is more than 10,000 times less luminous. This main sequence trend is not exact, but it does show a basic relationship between a star's luminosity and its photospheric temperature. Notice that of the 37 nearest stars to the Sun only five are more luminous than the Sun. A typical solar neighborhood star is less luminous than the Sun; many are less than 1% of the Sun's luminosity.

Each point on the H-R diagram represents the luminosity and photospheric temperature of an individual star. We also know that there is a relationship between stellar luminosity, photospheric temperature and stellar radius given by Equation 17.2, which can be written as:

**Equation 17.3:** $\mathbf{L = 4\pi R^2 T^4}$.

Given the photospheric temperature and luminosity for each point in the H-R diagram, we can determine its stellar radius. Figure 13 shows the H-R diagram for the 37 nearest stars with lines of equal radius superimposed as determined from the equation above. The main sequence trend follows a trend of nearly constant stellar radius. In other words, since stars on the main sequence have nearly the same size, differences in their luminosity are a result of differences in photospheric temperature.

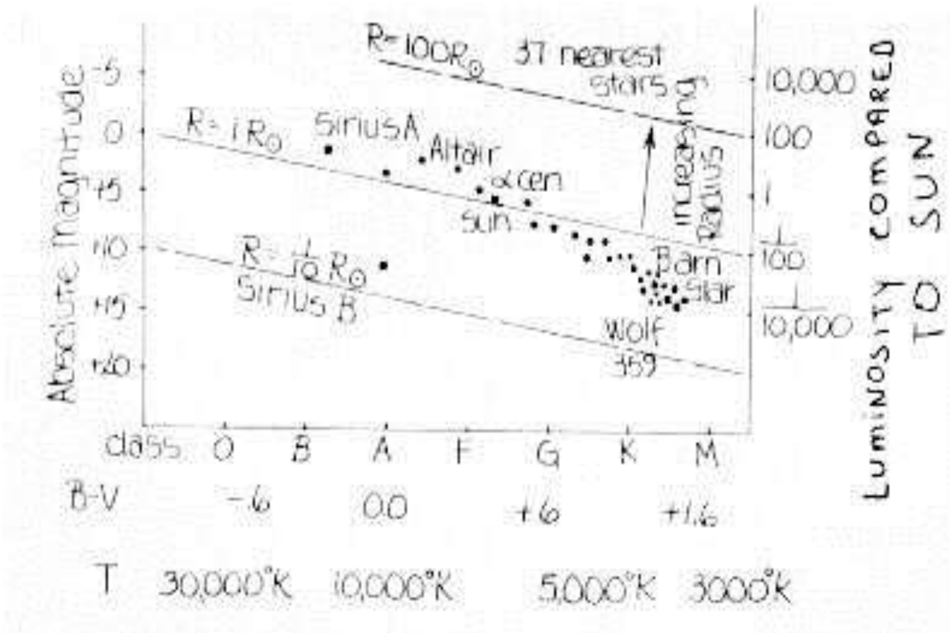


**Figure 13.** *The radii of the 37 nearest stars. The H-R diagram for the 37 nearest stars is drawn with lines of constant stellar radius. Main sequence stars are close to one solar radius in size.* ***Original.***

*The Brightest Stars*

In Figures 14 and 15 we plot the brightest stars in the sky on the same H-R diagram with the 37 nearest stars. Notice that all of the brightest stars in the sky are more luminous than the Sun. This means that they are intrinsically very bright, and do not just appear bright because they are close to us. Some of the brightest stars extend the main sequence trend line that we found for the nearest stars, but others are found in the upper right-hand corner of the H-R diagram, far removed from the main sequence. Stars in this corner of the H-R diagram are not only very luminous, but they are very large. These stars are called **giants** and **supergiants**. Very small stars occupy the lower left-hand corner of the H-R diagram; they are called **white dwarfs**.

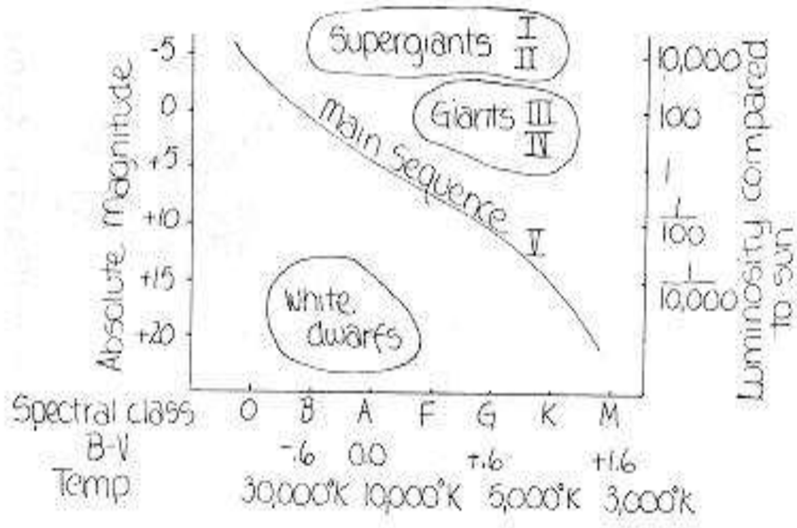


**Figure 14. Panel A:** The H-R diagram for the 37 brightest stars in the sky. Main sequence stars, giants, supergiants, and white dwarfs are labeled. **Original.**

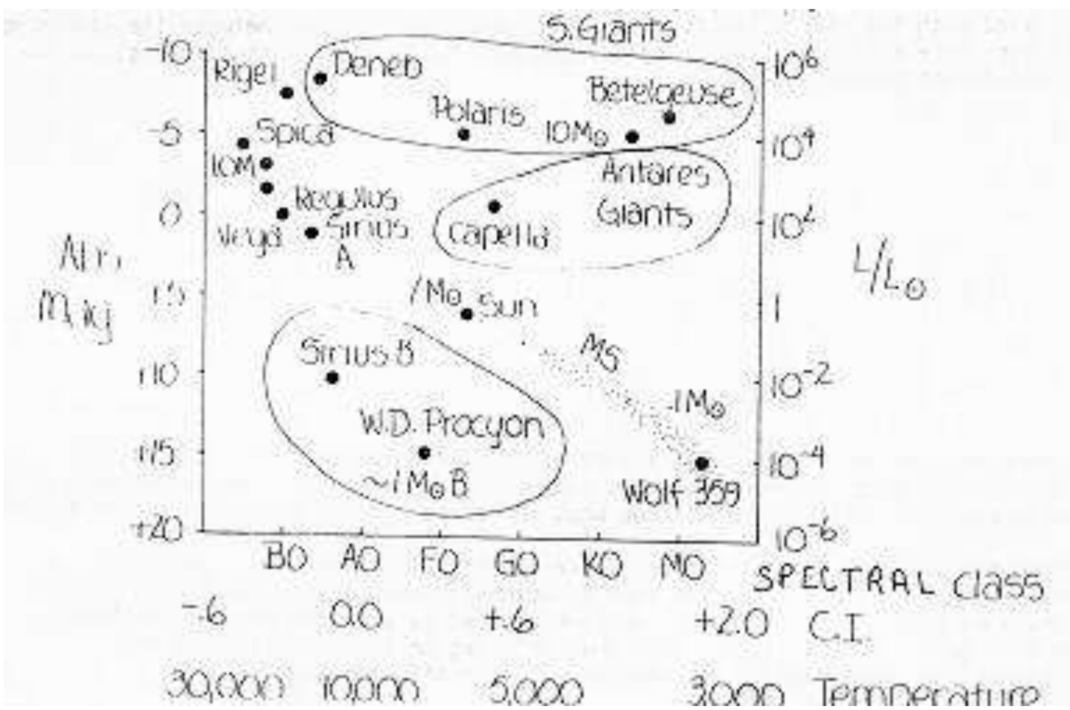


**Figure 15.** *Masses of the 37 brightest and 37 nearest stars. Notice that the main sequence is a mass sequence with the least massive stars the least luminous and the most massive the most luminous.* ***Original.***

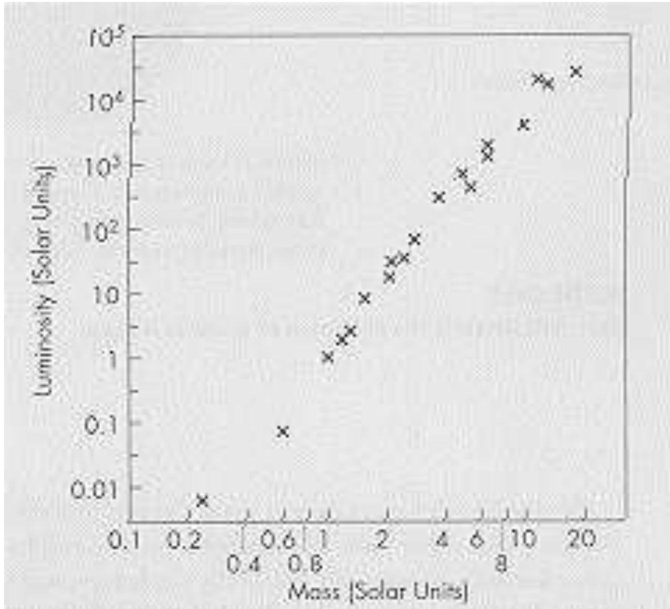


**Figure 16.** *The mass-luminosity relationship for main sequence stars.* ***FMW 349-17.9.***

*The Main Sequence: a Mass Sequence*

We have used the H-R diagram to look at the correlation of the fundamental stellar properties of luminosity, photospheric temperature, and radius**. How does a star's mass correlate with its position on the H-R diagram?** In Figure 15 we see the masses of selected stars marked on the H-R diagram. Studying this diagram, it is easy to see that giant and supergiant stars are generally more massive than other stars; the two supergiant stars shown are both about 10 solar masses. The white dwarfs are both about one solar mass. There is a definite mass trend along the main sequence with the least luminous, smaller stars in the lower right-hand corner having the least mass, changing to more massive, larger, more luminous stars as the main sequence is followed to the upper left-hand corner of the H-R diagram. **The main sequence is a mass sequence.**

It is important to note that although mass doesn't change much over the H-R diagram (only varying between 0.1 solar mass and 10 solar masses in this diagram), stellar radii vary by a factor of one thousand, and stellar volumes vary by the stellar radius cubed (or a factor of 1000 x 1000 x 1000 = 1 billion). The result is that stellar densities (mass divided by volume) vary widely, from a supergiant with a density close to that of water to a white dwarf, one tablespoon full of which could weigh a ton.

**IIX. Stellar Lifetimes**

**What can we say about the ages of stars from the H-R diagram?** How long can a star live? Let's assume that stars fuse their nuclear fuel at a constant rate. The estimated longevity of a star is then the mass of the star, the amount of nuclear fuel available, divided by the rate that it burns this fuel, which is proportion to its luminosity. Our simple mathematical model of the maximum lifetime of a star is represented by the following equation:

**Equation 17.4: lifetime = constant of proportionality x mass /luminosity,**

What is the constant of proportionality? We have estimated 10 billion years for the expected lifetime of the Sun. If we **Equation 17.4** to solve for the lifetime of the Sun, and use solar mass, solar luminosity, and years for our units of mass, luminosity, and age, we obtain the following:

**10 billion years = constant of proportionality x 1 solar mass / 1 solar luminosity,**

**or constant of proportionality = $10^{10}$ years x solar luminosity/solar mass,**

Our **Equation 17.4** can then be written:

**Equation 17.5: lifetime = $10^{10}$ years x mass/luminosity,**

where mass is in units solar mass and luminosity is in units of solar luminosity.

**How long are a 10 solar mass main sequence star and a 0.1 solar mass main sequence star expected to live (i.e. fuse hydrogen into helium)?**

From Figure 16 we see that a 10 solar mass main sequence star has a luminosity of about 3000 times the luminosity of the Sun. From Equation 17.5 we have:

Lifetime of a 10 solar mass star = $10^{10}$ years x 10/300 = 3 x $10^{7}$ years.

From Figure 16, a 0.1 solar mass main sequence star has a luminosity of only one-thousandth of the Sun's luminosity, so:

Lifetime of a 0.1 solar mass star = $10^{10}$ years x 0.1/0.001 = $10^{12}$ years.

These ages are summarized in Table 18.2.

From Table 17.2 we see that stellar ages for stars on the main sequence vary by a considerable amount, mainly because high mass stars burn their fuel at an incredible rate, far out of proportion to their mass, while low mass stars have a low nuclear metabolism.

**Table 17.2** *Lifetimes of Stars on the Main Sequence*

| Stellar Mass | Stellar Luminosity | Stellar Lifetime |
|---|---|---|
| 10 solar masses | 3000 solar luminosities | 3 x $10^{7}$ years |
| 1 solar mass | 1 solar luminosity | $10^{10}$ years |
| 0.1 solar mass | 0.001 solar luminosity | $10^{12}$ years |

**Star Clusters**

The key in studying the evolution of stars is the comparison of H-R diagrams of star clusters. Star clusters are groups of stars that were born at roughly the same time and place, having gravitationally condensed out of a single cloud of gas and dust. Because the stars formed at the same location, they are at the same distance. This makes it easy to measure their relative luminosities. Because they formed at nearly the same time, this makes it easy to determine which stellar properties are not age-related. Studying a series of star clusters of differing ages is like studying the evolution of humans by taking year-book pictures of students from different grades, say pre-school through seniors in college, and determining which physical features change with age and which don't.

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**Summary**

Some of the fundamental properties of stars are mass, diameter, photospheric temperature, distance, composition, and luminosity. The distance to a nearby star can be measured from its parallax. From its apparent brightness and distance its luminosity can be determined, using the inverse-square law. The photospheric temperature of a star can be measured using filter photometry and applying Wien's law relating color and temperature. Spectroscopy can also be used to determine the photospheric temperature of a star in addition to its composition. Once the photospheric temperature and luminosity of a star are determined, the Stefan-Boltzmann law can be used to derive its diameter.

One of the most powerful methods of analyzing the structure and evolution of stars is through the Hertzsprung-Russell diagram, a plot of the luminosities and photospheric temperatures of a group of stars. Most stars fall along a line in the H-R diagram called the main sequence. The main sequence is a mass sequence, representing the trend that the more massive a star is, the more hot and luminous it is. Stars on the main sequence are nearly the same diameter as the Sun. A star's lifetime on the main sequence is proportional to its mass divided by its luminosity. Because massive stars are luminous well out of proportion to their mass, they have much shorter life spans than low mass stars.

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**Key Words & Phrases**

1. **Absolute magnitude** - the magnitude a star would have if moved to a distance of 10 parsecs
2. Apparent magnitude -
3. **Balmer lines** - absorption lines produced by an electron orbiting the hydrogen nucleus moving from level 2 to a higher energy level, or emission lines produced by a hydrogen electron moving from a higher energy level to level 2
4. **Binary stars** – two stars that appear to close together on the sky
5. **Double stars** - two stars that appear to be close together on the sky, by are widely separated in three dimensions, so that they are not gravitationally bound
6. **Giant** – a post main sequence star of large radius and luminosity

7. **Hertzsprung-Russell diagram** – a plot of the luminosity vs. photospheric temperature for a group of stars. (Historically it was the plot of absolute magnitude vs. spectral class.)
8. **Light year** – the distance that light travels in one year, about six trillion miles
9. **Lyman lines** - absorption lines produced by an electron orbiting the hydrogen nucleus moving from the lowest energy level to a higher energy level, or emission lines produced by a hydrogen electron moving from a higher energy level to the lowest energy level
10. **Luminosity** - total energy output per unit time
11. Main sequence -
12. **Multiple star systems** - stars that are seen to be close to each other on the sky
13. **Optical doubles** - two stars that appear to be close together on the sky, by are widely separated in three dimensions, so that they are not gravitationally bound
14. Parallax –
15. **Parsec** – a distance of 3.26 light years. The distance of an object which exhibits a parallax of one arc-second.
16. **Photoelectric photometry** - a precise way of measuring the brightness of an object such as a star using an electronic instrument that measures the brightness of light by converting photons to an electric current
17. **Photometry** – brightness measurements
18. Spectroscopy -
19. **Supergiant** – a post main sequence star of the largest luminosity and radius
20. **True binaries** – two stars orbiting a common center of mass
21. White dwarf -

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**Review for Understanding**

1. What do stellar spectra tell us? How?
2. Sketch an H-R diagram plotting the approximate location of the 30 brightest stars and the 30 nearest stars. Label the axes, including units. On the diagram label the regions containing the stars of largest radius, smallest radius, stars having nearly the radius of the Sun, blue stars, and red stars.
3. What is a light year?
4. Explain the difference between a binary star system and a true binary.
5. In your own words, what is the main sequence?
6. How can one measure the temperature of a star?
7. How do we know that helium exists in the Sun?

**Essay Questions**

1. Explain why hydrogen absorption lines are not prominent in the spectra of stars hotter than 25,000 K. Cooler than 3,000 K.
2. How do the 30 brightest stars in the sky compare with the 30 nearest stars in luminosity? How do the 30 brightest stars compare in luminosity with the Sun? How do the 30 nearest stars compare in luminosity with the Sun? Explain.

# Chapter 18 - Origin and Evolution of Stars

*The test of all knowledge is experiment. Experiment is the sole judge of scientific truth.* – Richard P. Feynman

**Chapter Photo.** *The Lagoon Nebula (M8), a region of intense star formation at the edge of a dust-laden molecular cloud. The Hubble Space Telescope took this image in 1995.* ***NASA, APOD.***

**Chapter Preview**

One of the greatest advances in astrophysics in the second half of the 20$^{th}$ century is the study of star formation. Prior to the development of infrared astronomy in the 1970s, little observational data existed on star formation, for stars in their infancy are enshrouded by clouds of dust that are opaque to visible radiation. Observational data was not keeping pace with theoretical models of star formation. Now radio, microwave, and infrared technology allow the study of clouds of gas and dust collapsing into fragments that eventually form infant stars and star clusters and the study of young stars still covered by their dusty cocoons. Now it is the theorists who must struggle to keep pace with observational data.

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**Key Physical Concepts to Understand:** the *process of star formation, the use of star cluster H-R diagrams in studying stellar evolution, the relationship between a star's mass and the tempo of its evolution*

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## I. Introduction

In Chapters 13 and 14 we saw how the process of planetary system formation occurs in a spinning and collapsing cloud of dust after the formation of a central star. In this chapter we will look earlier in the formation process and on a larger scale, in order to understand the formation of stars and groups of stars. The premise is the same, that stars form from the collapse of clouds of gas and dust. Gravity is the ever-present and essential ingredient in the formation process. First let us look at the medium in which the star birthing process takes place.

*The Interstellar Medium*

Our Milky Way galaxy is composed of stars and the near-perfect vacuum between them. This vacuum is near-perfect by Earth standards, but at a density of one million particles per cubic meter it holds 10% of the mass of the Milky Way and is the raw material out of which new stars condense. The gas and dust composing this interstellar medium is 74% hydrogen, 25% helium, and 1% heavier elements by mass. The temperatures of dark interstellar clouds are incredibly cold, typically between 10 and 20 K.

*Giant Molecular Clouds*

**Figure 1.** *The Eagle Nebula (M16). A cluster of stars illuminates the Eagle Nebula, a site of current star formation, that formed about two million years ago, seen in the upper right hand part of this image.* ***FMW 398-20.1.***

The interstellar medium is far from uniform. It is populated by numerous giant clouds where gas and dust are 10,000 times denser than the ambient interstellar medium. These clouds have typical densities of $10^{10}$ hydrogen molecules per cubic meter, masses of one million solar masses, and are 50 to 300 light years in diameter. Roughly 6,000 of these **giant molecular clouds** are known to exist in the Milky Way, many are seen in the Orion region of the sky (Figure 1).

Giant molecular clouds are opaque to visible light from the silicate and ice dust grains spread throughout their volumes. Dust grains are important to the chemistry of the interstellar medium. Hydrogen atoms collide with individual dust grains, stick to the surface and react to other hydrogen atoms forming molecular hydrogen, $H_2$. The dust protects the molecular hydrogen from destruction by energetic ultraviolet radiation from hot stars. Dust clouds also serve as a sanctuary for other molecules, including carbon monoxide, water, ethyl alcohol, and several **amino acids**, one of the building blocks of life on Earth. Because of their high density relative to the rest of the interstellar medium, molecular clouds are the active sites of current star formation, nurseries for newborn stars.

*Supernovae Trigger Star Collapse*

A Supernova is the violent explosion at the end of the life of a high-mass star that destroys the star and blows away most of its mass at supersonic velocities, several thousand kilometers per second (Figure 2). As this supersonic gas plows through the interstellar medium it smacks into giant molecular clouds, compressing them enough to trigger their collapse.

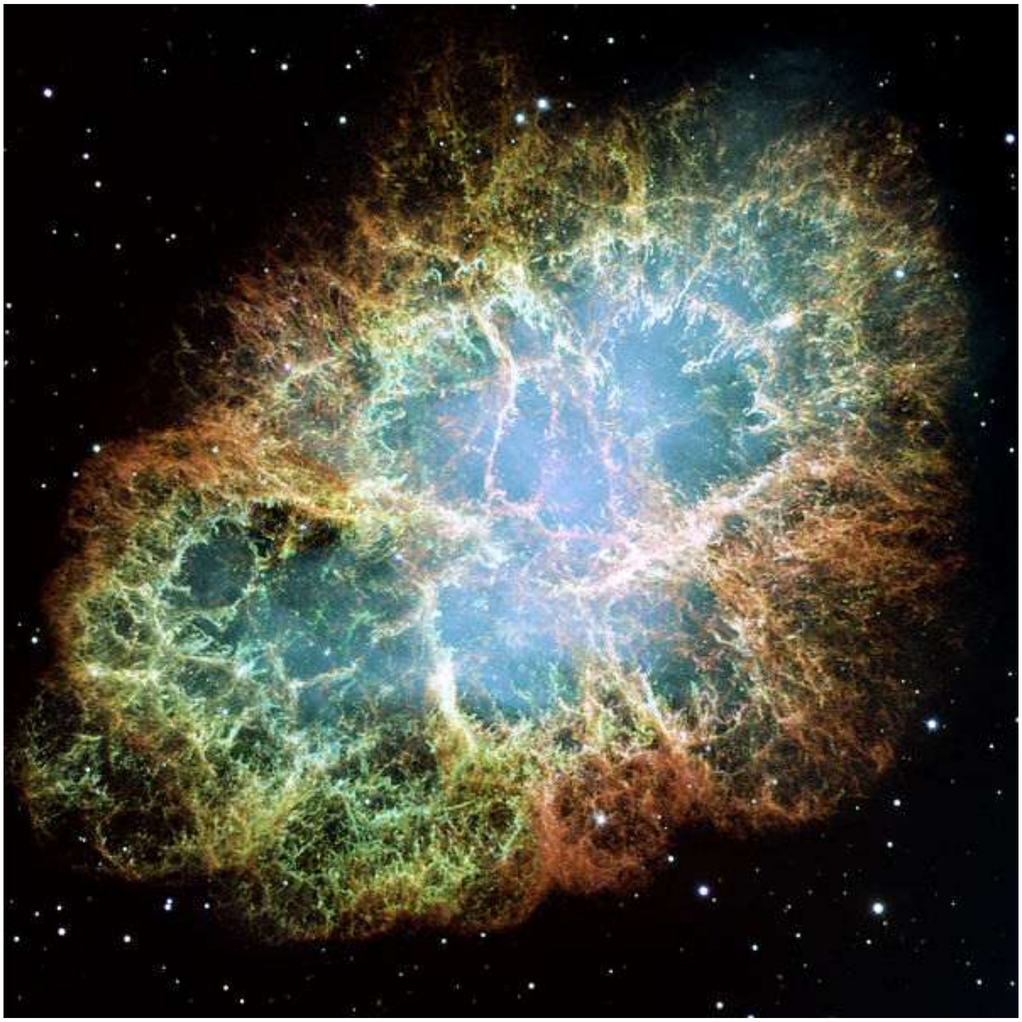

**Figure 2.** *The Crab Nebula, gaseous remnants of a supernova that exploded in 1054 AD.* ***NASA.***

There are other possible triggers for giant molecular cloud collapse, including the random collisions which occur between giant molecular clouds and the intense radiation from a newly formed bright star or group of stars embedded in a molecular cloud. In each case the cloud is compressed, seeding denser portions of it to collapse if they are cool enough so that gas pressure pushing outward can't support the cloud against the gravitational collapse of cloud fragments.

Infrared observations show compact regions or dense cores in giant molecular clouds (Figure 3) with temperatures of about 10 K that are likely to collapse to form stars. Giant molecular clouds typically contain 100s or 1000s of such dense cores. The result is that a molecular cloud is eventually expected to form an open cluster of stars from the collapse of its core condensations.

**Figure 3.** *A molecular cloud serves as a nursery for newly forming stars. Nearby are recently formed stars that have blown away the nearby gas and dust.* ***HST, NASA.***

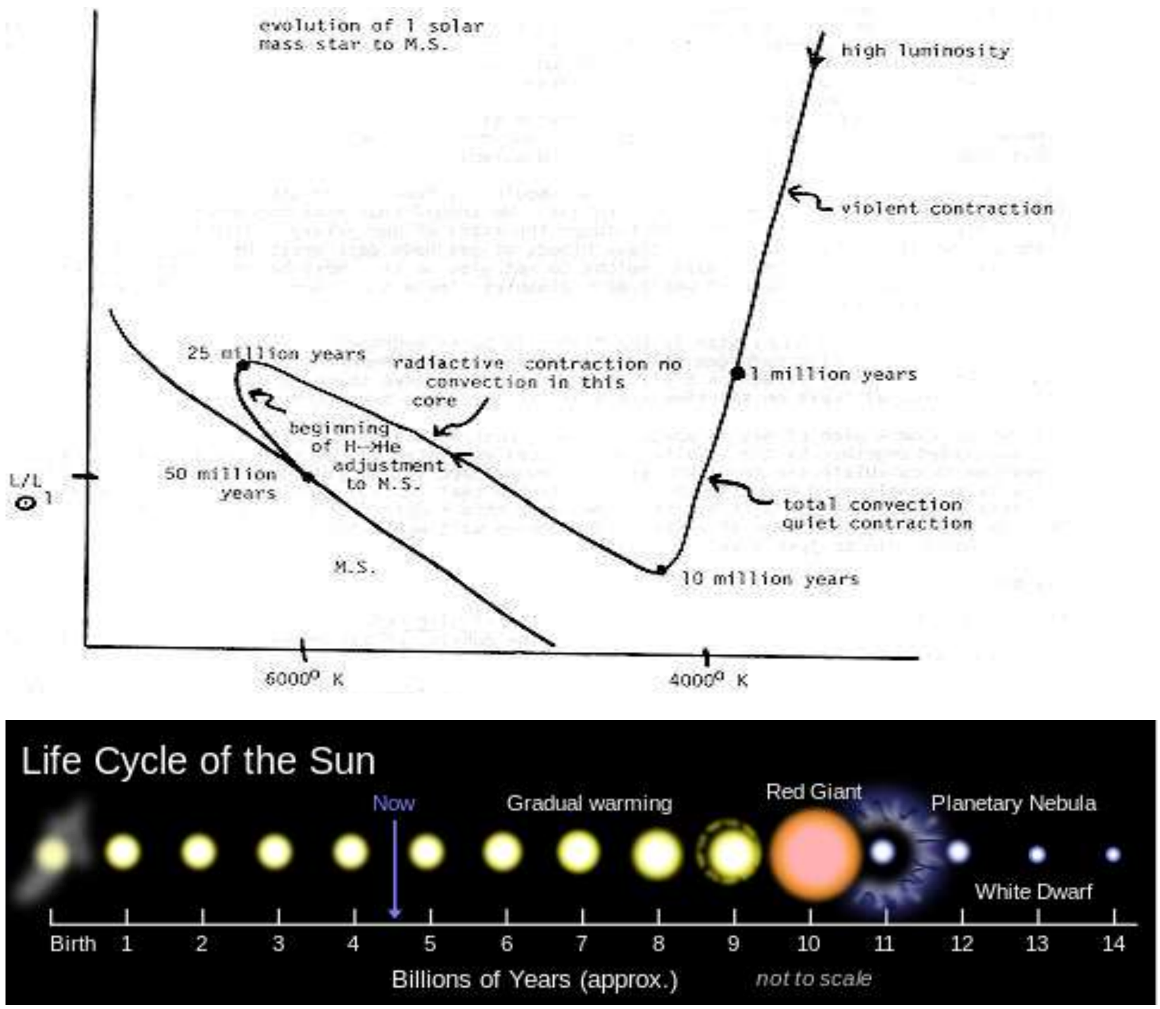


**Figure 4.** *Evolution of a one solar mass star. Upper Panel: The evolution of a one solar mass star onto the main sequence.* ***Original.*** *Lower Panel: The appearance of a one solar mass star over its lifetime.* ***Wikimedia Commons.***

A collapsing molecular cloud core is a region of enhanced density thousands of times larger than our own Solar System. The inner part of the contracting core will eventually collapse into a visibly self-luminous protostar with its energy generated by gravitational collapse. The protostar has yet to commence nuclear fusion. If the core is not spinning it is expected to collapse directly into a sphere, eventually becoming a single star. If it is rotating it will collapse into a spinning disk of gas and dust, similar to β Pictoris (Chapter 12) forming a multiple star system or a single star with orbiting planets.

## II. Evolution of Protostars onto the Main Sequence

*Computer-Scenarios of Pre-Main Sequence Stellar Evolution*

Computer models are required to simulate the collapse and birth of a star from a cloud of gas and dust in our own galaxy. Computers are required for the extensive bookkeeping needed to model the gravitational forces everywhere in a collapsing knot of matter in a gas cloud and to follow its evolution in time. The problem is so complicated that usually a fair number of assumptions are made; for example: the cloud is not rotating and it does not have a magnetic field. It still takes millions of steps of computation to follow the evolution of a collapsing cloud into a fully formed main sequence star. We will summarize the major steps in the collapse of a one solar mass star (Figure 4).

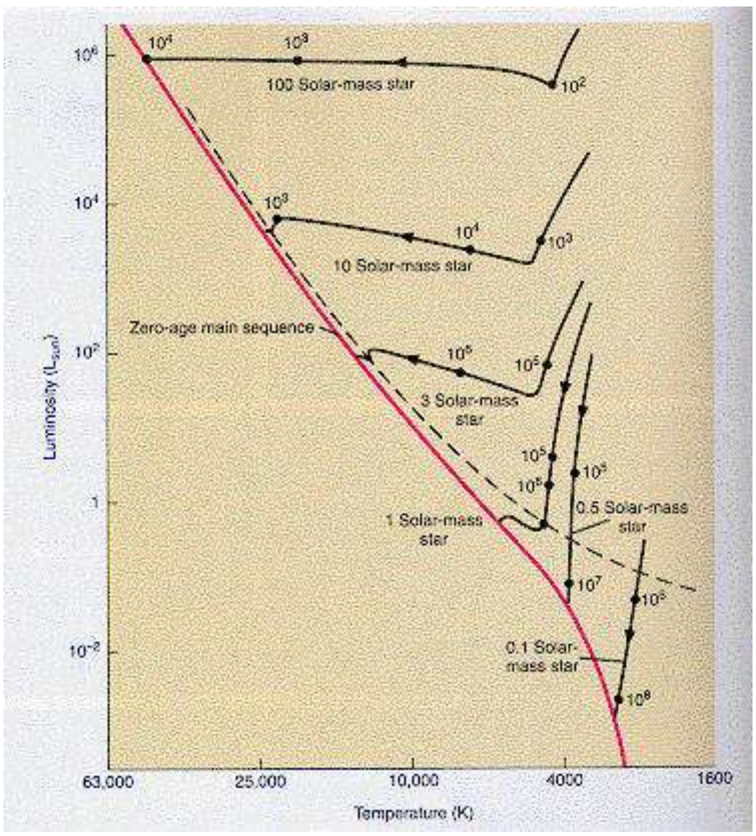


**Figure 5**. *The evolutionary tracks of stars of a range of masses, evolving onto the main sequence. The numbered dots indicate the ages of these stars at different phases of their evolution. The more massive a star, the faster it evolves at every phase. Points above the dashed line represent stars that are probably hidden by their dust cocoons.* ***Modify to include Hayashi track. FMW 406-20.11.***

*Scene I: A star is born.*

*The knot in our stellar cloud, soon to birth a star, before contraction it has the following vital statistics: a mass of one-solar mass, a temperature of 10 K, a radius of one light-*

*year, and a density of $10^{11}$ atoms/cm$^3$. (This a large number, but don't be fooled, it is only $10^{-16}$ the density of the air we breath.) This knot is cold, large, and very tenuous.*

*A small core seeds the center of the knot. The center of our one solar mass knot becomes opaque, and as a result, the energy it generates from gravitational collapse is not completely radiated into space; instead the knot becomes warmer. The core now contains 0.5% of the mass of the entire knot and has a temperature of about 170 K. The density of the core is $10^{-7}$ of our air pressure at the Earth's surface and the core diameter is 4 A.U. Matter falls from the outer regions of the knot onto the core and releases energy.*

*Scene II: A year later…*

*The core of the collapsing protostar has contracted to a diameter of twelve times the diameter of the Sun. It has grown to 1% of the entire mass of the knot and its temperature has risen to 20,000 K.*

*Scene III: 80,000 years later…*

*Gravity is winning its war with this molecular cloud knot. The protostar core now contains more than 50% of one solar mass. It has a surface temperature of 8,300 K and a luminosity 30 times that of the Sun. The protostar is beginning to look like a real star. It won't be this luminous again until it becomes a red giant, in some 10 billion years time. With this fantastic luminosity, still generated by gravitational contraction, the properties of the protostar are changing rapidly.*

*Scene III: A million years later…*

*The breathlessly rapid evolution of the protostar is beginning to slow. Its properties are starting to approximate the fully formed main sequence star that it will be. It is now twice the diameter of the Sun with 1.3 times the Sun's luminosity. It has a 4,400 K surface temperature and its contraction has slowed to a walk. The core temperature is now up to several hundred thousand K, still far short of thermonuclear ignition. The star's interior is transporting energy to its surface by convecting hot bubbles of gas, mixing the hot interior with the cooler surface gas.*

*Scene IV: 24 million years later…*

*The core temperature of the star has reached 10 million K. The star has replaced gravitational contraction with a new energy source. Hydrogen fusion to helium finally begins! Over the next 25 million years gravitational contraction will cease, and our star will settle into hydrostatic equilibrium on the main sequence for the next 10 billion years.*

**How long does it take for a star to form?** Table 18.1 shows the length of time from initial core formation until thermonuclear ignition takes place. The phases of pre-main sequence evolution are the same for stars of all masses, but the pace of evolution is tied to the mass of the protostar (Figure 5). The more massive the protostar, the more rapid is its evolution through all of the phases of pre-main sequence evolution.

**Table 18.1:** *Time for a Star to Evolve onto the Main Sequence*

| Mass of Star (Solar masses) | Time to Evolve to Main Sequence |
|---|---|
| 0.08 | Never fuses hydrogen |
| 0.1 | 1 billion years |
| 0.5 | 150 million years |
| 1 | 50 million years |
| 3 | 2.5 million years |
| 5 | 580,000 years |
| 15 | 60,000 years |

**Figure 6.** *The newly formed open cluster NGC 2264. This star formation complex is at a distance of about 2,500 light years and contains a dark cloud of gas and embedded dust, and recently formed stars embedded in the gas and dust which illuminate it, causing the characteristic red hydrogen line emission**. ESO.***

## III. Current Examples of Star Formation in Star Formation Regions

Star formation occurs in clouds of gas and dust in the Milky Way and in other galaxies. In this section we will look at typical regions in the Milky Way where star formation is going on or is known to have happened recently, at least by astronomical standards. These include HII regions, compact infrared sources, and T Tauri stars.

*Roadmap of Star Formation in an HII Region*

Emission nebulae are regions of gas surrounding unusually hot stars, **called O and B stars**, 15,000 to 35,000 K, which ionizes the gas surrounding them (strips electrons off atoms) with their intense ultraviolet radiation (Table 18.2 and Figure 6). Once the electrons are stripped off an atom, they become available to mate with the first atom with which they collide, emitting photons as they cascade from a higher energy state to the atom's ground state. Particularly prominent is the so-called **hydrogen alpha** line, produced by the transition of an electron from the third to the second energy state in hydrogen (Figure 7). The result is a red photon at 656 nanometers ($10^{-9}$ m) wavelength. These hydrogen alpha photons give emission nebula their red glow. Emission nebulae are also called **HII regions** (HII signifies ionized hydrogen, **HI** unionized hydrogen).

**Table 18.2:** *Stellar Temperature Classes*

| Class | Temperature | Wavelength of Peak Emission |
|---|---|---|
| O | > 25,000 K | Ultraviolet |
| B | 11,000 – 25,000 K | Ultraviolet |
| A | 7,500 – 11,000 K | Blue |
| F | 5,000 – 7,500 K | White to blue |
| G | 5,000 – 6,000K | Yellow to white |
| K | 3,500 – 5,000 K | Red to orange |
| M | < 3,500 K | Infrared to red |

**Figure 7.** *H alpha emission from the interstellar gas surrounding the Horsehead Nebula.*

HII regions are seen as areas of intense hydrogen alpha emission in giant molecular clouds, and are the sites of recent star formation. Since the hot main sequence stars illuminating HII regions only fuse hydrogen on the main sequence for a few million years, by definition these were active star-forming regions not long ago, at least by stellar evolution standards. A few hot, blue stars at the core of an HII region is called an **OB association**. An example of an OB association embedded in a molecular cloud is the Orion Nebula, which contains four OB stars that ionize the surrounding HII region, surrounded by a giant molecular cloud of 500,000 solar masses (Figure 8). The young hot stars in an OB association drive a fierce stellar wind and intense, ionizing ultraviolet radiation. The winds and radiation blow out a tenuous cavity of ionized gas in the giant molecular cloud, compressing hydrogen gas in front of it. The result is compression of the gas at the intersection between the giant molecular cloud and the HII region. This compression spurs the collapse of cores at the edge of the giant molecular cloud, triggering star formation. An association of recently formed stars is triggering the formation of the next generation of stars, which will form another association. In this way the Orion molecular cloud is slowly being eaten away by successive generations of massive stars.

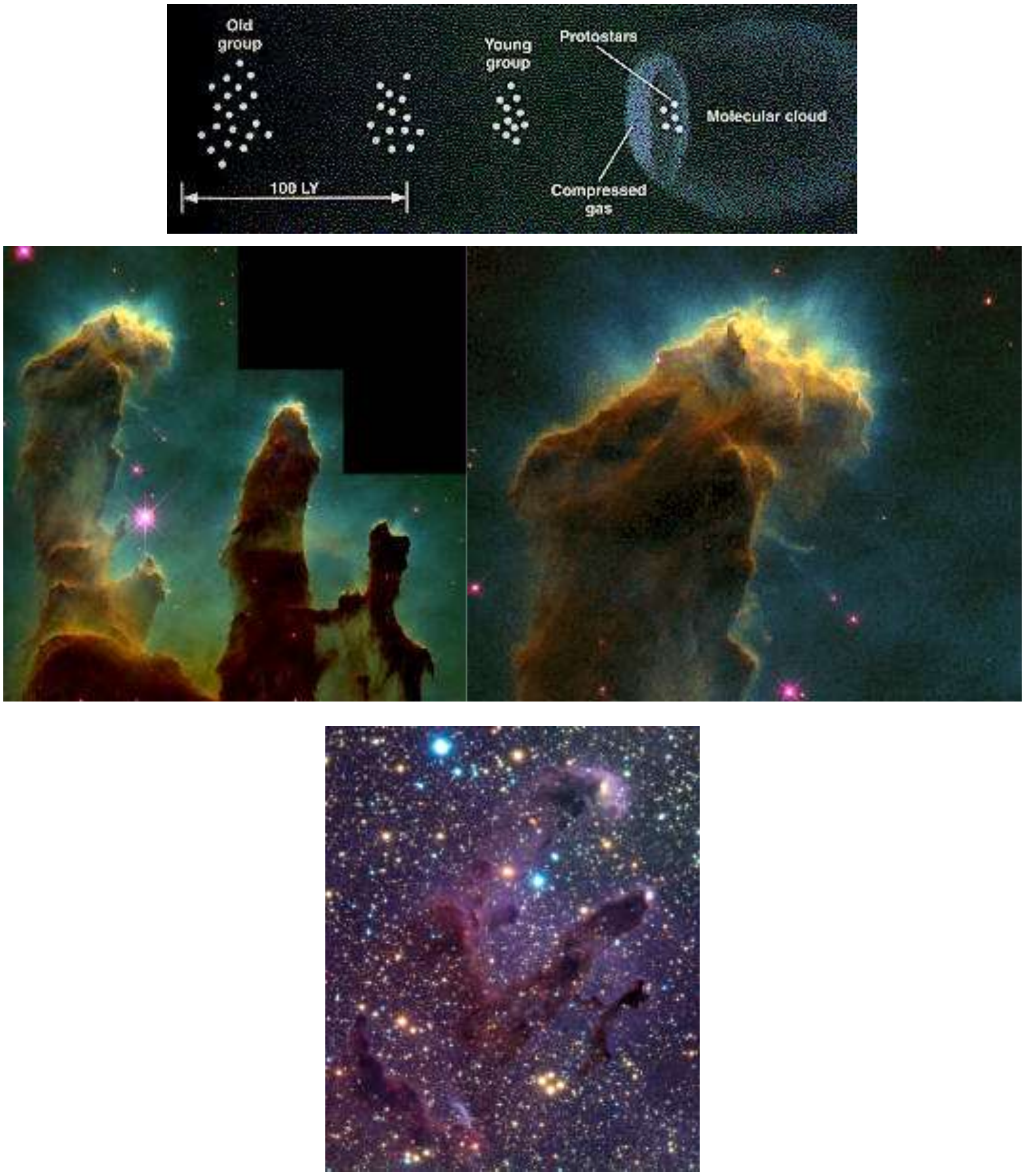


**Figure 8.** *Star formation in molecular clouds.* ***Panel A:*** *This schematic shows the stages of star formation in a molecular cloud progressing from right to left. First stars condense out of molecular cloud fragments. These stars in turn ionize and compress the face of the molecular cloud out of which they formed, causing a second round of compression, cloud collapse, and eventually star formation. As a young association of stars form, without sufficient mass to bind the group, the stars will spread out and eventually separate, each going its own way.* ***FMW 401-20.7, modified. Panel B****: The Eagle Nebula (M16). Molecular cloud columns are illuminated by recently formed, bright young stars. Star-forming molecular cloud cores are emerging from the ends of the columns of molecular cloud.* ***HST. APOD. Panel C****: An infrared of the Eagle Nebula. At this wavelength, one can see through the dust that shrouds visible wavelength images, to see both background starts as well as infant stars buried in the dust cloud.* ***HST, APOD.***

*Cocoon and Infrared Stars*

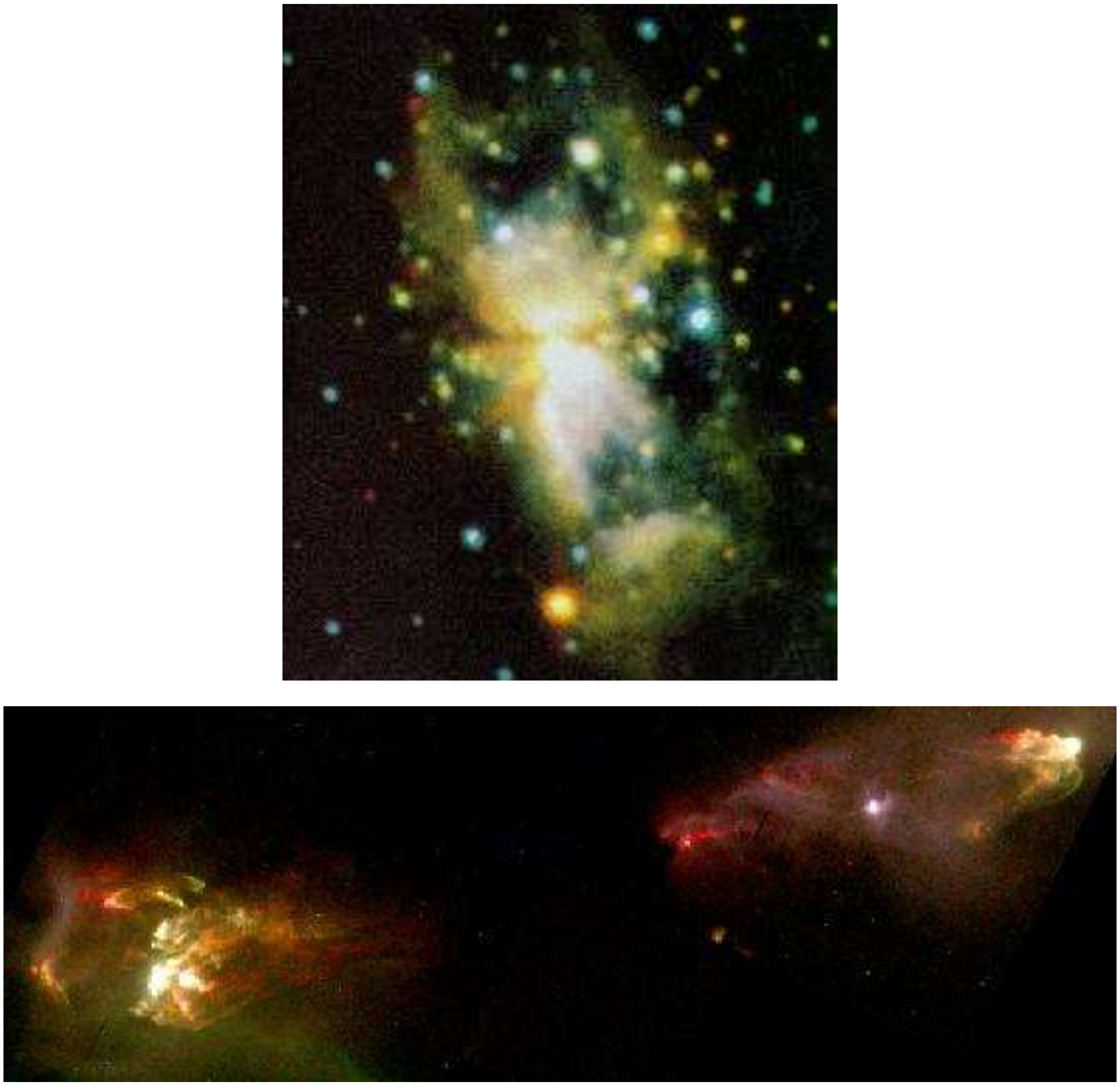

**Figure 9.** *Protostars.* ***Panel A****: An infrared image of the protostar S106. S106 contains a protostellar dust disk seen nearly edge on which coincides with the narrowest point in the nebula. Gas is seen to flow in the two directions perpendicular to the disk.* ***FMW 403-20.9. Panel B:*** *Two Herbig Haro objects imaged by the Hubble Space Telescope. Herbig Haro objects are supersonic outflows from newly formed stars producing shock waves as they plow through the interstellar medium.* ***HST, NASA.***

Young stars form from collapsing clouds of gas and dust, so these newly born stars are expected to be surrounded by cocoons of dust blocking their visible radiation from view (Figure 9). Starlight is swallowed up by the dust envelope, roasting the surrounding dust to temperatures of several hundred K, and re-radiating light in the infrared. After a protostar begins to emit light intensely, radiation and light pressure will blow the dust away, the stars becoming visible at optical wavelengths a few million years later.

Examples of cocoon nebulae are stars in the Orion star-forming region, which includes the Orion nebula, only 400 to 700 parsecs away (Figure 10).

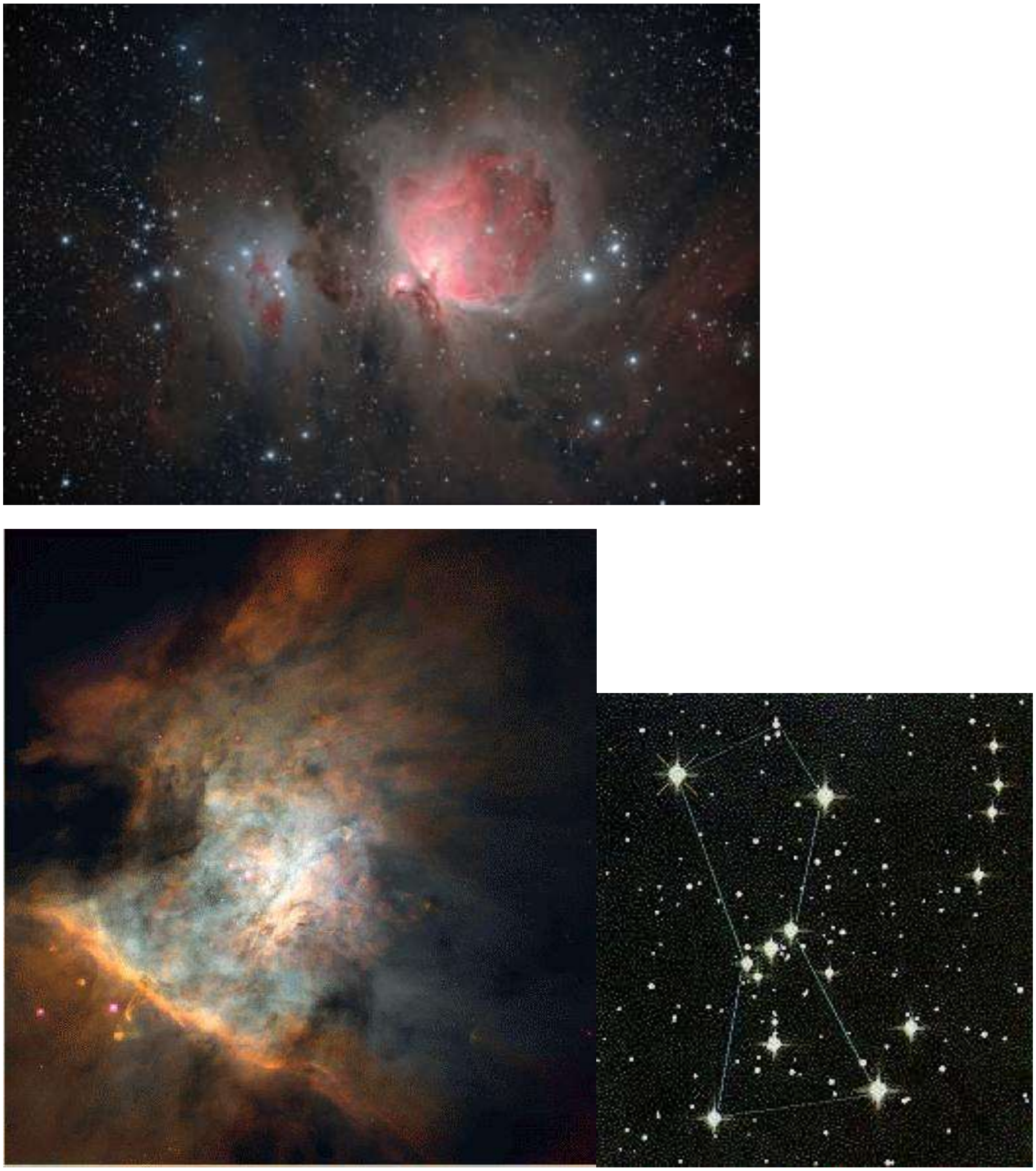

**Figure 10.** *The Orion Nebula at different wavelengths and "magnifications."* ***Lower right:*** *The bright stars in Orion outline the hunter of Greek mythology (demarcated by lines). Dangling from Orion's three-star belt is his sword. One of the bright sword stars is the Orion Nebula a noted site of recent and ongoing star formation.* ***FMW 399-20.2, Modified. Lower left:*** *A close-up of the central part of the Orion Nebula, 2 light years across, taken with an infrared camera which is sensitive to emission from hot dust. This is a false color image, with blue indicating high temperature emission. Seen in blue is a cluster of hundreds of recently hot stars, purple, and red demarcating hot and cool dust,*

*respectively.* ***NASA, HST. Upper left:*** *An expanded view showing the Orion Nebula (lower right hand corner). The entire image covers a dark giant molecular cloud lurking in the background. The Orion Nebula itself is a recently formed OB association reflecting light from the dusty background molecular cloud.* ***Wikimedia Commons.***

*T-Tauri Stars*

Just before a star undergoes thermonuclear ignition, arriving on the main sequence, it goes through a pre-main sequence phase of evolution called the **T Tauri phase**. Stars in this class are named after their prototype variable star, T Tauri, in the constellation Taurus (Figure 11). The T Tauri phase is the transition stage between infrared stars in a cocoon nebula and main sequence stars. T Tauri stars lie to the right of the main sequence. Stars remain in a T Tauri phase for roughly 20,000 to a million years immediately preceding their life on the main sequence.

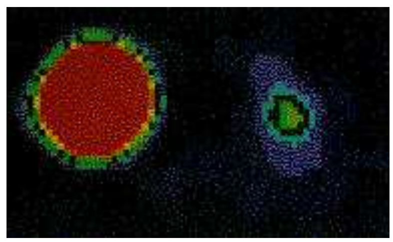

**Figure 11.** *A radio image of T Tauri (left) and its companion. T-Tauri stars are young, pre-main sequence stars, enshrouded in dust.* ***P 424-24.6.***

## IV. Hayashi track

As a protostar begins to form, contracting from a cloud of gas and dust, it is initially very large with a low temperature. As a result its rather large luminosity and low temperature place it in the upper right corner of the H-R diagram. As contraction continues the temperature of the "surface" of the protostar remains nearly constant while the surface area decreases, the protostar continuously becoming fainter. The result is that the evolutionary path of a protostar is expected to follow a vertical downward path on the H-R diagram, called the **Hayashi track** (Figure 5). Eventually the temperature of the protostar increases and its luminosity remains constant, so that the protostar evolves in a horizontal path from right to left on the H-R diagram. Finally the protostar reaches the main sequence and remains there as it commences hydrogen fusion into helium and reaches hydrostatic equilibrium.

## V. Star Clusters and the Determination of Stellar Ages

Trying to determine the ages of stars is one of the greatest challenges in astronomy. Stars far outlive human beings and change only on time-scales of millions and even billions of years. We can't simply watch them age. When combined with the fact that stars are remote and inaccessible to direct experimentation, determining a star's age seems to be an insurmountable problem.

**Figure 12.** *Star clusters.* ***Panel A****: The largest known globular cluster, Omega Centauri. This image is approximately 90 light years across and contains roughly 10 million stars.* ***APOD, Fred Lehman. Panel B:*** *The Jewel Box, a young open star cluster approximately 8,000 light years distant.* ***NASA, HST.***

Star clusters are key to stellar age determination. Star clusters are groups of stars, from dozens to millions, found in the same small region of space. Because stars in a star cluster are found together, they are generally believed to have been formed at roughly the same time and in the same neighborhood. In our Milky Way galaxy there are two main types of star clusters: **open clusters** and **globular clusters** (Figure 12). We will learn more about star clusters and where they are found in the Milky Way in Chapter 21.

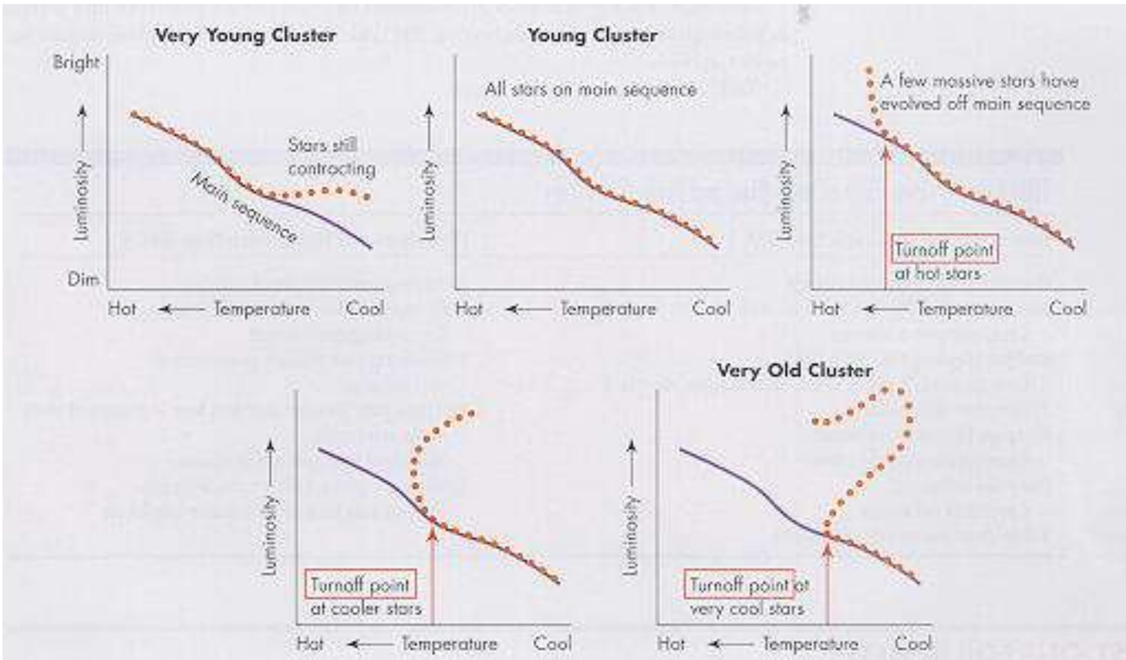


**Figure 13.** *Graphic of HR diagrams representing star clusters in our race at 1 million years, 100 million years, and 10 billion years.* ***Modify. Arny.***

Open clusters are small and irregularly shaped, typically containing 1000 members. They have a large range of ages from very young to 10 billion years old. The color of an open cluster as a whole ranges from blue to red, and as we will see, this depends on the cluster's age. Open clusters are loosely bound and it is usually easy to identify individual stars in nearby open clusters.

Globular clusters are large spherical clusters of stars, containing as many as 1 million members, but 100,000 constituent stars is more typical. Globular clusters are all red and are all old, typically 10 billion years old. Globular clusters are always larger than open clusters and appear to be so dense at their center that it is not possible to pick out single stars there.

*The Tortoise and the Hare: Small Stars Finish Last*

Consider the evolution of a star's in a cluster as a race, from the initial stage of pre-stellar cloud collapse through main sequence hydrogen fusion to stellar death (Figure 13). In today's race we have three contestants. In the pole position is the odds on favorite a 10 solar mass star, nicknamed the Hare. In the middle lane is the darling of the crowd, a well-known 1 solar mass underdog, the Sun. On the outside is the unknown and underweight 0.5 solar mass star, the Tortoise.

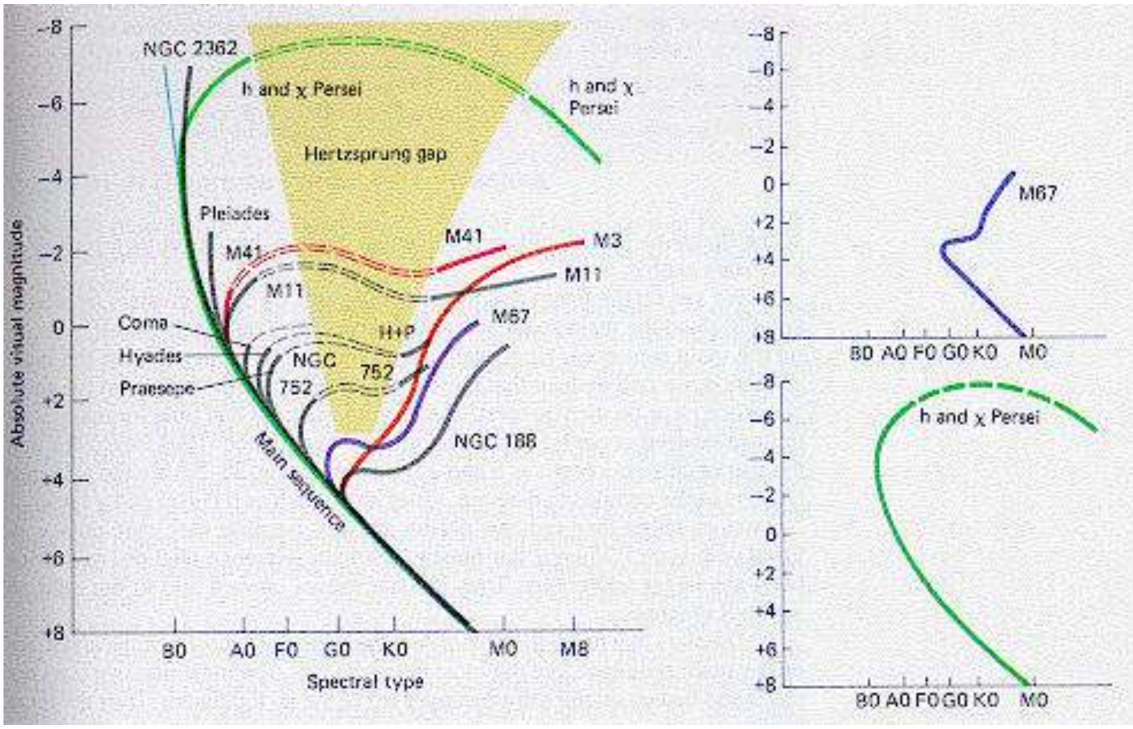


**Figure 14.** *The H-R diagrams of a number of open clusters and one globular cluster (M3) in the Milky Way. Individual H-R diagrams, like the two shown on the right, are superimposed. Differences between the appearance of the plots are largely due to cluster age. Stars in the upper main sequence evolve off the main sequence and become giants first, as high mass stars in a cluster evolve and die the most quickly. The result is that the turn-off point, the point at which the giant branch joins the main sequence, moves to lower luminosities and temperatures as a cluster ages. The dashed regions of the giant branches represent the so-called Hertzsprung gap where few stars are seen, because stars evolve through these regions quickly.* ***P 381-22.25.***

They're off! After 1 million years the Hare is in the lead having already contracted onto the main sequence. The Sun isn't far behind, having completed half of its contraction onto the main sequence. The Tortoise is in back, still in an early contraction phase.

After 100 million years (the race-goers are becoming somewhat bored already), the Hare is in the stretch; it has finished its core hydrogen fusion and has moved into the super-giant phase. The Sun is on the main sequence and the Tortoise has just commenced main sequence hydrogen fusion.

Whoops, we dozed off. At 10 billion years, it appears that the Hare has already won the race, it erupted in a supernova some time ago. The Sun is now a red giant and the Tortoise is still in the middle of main sequence hydrogen fusion.

The moral to this story is that small stars finish last. Whether this is viewed as a win or a loss is up to the viewer. What is relevant is what we expect to see from a cluster of stars, all viewed at the same time. The most massive stars have the highest stellar metabolism; they use up their fuel rapidly, become blazingly bright, and die out quickly. The least massive stars conserve fuel, they have a rather dull and common luminosity, but their longevity is outstanding. Let's see what this picture looks like on a series of H-R diagrams, each diagram essentially a snapshot of a group of stars at a single instant in the "race".

Figure 13 shows H-R diagrams for clusters of the epochs used in our "race": 1 million years, 100 million years, and 10 billion years. These are H-R diagrams based on mathematical models of stellar evolution, using all of the known physics **of hydrostatic equilibrium** of a gas and thermonuclear energy generation. Compare these H-R diagrams with H-R diagrams measured for real star clusters in Figure 14.

The theoretical H-R diagrams can be characterized by:

1. The point at which stars are just beginning to leave the main sequence, or the **turn-off point**, when they finish core hydrogen fusion.
2. The point at which pre-main sequence stars are just beginning to enter the main sequence and begin hydrogen fusion.
3. The shape of the red-giant "branch" on the H-R diagram.

The point at which pre-main sequence stars are just beginning to enter the main sequence is only seen in the youngest clusters and would be relatively hard to see as it represents the faintest stars in a young cluster. The shape of the red-giant branch is sensitive to both age and the chemical composition of the star cluster, so it is not straightforward to use this as an age-indicator. The turn-off point is the best age-indicator for a cluster because it is reliable and since it is in the high-luminosity portion of the H-R diagram, it is easy to see.

**What are the results of age-determinations for star clusters?** When H-R diagrams are constructed from star cluster measurements and compared with theoretical H-R diagrams based on computer models, ages can be assigned to observed open and globular star clusters in the Milky Way. Open clusters are seen with ages from 0 to 10 billion years; globular clusters are all about 10 billion years old.

The ages and colors of star clusters are related. Globular clusters are all old, and contain only low temperature main sequence stars and red giants. All of the globular cluster stars have low temperatures and are red; as a result, all globular clusters appear red. Similarly, old open clusters contain only red stars and appear red. However, young open clusters contain both high-luminosity, high temperature main sequence stars and low-luminosity, low-temperature main sequence stars. Young open clusters contain high-luminosity blue stars in their mix; globular clusters don't. As a result, young open clusters appear bluer than older globular and open clusters. **There is a direct correlation between the age of a cluster and the color of its stars, with younger clusters appearing bluer, on average, than older clusters.**

**Web Activity: Interactive H-R Diagram**
**http://aspire.cosmic-ray.org/labs/star_life/starlife_main.html**


## Summary

Stars are born when giant molecular clouds in the galaxy collapse and fragment into multi-solar mass contracting knots. As the cores of these knots shrink they become luminous, generating energy by their gravitational collapse. Eventually they become hot enough in their cores to begin stable thermonuclear fusion. At this point they acquire a luminosity and photospheric temperature that places them on the main sequence of the H-R diagram.

H-R diagrams of star clusters provide a snapshot of the evolution of a group of stars of the same age and varying mass. Such diagrams confirm the theory that the more massive stars evolve more rapidly throughout their lifetimes than do lower mass stars. The age of a star cluster is related to the shape of its H-R diagram, in particular the oldest clusters have the lowest temperature turn-off points.


## Key Words & Phrases

1. Amino acid –
2. Giant molecular cloud – a giant cloud of molecular hydrogen gas and dust seen in the Milky Way and other galaxies
3. **Globular cluster** – a large spherical cluster of stars, containing as many as 1 million members
4. Hayashi track -
5. **HI –** un-ionized hydrogen
6. **HII region** – an emission nebulae composed of ionized hydrogen
7. **Hydrogen alpha line** – an emission line produced by the transition of an electron from the third to the second energy level in hydrogen, or an absorption line produced by the transition from the second to the third energy level in hydrogen
8. Hydrostatic equilibrium
9. **OB association** – a number of hot, blue stars at the core of an HII region
10. **Open cluster** – a small and irregularly shaped star cluster, typically containing 1000 members
11. **T Tauri star** - a young star at a stage between an infrared star in a cocoon nebula and the main sequence
12. **Turn-off point** – the point on the H-R diagram at which stars have finished core hydrogen fusion and are just beginning to leave the main sequence

## Review for Understanding

1. Describe the evolution of a 0.5, 1, and 10 solar mass star from the initial stage of cloud collapse until it reaches the main sequence.
2. What is the scientific importance of studying giant molecular clouds?
3. What is an HII region? Why do they appear red?

4. Compare a T Tauri star and an infrared star embedded in a cocoon nebula.
5. Compare the properties of open and globular clusters.
6. In the H-R diagram below, which is older, cluster A or cluster B? Explain.
7. Sketch an H-R diagram for an old star cluster and a young star cluster. Label the axes, including units. Mark the position of the Sun, main sequence, turn-off points, and giant branch.

**Essay Questions**

1. Some open clusters have a greater luminosity than globular clusters having more than 100 times more stars. Explain how this can happen, using an H-R diagram for illustration.
2. Explain the scientific importance of studying star clusters.

**Figure Captions**

Figure 14. *Graphic for the pace of star formation for stars of three masses.*

# Chapter 19 – Origin of the Life-Giving Heavy Elements: Dying Stars

*This method of viewing the heavens seems to throw them into a new kind of light. They are now seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For, to continue the simile I have borrowed from the vegetable kingdom, is it not always the same thing, whether we live successively to witness the germinations, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view?*
--William Herschel (1738-1822) in Construction of the Heavens

**Chapter Preview**

As stars are born they must die. Although stars of all types appear to be born in a common way, the collapse and fragmentation of large clouds of interstellar dust and gas, the endpoints of a star's life are highly varied. Some stars simply burnout, shrink, and fade away, into super-dense objects that slowly cool and grow fainter with time. Others end their lives in the fireworks of tremendous explosions, outshining a galaxy of billions of stars for a short but memorable time. In both cases stars shed some of their gaseous innards back into the interstellar gases from which they formed. In doing so, dead stars seed heavier elements, even metals such as gold and silver, which they brewed in their own interiors through thermonuclear fusion, into the interstellar medium, out of which future generations of stars will form. It is this recycling process that has brought the elements necessary for life on Earth, such as carbon, nitrogen, and oxygen, into our own Solar System. In a very real way, a previous generation of dying stars has provided the conditions on Earth for the evolution of biological life.

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**Key Physical Concepts to Understand:** *the process of stellar death, supernovae, the origin of heavy elements in the interstellar medium and in our Solar System, electron and neutron degeneracy, the properties of neutron stars, white dwarfs and pulsars, how stars recycle material back into the interstellar medium*

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**I. Introduction**

Astronomers have developed highly sophisticated mathematical models of stellar evolution which predict the change in stellar properties as stars of differing masses age. These models predict the photospheric temperature and luminosity of stars, and therefore their position on the H-R diagram, as they age. But science is an empirical endeavor. **How do astronomers check their mathematical models of stellar structure and evolution?** This is extremely difficult for a star's longevity far outlasts an astronomer's; a star might live for billions of years without exhibiting a measurable change in temperature or luminosity.

The method that astronomers use for checking models of stellar evolution is somewhat akin to the botanist who walks into the forest to study the evolution of the redwood tree. It isn't practical for a biologist to watch a tree grow from a seedling to a giant adult redwood. In the forest one may see redwood seedlings, young saplings, young adult redwoods, mature redwoods, and decaying logs. From this a complete picture can be inferred of the biological evolution of the redwood, from seed to decaying log. Similarly, the astronomer must piece together the complicated picture of the life cycle of a star from the measured properties of the vast numbers of stars seen in the sky. This is done by assuming that stellar properties are a function of a star's mass, composition, and age. Current theories of stellar evolution are not perfect, but they explain most of the stellar properties that we can measure.

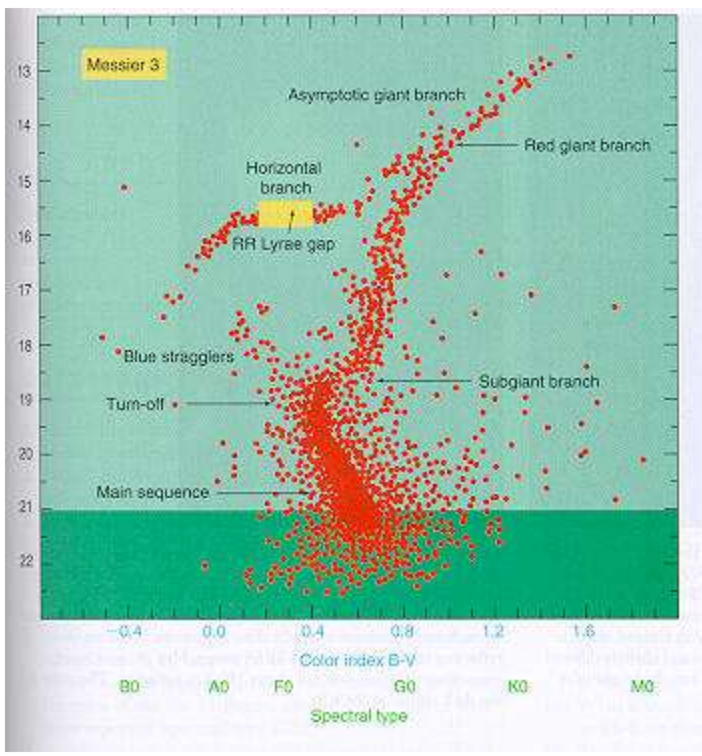


**Figure 1.** *H-R diagram for a cluster of stars.* **Modify. P2 413-25.22.**

**The tempo of a star's evolution is tied to its mass. The more massive a star is, the faster it evolves through all phases of its life cycle.** The density of points on an H-R diagram of stars is related to the pace at which a star evolves through the different phases of its life. The reason that the main sequence is the most densely populated region of the H-R diagram for a random selection of stars (Figure 1) is that stars spend the majority of their lives there. When we randomly select a star in the sky to study, the probability is that it will be a low-mass main sequence star, for there are far more low-mass stars in the sky than high-mass stars, and stars spend most of their lives on the main sequence.

## II. Red Giants and Supergiants

**What happens when the hydrogen in the hydrogen-fusing core of a star has been converted to helium?** This happens to a one-solar mass star after about 10 billion years; it will happen to the Sun in another 5 billion years.

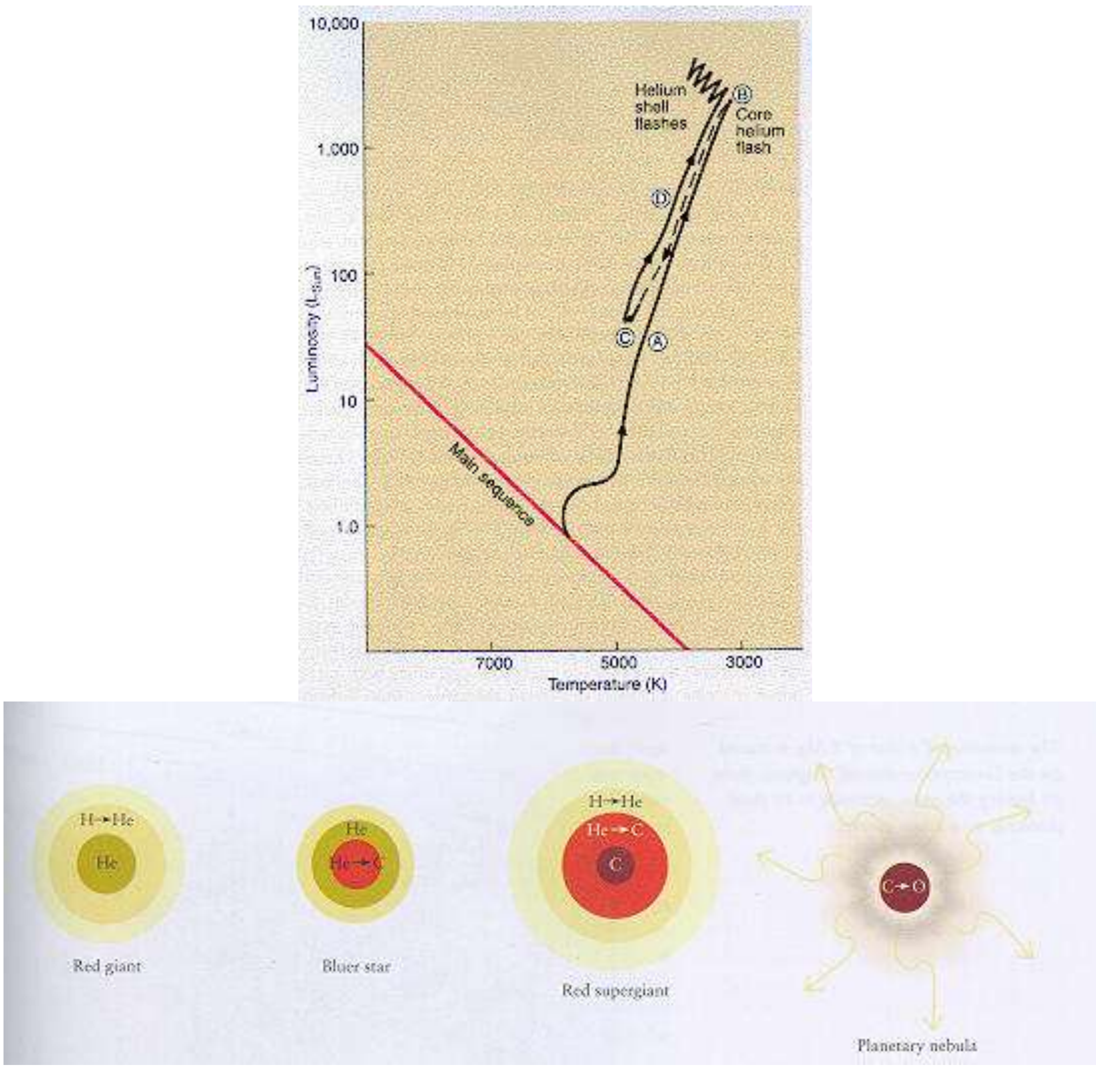


**Figure 2.** *The post-main sequence evolution of a one solar mass star.* ***Panel A. a:*** *The star exhausts the hydrogen in its core, leaving the main sequence. As shell hydrogen burning takes place the star increases in size and decreases in photospheric temperature.* ***b:*** *The helium flash occurs.* ***c:*** *Helium is fused to carbon at the core of the star. Panel: When helium is exhausted the star again expands and experiences a decreasing photospheric temperature.* ***d:*** *Core helium is exhausted. The burned-out star shrinks and cools, becoming a white dwarf.* ***Modified (d: is inaccurate). FMW 427-21.14. Panel B.*** *The shell structure of a one solar mass star as it experiences post main sequence evolution.* ***Silk.***

As a star's nuclear fuel runs out, it nuclear energy source is replaced by its gravitational energy source and it starts to contract (Figure 2). The core temperature increases as the core collapses. The core is mostly helium, but it is surrounded by hydrogen in a spherical shell extending from the outer edge of the core through the photosphere. As the core temperature increases, eventually a shell of hydrogen surrounding the core will reach the temperature for thermonuclear ignition. As the core temperature continues to increase, the hydrogen shell fusion increases rapidly. The fusing shell moves outwards and the core diameter increases as hydrogen is consumed in the shell source. The outward appearance of the star is changing dramatically as the core is evolving. The outer layers of the star expand and become cooler, so the star becomes redder. As the aging star experiences a contracting helium core, a thermonuclear hydrogen shell source, and an expanding and cooling photosphere, it appears to become redder and more luminous, evolving into the red giant region on the H-R diagram.

The luminosity of a star evolving into a red giant increases even though it photospheric temperature decreases because it is expanding into a star of greater size. It takes a one solar mass star about 100 million years to evolve off the main sequence and become a red giant.

When the increasing helium core temperature reaches 200 million K the helium core begins to fuse, becoming a new energy source for the star. Three helium nuclei fuse to form carbon nuclei ($3He \Rightarrow C$) and liberate the mass difference between the reacting helium and the carbon product as energy ($E = mc^2$), producing gamma rays (just as $4H \Rightarrow He$). In a one solar mass star the helium fuses rapidly and explosively, producing the so-called **helium flash** in a burst of luminosity. The helium flash doesn't blow the star apart, but it does change the star's composition and evolution. Stars much more massive than the Sun do not undergo a helium flash, but they burn helium in a stable helium fusing hydrostatic equilibrium like the hydrogen fusing hydrostatic equilibrium found in stars on the main sequence.

After a time the core helium becomes exhausted in producing a carbon core. When the core helium becomes depleted, the star again evolves into the red giant region. If the star has enough mass its core temperature eventually increases to 600 million K, where carbon fuses into neon producing gamma rays ($2C \Rightarrow Ne + He +$ gamma rays); our star has a new energy source.

**Table of stellar mass, shell composition, core temp.**

For star exceeding 8 to 10 solar masses it will follow the following fusion sequence in its core, after fusing carbon to neon:

- Neon to Oxygen
- Oxygen to Sulfur
- Sulfur to Magnesium
- Magnesium to Silicon
- Silicon to Iron

As a star goes through this fusion sequence it acquires a very complicated shell structure and may concurrently have several forms of fusion generating energy in a core and multiple shell sources. For this reason the exact evolutionary path of high mass giants past the point of a helium-fusing core is not known (Figure 3).

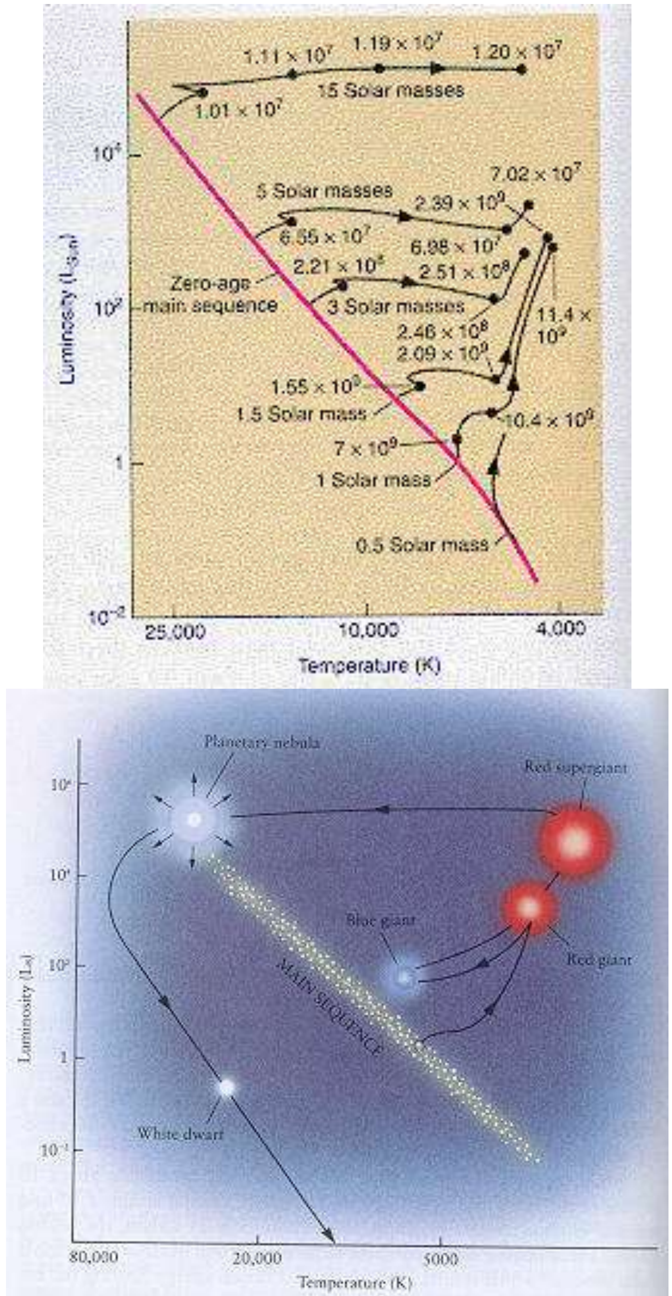


**Figure 3.** *The evolution of stars of varying mass through post-main sequence evolution. Each solid point is marked with the time elapsed since the star left the main sequence. Stars of the greatest mass experience the most rapid evolution at all evolutionary stages.* ***Modified.*** *Hybrid of* ***FMW 420-21.3 with Silk.***

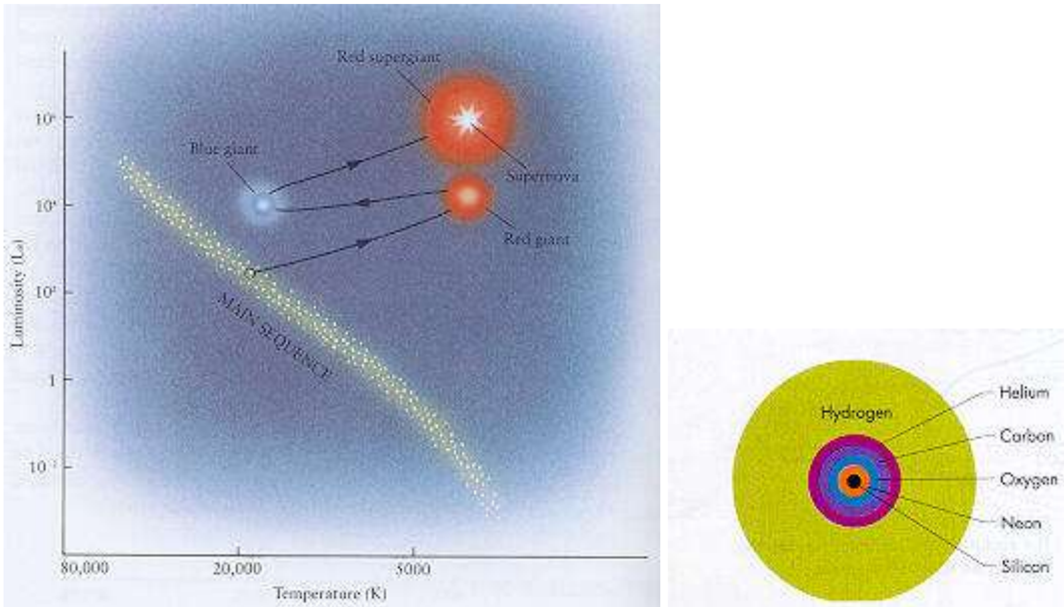


**Figure 4.** *Shell fusion in post-main sequence stars.* ***Panel A:*** *A schematic of the evolution of a ten mass star through its various core-fusion stages. The real path of a high mass star through all of its stages of post-main sequence evolution is complex and uncertain.* ***Silk Panel B:*** *A schematic of an iron-core star with a complex array of shell of differing composition with a hydrogen fusing shell source. This represents a high-mass star just before it supernovas.* ***Arny, Modify.***

A star that has burned silicon to iron has an onion-like layered structure with shells of differing composition from all the previous stages of fusion (Figure 4). The iron core is at least at a temperature of 2 billion K, the temperature required to fuse silicon to iron. As the core runs out of silicon, it contracts and its temperature grows even higher. One might expect the iron core to begin fusing to a heavier element at some temperature, but *that can never happen*. The iron nucleus is the most stable nucleus of all of the elements. Fusion of light nuclei to iron produce energy, in going from less stable nuclei of *higher total mass* into the iron nucleus with a *smaller total mass* (Figure 5). Mass is transformed into energy. Fusion of iron into heavier nuclei takes energy in going from iron nuclei of *smaller total mass* to heavier nuclei of *higher total mass*. An increase in mass requires the input of energy. This is why **fission** (splitting or breaking up atomic nuclei) produces energy for high-mass nuclei (Figure 6). Fission produces energy if the nucleus being split is of a higher mass than iron (uranium for example) and requires energy for splitting low-mass nuclei. Similarly, fusion produces energy if the nuclei being fused produce a nucleus of mass equal to or less than iron (hydrogen fusing into helium, for example) and requires energy for fusing high-mass nuclei.

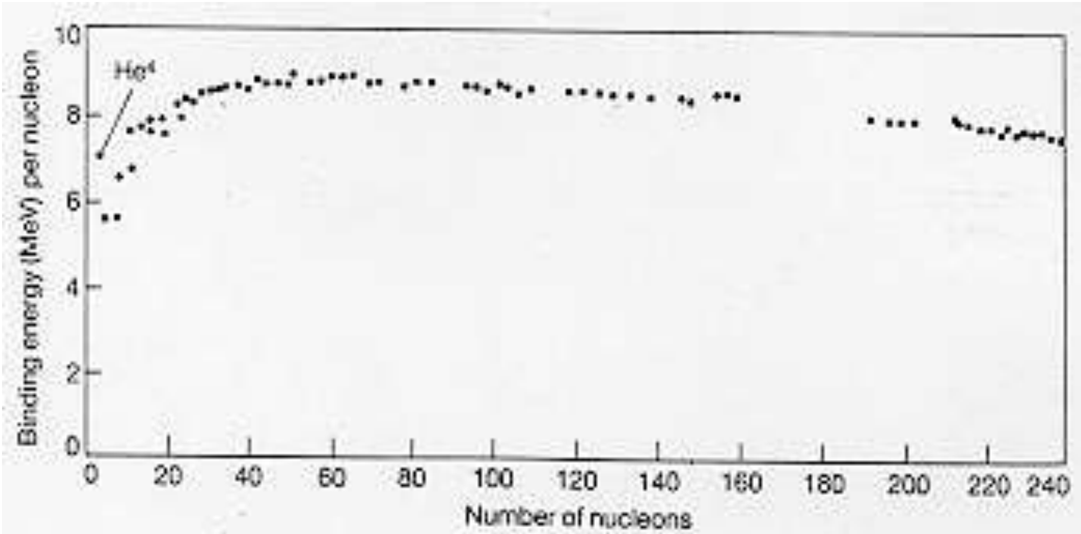


**Figure 5.** *Binding energy of nuclei of differing atomic mass. The maximum binding energy per nucleon (proton or neutron) occurs for an iron nucleus, with an atomic mass of 56. The greater the binding energy of a nucleus per nucleon, the greater is its stability.* ***Harrison.***

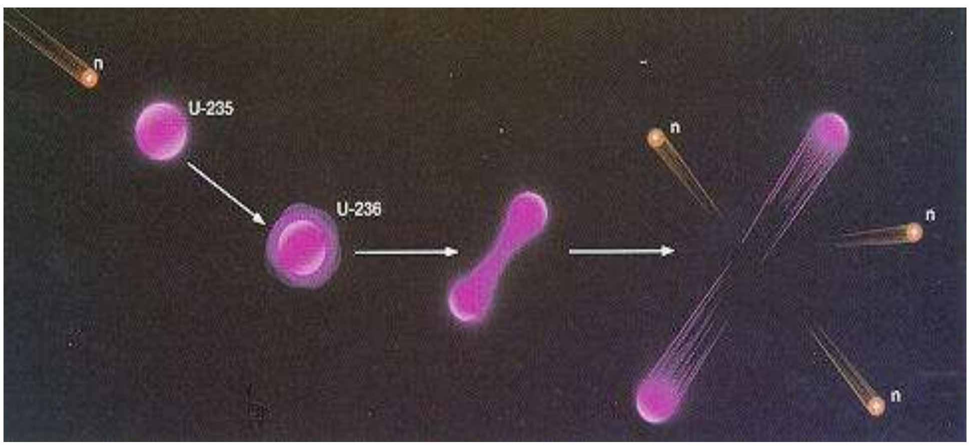


**Figure 6.** *When Uranium 235 nucleus captures a high-velocity neutron of sufficient energy it will fission forming less massive nuclei, two or more neutrons, and high-energy photons.* ***KW 616-25.9****.*

**III. Supernovae & Cosmic Recycling**

**What happens to a star with an iron core as it collapses and heats beyond 2 billion K?** The core begins to fuse iron, but instead of having an energy-producing source, the fusion of iron is an energy-removing sink. The iron-fusing core removes the energy needed to keep the high temperature and pressure needed to support the star through hydrostatic equilibrium. The star cannot maintain the pressure needed to support itself against gravitational collapse. The core begins to collapse to generate the temperature needed to supply the pressure to balance itself against gravity. But any additional temperature makes energy-depleting iron-fusion proceed faster. The core collapses even faster, and eventually collapses catastrophically. The core no longer supports the material outside the star's core, so it collapses as well and reaches temperatures of about one trillion K. At this temperature, all of the nuclei lighter than iron outside the core can fuse, producing energy explosively. The result is the rapid explosion of a star, a **supernova**, expelling most of its mass into space (Figure 7).

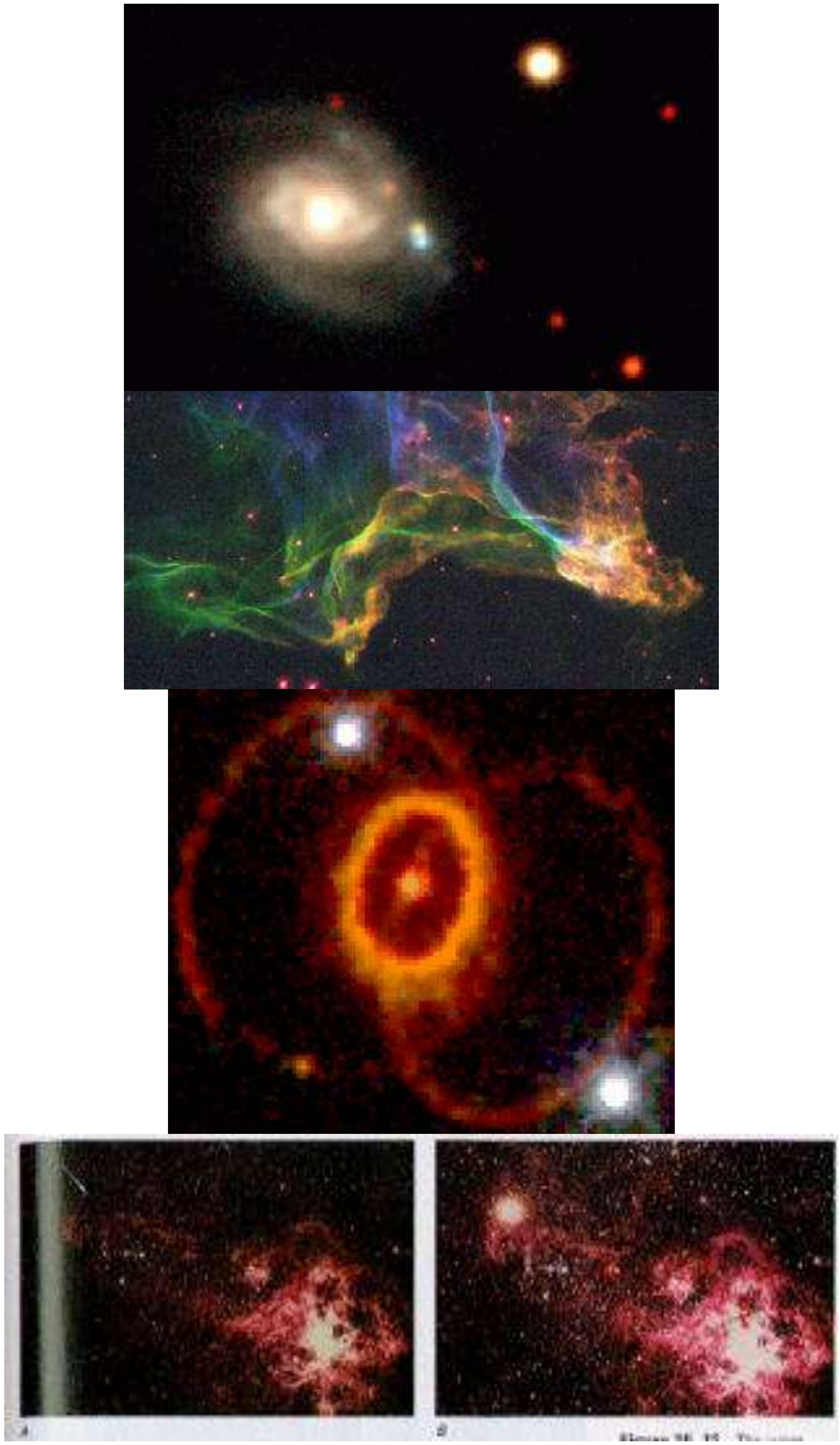

**Figure 7.** *Supernovae.* ***Panel A:*** *Twin supernovae in the galaxy NGC 664, at a distance of 300 million light years. This pair of supernovae, one blue (hotter) and one red (cooler)*

*is seen below and to the right of the galaxy nucleus.* ***APOD. Panel B:*** *A Hubble Space Telescope image of the Cygnus Loop, a supernova remnant in the constellation Cygnus. Gas from a supernova explosion 15,000 years ago has collided with a gas cloud, causing it to emit visible light.* ***HST, APOD. Panel C****: A Hubble Space Telescope image of the remnant of Supernova 1987a in the Large Magellanic Cloud. The origin of the loops is an enigma.* ***HST, APOD. Panel D:*** *Before and after pictures of Supernova 1987a. The arrow in the lefthand image indicates the position of the supernova.* ***P 463-26.15.***

This explosion takes place on a time scale of hours. For a period of days after the explosion the supernova can appear brighter than a galaxy of billions of stars. In the supernova free neutrons can combine with nuclei to build up atoms that are heavier than iron. This is the only means by which elements heavier than iron can be made.

*As we will see in Chapter ???, astronomers think that the early Universe was composed mainly of hydrogen and a little helium. But the existence of life on Earth depends on molecules made of carbon, nitrogen, and oxygen, as well as hydrogen. The Earth itself is thought to be mostly iron in composition.* **Where do the elements on Earth heavier than iron originate?**

Elements in the Earth that are heavier than iron, such as the gold and silver in our jewelry, and the uranium used in nuclear reactors, were produced in the supernova of a high-mass star that formed and regurgitated high mass nuclei into space. At some later time the Sun and planets condensed out of this material, recycling it into a second or third generation star and its planets.

There are other means by which stars lose mass into space that can later be incorporated into future generations of stars, and reprocessed:

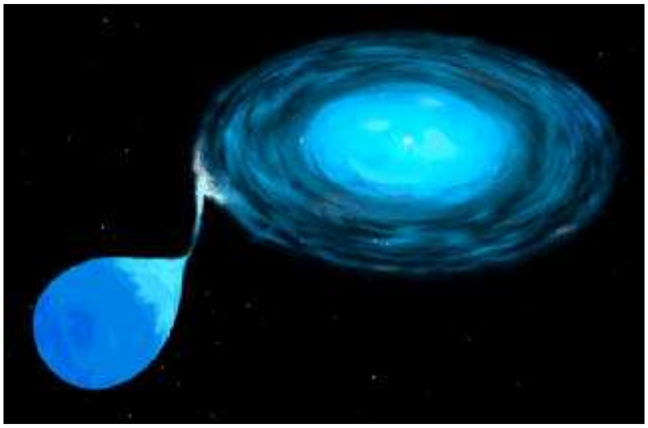

**Figure 8.** *An artist's conception of a binary star system with mass transfer from a companion onto the accretion disk surrounding a compact star, a white dwarf, neutron star, or black hole. Gas is spilled from the blue giant into a flattened disk surrounding the compact star. The gas spirals into the vicinity of the compact star, eventually falling onto it. Gas swirling in the inner part of the accretion disk is heated by friction, and may reach temperatures high enough to generate X-rays or gamma rays.* ***HST, APOD.***

***Stellar winds.*** Some of a star's mass is lost from its photosphere as high temperature gas exceeds the escape velocity of the star. This is typically a rather insignificant amount of material and it would not necessarily contain any of the heavy elements produced in the core.

***Binary star systems.*** In a binary star system where the stars are close together, strong gravitational forces can cause atmospheric gases to be exchanged between the stars, some of which can be lost into space (Figure 8). One particularly interesting example of this is the **nova**, the thermonuclear detonation of mass transferred onto the surface of a white dwarf (see Section V below).

***Planetary nebulae.*** In a low-mass star, the core can heat up so that the gas pressure of its hot core can for a time exceed the weight of the overlying atmosphere. It simply pushes the atmosphere away from the star, forming a shell of gas illuminated by the core, called a **planetary nebula** because of its roughly extended disk shape, as seen through a small telescope, is vaguely suggestive of a planet (Figure 9). The core remains in tact and will continue to evolve as a star. The outer envelope expands into space.

## IV. White Dwarfs

Stars less than about 8 solar masses can never ignite a carbon/oxygen core and get beyond the stage of fusing helium to carbon. In the last stages of their lives, after the core has finished helium fusion, the core pressure exceeds the gravitational force of the outer layers of the star, and the atmosphere is ejected into space, forming a shell of expanding gas, illuminated by the bare stellar core (Figure 10). This expanding gas shell is a planetary nebula. The exposed core is not massive enough to undergo further thermonuclear fusion, so it simply cools off by radiating its energy into space.

This dead star is called a **white dwarf**. A white dwarf is a star that can no longer be supported by gas pressure; it has collapsed until it is supported by what physicists call electron degeneracy. Electrons can be packed together to a maximum density governed by the **Pauli exclusion principle,** named after the Austrian physicist who proposed this rule in 1925 which later won him the Nobel prize. The Pauli exclusion principle dictates that two electrons cannot be at the same place at the same time. This electron degeneracy will support a stellar density of typically $10^7$ to $10^9$ kg/m$^3$ – (normal stars have densities ranging from 0.1 to 1000 kg/m$^3$) –a teaspoonful would weigh 1 ton on the Earth's surface.

One of the first white dwarfs to be discovered is Sirius B the companion to the bright star Sirius. In 1844 the German astronomer Friedrich Bessel measured the zigzagging motion of Sirius as it moved through space, due to the gravitational tug of an unseen companion (similar to the way unseen planets orbiting stars are detected, Chapter 13, Section IV). The companion was first seen in 1862. Measurements indicate that Sirius B has a blackbody temperature of about 30,000 K, but its low luminosity indicates a size close to that of the Earth's.

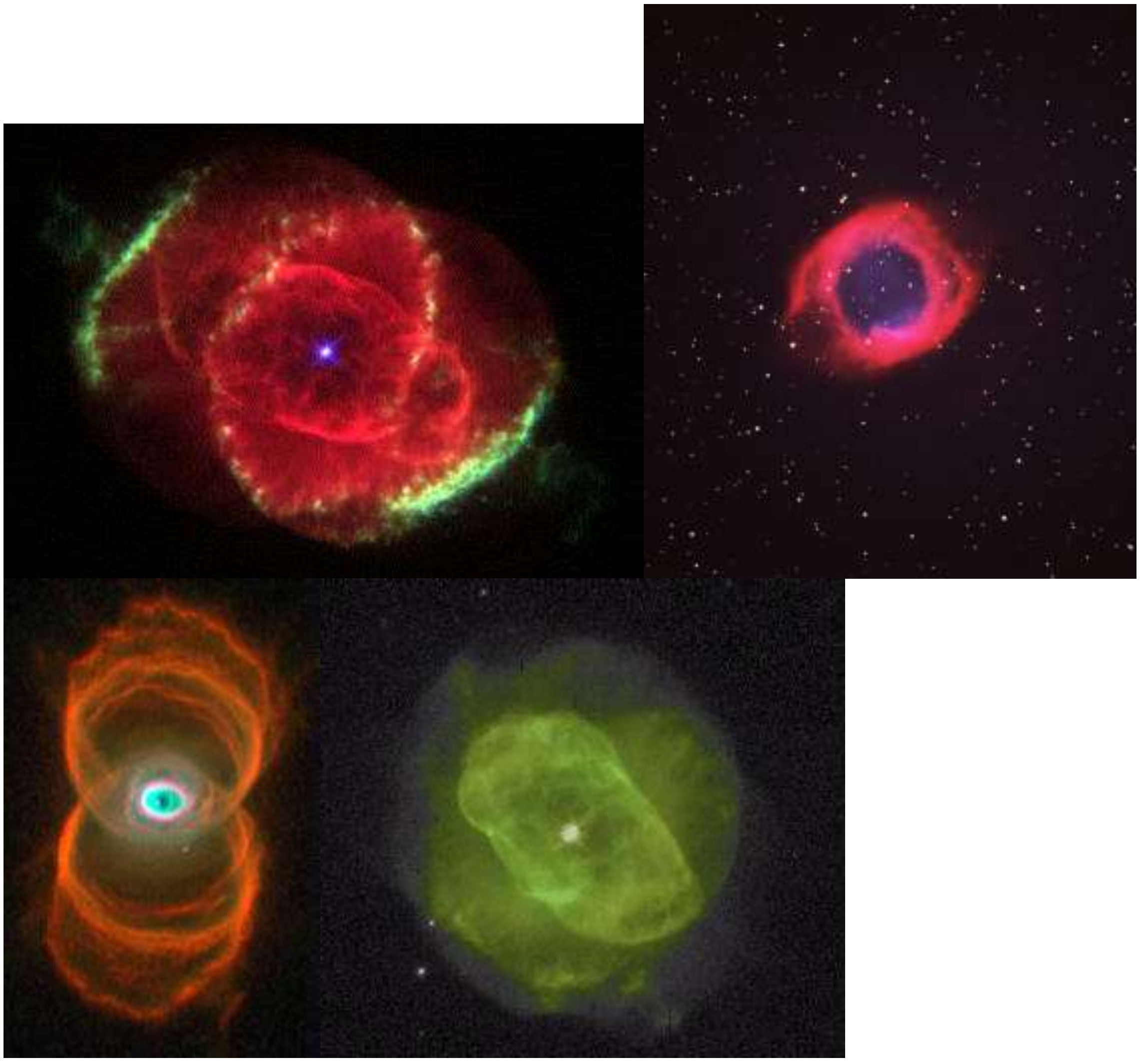

**Figure 9.** *Planetary nebulae. Planetary nebulae form after some stars finish hydrogen core fusion and shed their atmosphere, including up to 0.1 to 0.2 solar masses of the star.* ***Panel A:*** *The Hourglass Nebula.* ***APOD. FMW 440-22.6b. Panel B:*** *NGC 5882.* ***HST, APOD. Panel C:*** *The Cat's Eye Nebula.* ***APOD. FMW 440-226a. Panel D:*** *The Helix Nebula.* ***APOD.***

As a white dwarf cools both its luminosity and surface temperature decline so that it eventually becomes cold and dark. When it reaches 1 million K, the matter in the white dwarf has solidified into one giant crystal. After billions of years the white dwarf will have radiated almost all of its energy into space. At this time the white dwarf is the size of the Earth, the mass of the Sun, with its matter cooled and solidified into a solid mass. This is the fate of our Sun.

White dwarfs can have no more mass than 1.4 solar masses, the Chandrasekhar limit, named after Subrahmanyan Chandrasekhar, who won Nobel prize in physics for his theory of white dwarfs. Stars more massive than 12 solar masses are thought to produce carbon/oxygen cores above 1.4 solar masses, which would exceed the Chandrasekhar limit and could therefore not produce white dwarfs.

## V. Novae

Every once in a while star is suddenly observed to brighten by a factor of $10^4$ to $10^6$ (Figure 11). These stars are called **novae** (supernovae brighten by a factor of billions). This abrupt increase in brightness is typically followed by a gradual decline in brightness over several months.

Novae occur in binaries where one star is a white dwarf. Hydrogen from the companion flows out of its atmosphere, gravitationally attracted by the white dwarf, and accumulates on the hot surface of the white dwarf. It becomes more and more compressed with time, and as it is compressed it becomes hotter and hotter until it reaches the hydrogen fusion temperature. It this point the hydrogen ignites and explodes, blowing itself into space. Fresh hydrogen flows from the companion onto the white dwarf and the entire process repeats itself.

## VI. Neutron Stars and Pulsars

***<u>Neutron Stars.</u>*** As is outlined above, a supernova terminates the end of the life of a star of 12 solar masses or greater. The dense central core which survives the supernova is unimaginably compressed matter, having the density of an atomic nucleus, called a **neutron star** (Figure 12).

The neutron was discovered in 1932. Because of this discovery and the theory of electron degeneracy in white dwarfs, two American astronomers, Fritz Zwicky and Walter Baade predicted that stars above 1.4 solar masses would be supported by neutron degeneracy. As there is some ultimate density beyond which electrons cannot be compressed, so too is there a density beyond which neutrons cannot become compressed. But what happens to the electrons in a star above 1.4 solar masses? The stellar mass exceeds the crushing point of a degenerate electron gas but electrons cannot be compressed any further. The net result is that the protons and electrons in the degenerate gas are forced together, forming a degenerate neutron gas, essentially one enormous nucleus of neutrons.

The prediction of neutrons stars was not a popular one because of the outrageous properties that the star was predicted to have. Neutron stars would have a mass density the same as an atomic nucleus, about $10^{17}$ kg/m$^3$. If a teaspoon full of neutron star material were brought Earth it would weigh as much as a fleet of 2,000 battleships, 100 million tons. A 2 solar mass neutron star is predicted to have a diameter of only 8 km (5 miles). The escape velocity would be one-half the speed of light.

***<u>Pulsars.</u>*** In 1967, Jocelyn Bell and Anthony Hewish of Cambridge University conducted an all-sky radio survey. In the course of the survey they discovered a mystery source with pulses generated precisely every 1.34 seconds (Figure 13). The regular pulsation was surprising and had never been seen before in astronomical sources. Bell and Hewish first looked for manmade radiation as an explanation and even thought of extraterrestrial radio communication. The situation was clarified when they found several new sources with precisely regular pulsation with periods between 0.2 and 1.5 seconds. These objects were christened "**pulsars**".

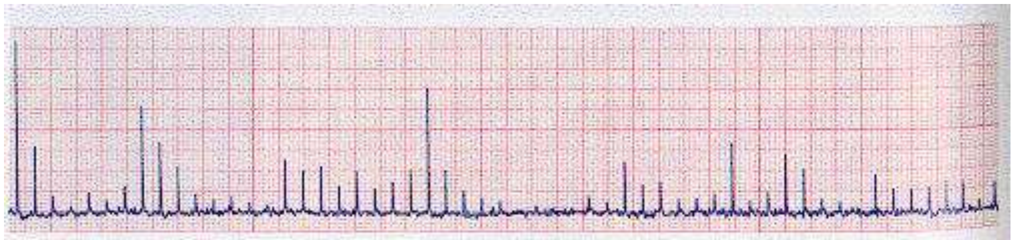

**Figure 13.** ***A paper strip chart recording of the pulses from the pulsar PSR 0329+54, which has a period of 0.7145. P 474-27.3?***

An explanation to the nature of the pulsar became evident when a pulsar was found at the center of the Crab Nebula, a supernova remnant (Figure 14). This pulsar is now called the Crab pulsar. The period of the Crab pulsar is 0.033 seconds. The periodic pulsation was thought to be associated with a star spinning with a 0.033-second period. This period demands a star with then-unheard-of compactness, for even a star as small as a white dwarf would fly apart at this spin rate. The Crab pulsar must be a neutron star.

**Figure 14.** *The Crab Nebula, a supernova remnant 6500 light years distant. The Crab Nebula is an expanding cloud of gas from a supernova observed 900 years ago. The core of the supernova is a pulsar, a neutron star that pulses 30 times a second.* ***APOD, AIUB.***

All stars rotate and have magnetic fields, but as a star condenses from a sun-sized object to a neutron star, its rotation speeds up (as angular momentum remains constant) from once a month to perhaps once a second. Its magnetic field also becomes denser, perhaps a billion times denser.

The rotation axis and magnetic field axis in a neutron star are not expected to be the same anymore than the magnetic axes of the Sun and Earth coincide with their rotational axes (Figure 15). As the neutron star rotates its magnetic field is swept across the sky. The star's sweeping magnetic fields would whip the electrons and protons in its atmosphere at high velocity, causing them to flow out its poles. The result is a thin beam of electromagnetic radiation emanating from each of the pulsar's magnetic poles. These beams are swept across the sky like a directed lighthouse beacon. If we are positioned fortuitously, one of the beams will sweep across the Earth, and as the beam sweeps through our field of vision we can see a short-lived pulse, once a rotation period. The Crab pulsar flashes on and off 30 times a second, and one of its polar beams happens to pass through a line-of-sight containing the Earth.

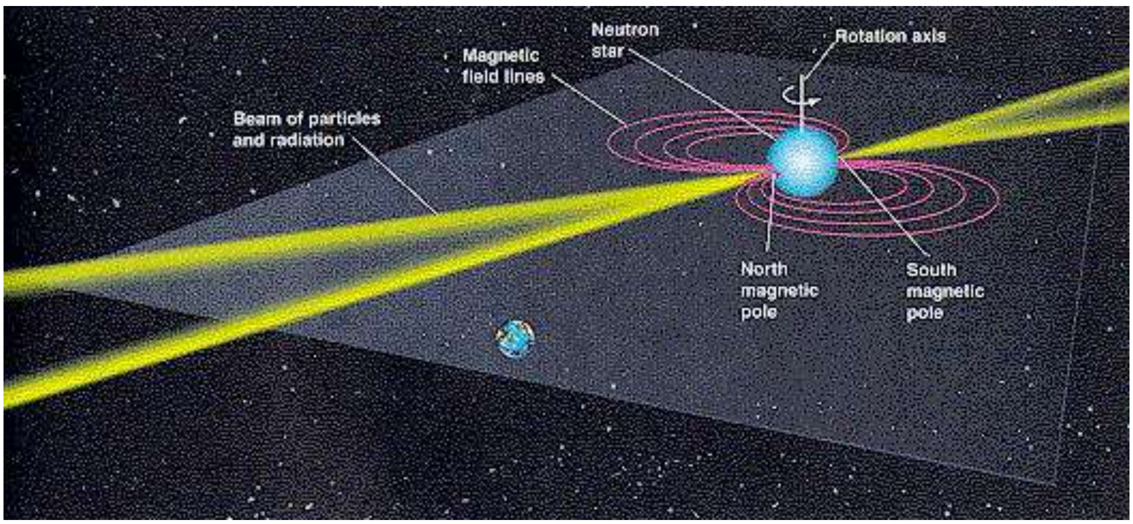


**Figure 15.** *The pulsar lighthouse model. The magnetic poles of a neutron star beam intense emission in two directions. The spinning neutron star rapidly sweeps these twin beams across the sky. An observer with a fortunate position sees the neutron star pulse as a beam comes into view.* ***Modified, FMW 451-22.16.***

**Web Note: Model of a Pulsar & Mass Transfer in Binaries**

## VII. X-ray binaries

The first X-ray Observatory Satellite was launched in 1979 from Kenya. To celebrate its African launch it was named Uhuru, for "freedom" in Swahili. In surveying the X-ray sky, Uhuru discovered X-ray pulses from the X-ray source designated Centaurus X-3 (for the 3$^{rd}$ brightest X-ray source in the constellation Centaurus). Centaurus X-3 was found to have a 4.84-second period. Later Hercules X-1 was found to be pulsing with a period of 1.24 seconds. These short periods were suspected to be associated spinning neutron stars.

**X-ray binaries** are not ordinary pulsars like the Crab pulsar. Centaurus X-3 turns off every 2.087 days for 12 hours, perhaps because is passes behind an unseen stellar companion. Hercules X-1 is an even clearer case. Its pulses turn off 6 hours out of every

1.7 days and these pulses exhibit a periodic Doppler shift with a period of 1.7 days. The pulses slightly are slightly less frequent than 1.24 seconds for half of the 1.7 day period before the pulses turn off and then slightly more for the other half of the 1.7 day period, suggesting orbital motion about an unseen companion (Figure 16).

Searches in visible light near Hercules X-1 showed a faint companion which varied in brightness with the same 1.7 day period seen in X-ray radiation. It was thought that this must be the companion to Hercules X-1.

Both Centaurus X-3 and Hercules X-1 have been successfully modeled as binary systems containing neutron stars. The short period X-ray variations are associated with a very short orbital period; this indicates that the stars are very close together. In both cases it is thought that a red giant's expanding atmosphere is attracted by the strong gravity of its neutron star companion and the giant spills some matter onto the neutron star. The neutron star is like an ordinary pulsar with a rapidly rotating magnetic field. The neutron star captures gas from its companion, which falls onto its magnetic poles at a significant fraction of the speed of light. The terrific impact of high velocity gas creates a 100 million K hot spot at each pole. The hot spots emit X-rays at 100,000 times the luminosity of the Sun. Each polar hot spot sweeps the sky, and is only visible from Earth during a fraction of the neutron star spin cycle. The result is an X-ray pulsing neutron star. As the neutron star passes behind its red giant companion, it is eclipsed for a matter of hours and its pulsing is not observed.

**X-ray bursters** are stars that emit X-rays at a constant low level for a time, then they exhibit an abrupt increase in X-ray luminosity, followed by a gradual decline. A typical burst lasts about 20 seconds.

These X-ray bursts are probably the result mass transfer in binary system from the atmosphere of one star onto the surface of a neutron star. The gas crashes into the surface of the neutron star; the impact heats the surface until it is hot enough to emit a modest level of X-ray emission. As soon as hydrogen gas hits the surface of the neutron star, it is hot enough to fuse, forming helium. A layer of helium collects on the surface until it reaches a thickness of about one meter, then it becomes hot enough to ignite, fusing into carbon and oxygen in a luminous burst of X-ray emission.

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**Summary**

The tempo of a star's evolution is determined by its mass with more massive stars evolving more quickly. A one solar mass star reaches the end of its main sequence lifetime in about 10 billion years when it runs out of core hydrogen to fuse to helium nuclei. At this point the star's core will contract, raising its temperature to the point where it can fuse helium to carbon. The star has become a red giant. After running out of core helium it contracts and increases its temperature, but thermonuclear fusion has ended in its core. As it cools it will become a solid white dwarf, a one solar mass star the size of the Earth.

A 10 solar mass star will reach the helium burning supergiant phase more quickly than a one solar mass star. After its helium-burning phase it will sequentially fuse carbon, neon, oxygen, sulfur, magnesium, and silicon. Next it will attempt to fuse iron, but iron is an energy sink and not an energy source. As a result the star will catastrophically collapse and then explode in a supernova. If the remaining supernova core is less than 1.4 solar masses it will form a white dwarf, if it is more massive it may form a neutron star, with a diameter of roughly 10 km.

Some spinning neutron stars are seen as pulsars, rapidly pulsing stars whose light is produced by matter falling through the neutron star's magnetic field onto its magnetic poles.

The heavy elements in the interstellar medium are produced by thermonuclear fusion in stellar interiors and then recycled into the interstellar medium with novae and supernovae explosions, solar winds, the shedding of a star's outer atmosphere into a planetary nebula, and in the spilling of matter transferred from one star to another in a binary system.

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**Key Words & Phrases**

1. **Fission** - splitting or breaking up an atomic nucleus into one or more smaller nuclei
2. **Helium flash** -
3. Neutron star -
4. Nova - a star that is suddenly observed to brighten by a factor of $10^4$ to $10^6$. This abrupt increase in brightness is typically followed by a gradual decline in brightness over several months.
5. **Pauli exclusion principle** - Two electrons with the same spin direction (up or down) cannot be at the same place at the same time.
6. Planetary nebula -
7. Pulsar -
8. **Supernova** - the explosion of a high-mass star
9. White dwarf
10. **X-ray burster** – binary star systems that emit X-rays at a constant low level for a time, then exhibit an abrupt increase in X-ray luminosity, followed by a gradual decline

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**Review for Understanding**

1. Describe how elements other than hydrogen are produced.
2. Sketch an H-R diagram labeling the regions where protostars, the Sun, main sequence stars, red giants, and white dwarfs can be found. Label the axes, including units.
3. Explain what provides the pressure that keeps white dwarfs and neutron stars from collapsing.
4. What evidence is there for the theory that pulsars are spinning neutron stars?
5. Match the phrases below with the lettered points on the H-R diagram below.
   Hydrogen fusing core

Hydrogen exhausted in the core
Helium fusion begins
Helium flash
White dwarf

6. Summarize the ways that stars can return matter back into the interstellar medium.
7. Which lives longer on the main sequence, a one solar mass star or a ten solar mass star? Why?

**Essay Questions**

1. Compare white dwarfs, neutron stars, and black holes by describing their similarities and differences. Consider properties like range in mass, luminosity, density, method of support against gravity, and state of matter.
2. An observer 1 AU from a neutron star, white dwarf, and main sequence star would feel a gravitational pull from each. How would they compare? How would the gravitational pull compare for an astronaut standing on the surface of each in turn?
3. Discuss the probable origin of the following elements in our Solar System: carbon, iron, and gold.

**Figure Captions**

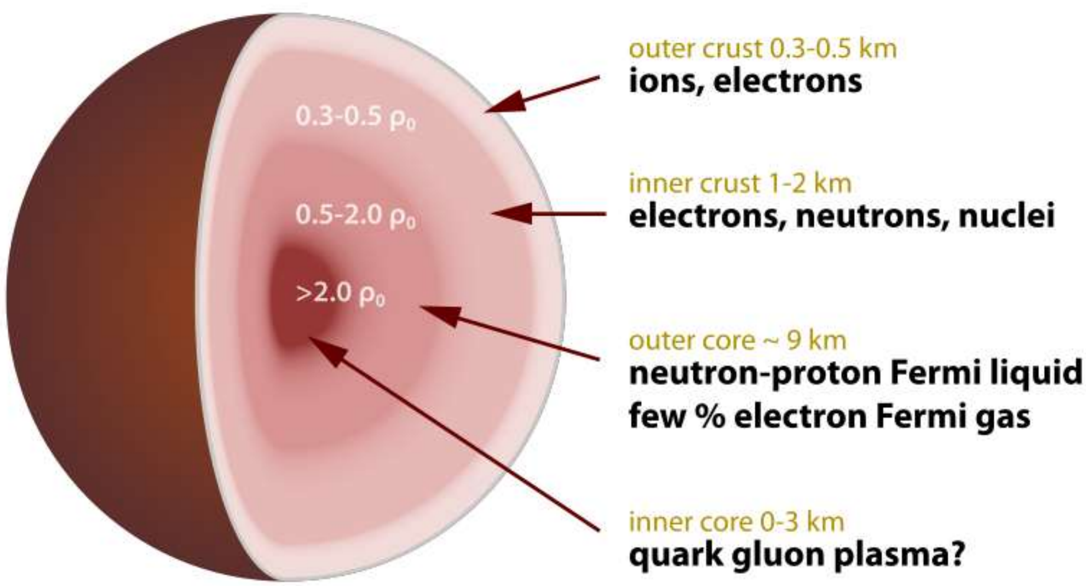


Figure 12. *Schematic of a neutron star. From Wikipedia Commons. Robert Schulze.*

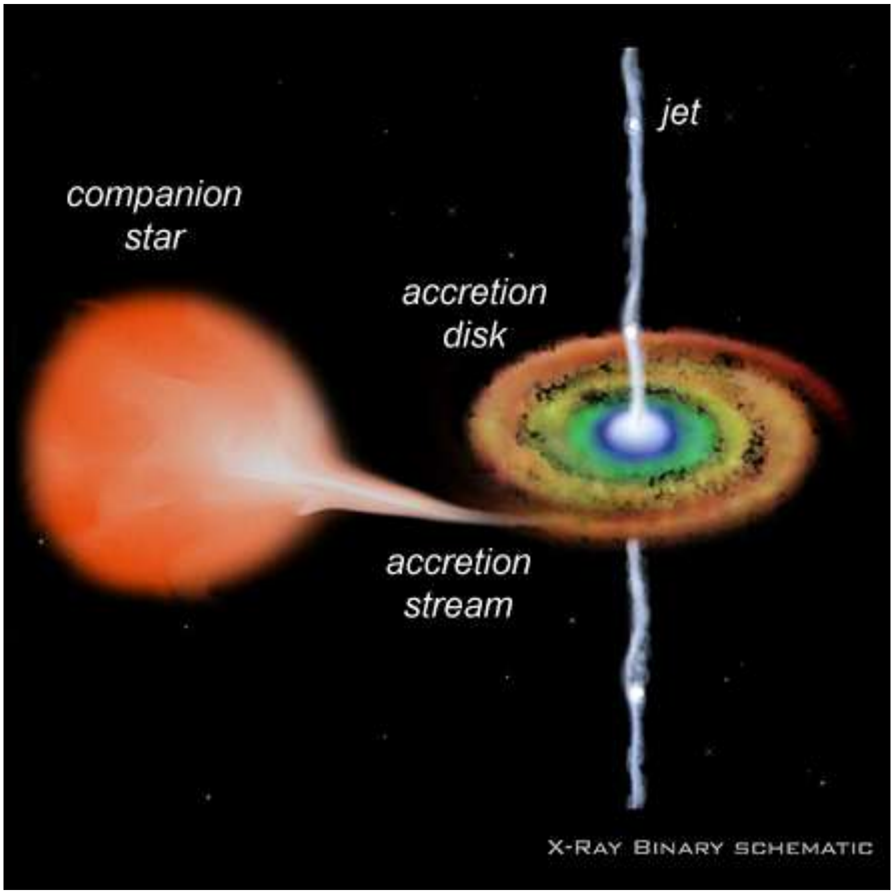


Figure 16. *X-ray binary.* *From http://chandra.harvard.edu/photo/2002/xtej1550/*

# Chapter 20 - Black Holes - the Ultimate Endpoint of Stellar Evolution

*"I can't believe that," said Alice.*

*"Can't you?" the Queen said, in a pitying tone. "Try again. Draw a long breath, and shut your eyes."*

*Alice laughed. "There's no use trying," she said: "One can't believe impossible things."*

*"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."*

--Lewis Carroll, Through the Looking Glass (1871)

**Chapter Preview**

Neutron stars and white dwarfs halt their collapse against the relentless pull of gravity when neutrons and electrons reach the ultimate limit at which they can be packed together. But what happens when even these forces are overwhelmed in the collapse of stars more massive than three solar masses? The result is a black hole, an object so dense that light cannot escape its gravitational pull. Einstein's General Theory of Relativity predicted the existence of the black hole eighty years ago. This theory predicts the bending and red shift of light by mass. Extremely dense objects will not allow light to escape their neighborhood, resulting in a black hole. The existence of black holes has been inferred in a number of binary star systems.

**Key Physical Concepts to Understand:** *General Theory of Relativity, Principle of Equivalence, gravitational bending of light, gravitational red shift, structure of black holes, detection of black holes*

## I. Introduction

One of the most exotic stellar objects is the black hole, the last stop in the process of stellar evolution and the point of no return for matter. A black hole is a collapsed star with a gravitational pull that is so great that neither light nor matter can escape it. The black hole was first predicted in 1916 by the astronomer Karl Schwarzschild, who used Einstein's newly published General Theory of Relativity to model the effect of gravity on light in the neighborhood of a collapsed star. Since then it has been popular in science fiction, owing largely to the strange natural phenomena which have been predicted to occur around these objects.

Are neutron stars the ultimate in the density to which matter can be crushed? For a star exceeding 3 solar masses, in which nuclear fusion has ceased, its collapse cannot be halted by the support of a degenerate electron or neutron gas. Collapse continues until, at a diameter of about 11 miles (for a 3 solar mass star), the escape velocity of material which could be ejected from its surface exceeds the speed of light. At this point, nothing, not even light, can escape the surface of the collapsed star. The collapsed star, in becoming a black hole, has left behind all evidence of its existence, except for its gravitational pull.

What happens to the matter inside the black hole? Scientists simply don't know. No one can see inside a black hole, and since no matter or energy can come out to give us any information; there is no way of knowing what happens inside. There is no force which can stop further collapse, so physicists and mathematicians talk about the matter in the black hole shrinking to an object of infinitesimal size, a point mass.

## II. The General Theory of Relativity Predicts the Existence of Black Holes

Gravity is the weakest of the four known natural forces (Table 1); it is $10^{36}$ times weaker than the electrical repulsion (attraction) between charged particles. Two protons have a force of electrical repulsion approximately equal to the gravitational attraction between two $10^9$ kg masses, separated by the same distance. Yet, over cosmic distances, gravity is the only force able to exert a significant effect on matter; at extreme levels it warps the fabric of space and time, producing a black hole.

*Table 1: Comparison of the strength of the four forces in nature (between two protons in a helium nucleus). The strong nuclear force is set to 1 for comparison.*

| Force | Relative Strength |
|---|---|
| **Nuclear Strong Force** (holds neutrons & protons together in the atomic nucleus) | 1 |
| **Electromagnetic Force** (between charged particles) | $10^{-2}$ |
| **Weak Force** (participates in radioactive decay) | $10^{-6}$ |
| **Gravity** | $10^{-38}$ |

### *A. The Principle of Equivalence*

Einstein's General Theory of Relativity predicts the effects of gravity on time and space. The underlying concept behind the **General Theory of Relativity** is the **Principle of Equivalence**: **gravity and acceleration are equivalent**. What is meant by equivalence? Simply that there is no experiment that one can perform anywhere in the Universe that would enable one to tell the difference between the forces of gravity and acceleration, without prior knowledge. We will demonstrate this principle with the following thought experiment. Imagine being kidnapped and finding yourself standing in a rocket ship with 1 g of force exerted on your body (1 g is the force normally exerted on one's body by the Earth's gravity, when one is resting on the Earth's surface). Is the rocket ship resting on the surface of the Earth (Figure 1)? The alternative is that the rocket is in space, well outside the influence of the Earth's gravitational pull, or the gravitational pull of any other mass. Imagine a rocket taking off from the surface of the Earth. After takeoff, the rocket begins its motion upward, accelerating from a standing stop to some constant upward velocity. The Principle of Equivalence says that there is no test that one can perform to determine whether the rocket is being accelerated or is simply acted on by the gravitational pull of another mass. (Your rocket is windowless. Looking through a window in the cabin to observe the rocket sitting on the surface of the earth and subsequently inferring that the only force pulling you to the floor of the cabin is gravitational is an example of using prior knowledge.) For example, standing in each of the possible rockets, in turn, you would feel a force pulling you downward (relative to the rocket), in one case by the force of the Earth's gravity, in the other case by the force due to the acceleration of the rocket. Note that when the rocket is moving at a constant velocity, there is no force due to acceleration, and no equivalent gravitational force.

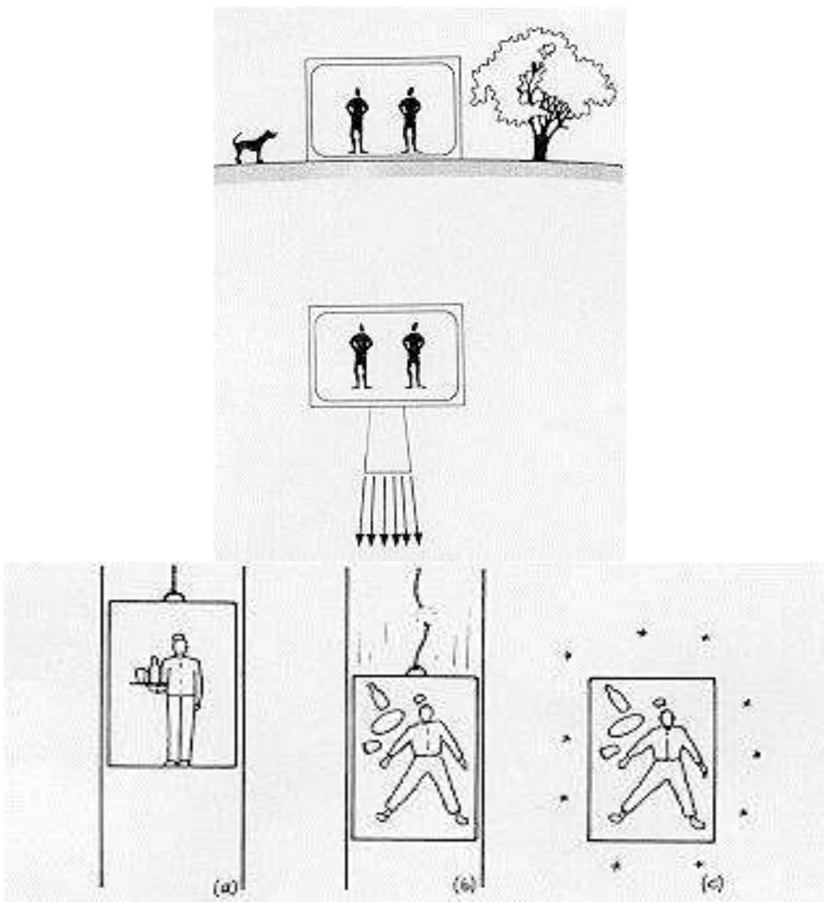

**Figure 1.** *The Principle of Equivalence illustrated. Assume that we have two identical laboratory/rockets, one (A) resting on the surface of the Earth and the other (B) in space; no experiment that can be performed inside either rocket will discriminate between the effects of gravity and the effects of acceleration.* ***Harrison.***

The Principle of Equivalence is a precise quantitative relationship. We can compare the forces on an accelerating rocket to one sitting on the surface of the Earth. The acceleration of gravity at the surface of the earth, g, is 9.8 m/sec/sec. If a rocket in space accelerates upward at 9.8 m/sec/sec, it produces the same forces on the body of the passenger as would gravity at the Earth's surface.

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**The Principle of Equivalence: Gravity and acceleration are equivalent.**

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*A. Thought Experiment 1 - Gravitational Bending of Light*

Imagine a much more precise, physical experiment, which we can perform (in principle) in our rocket ship. We shine a laser beam across the bottom of the cabin, parallel with the floor (Figure 2). As a short pulse of light travels across the cabin floor it travels the width of the cabin in time interval, t, illuminating a target on the opposite side. The light takes a finite, though extremely small, time to reach the opposite side of the cabin. If the rocket is accelerating upward during the time that the light is traveling from wall to wall, the rocket has moved upward a small amount during this time interval. When the light strikes the opposite wall, it will be closer to the floor than it was when it began its trip, although we aimed the laser to be parallel to the cabin floor. In other words, we measure the path to be bent across the cabin! Using the Principal of Equivalence, a rocket that is not accelerated, but is pulled by an equivalent amount of gravitational force, will bend parallel light in the same way! In other words, although light has no mass, it is bent by gravity.

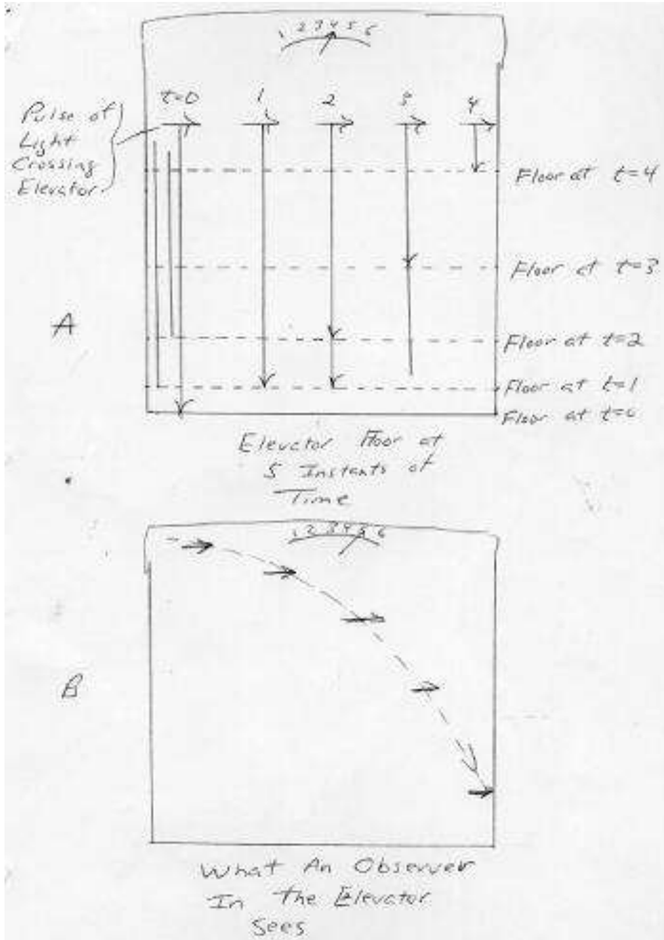


**Figure 2.** *A light pulse traveling across an accelerating rocket cabin seems to be slightly bent as seen by an observer in the cabin as the cabin moves upward toward the light beam. The Principle of Equivalence predicts that light will also appear bent by gravity, although it has no mass.* ***Panel A*** *shows a burst of light from a laser traveling across the cabin, seen in five instants in time. Dashed lines represent the cabin floor for each of the five instants in time. From this, we can deduce the appearance of the beam of light to an observer riding in the rocket cabin, as illustrated in* ***Panel B. Original.***

Web Animation - Gravitational Bending of Light

This conclusion produces an intriguing dilemma. How do you define a straight line? You could use a straight edge or ruler. But how can you determine whether it is really straight or not in the first place? If you were to view it under a microscope, it would appear ragged and irregular and perhaps warped and curved. A straight line is really a theoretical construct - the shortest distance between two points. Let us simply *define* a straight line as the path light follows. If we use this definition, then we would say that straight lines are bent by the gravitational force of nearby massive objects. The more massive the object means the more striking the degree of bending. Since directions in space are defined by straight lines, we can say that space is bent or warped by the gravity originating from objects embedded in it.

Warping of space is analogous to rolling a ball across a flexible rubber sheet with a billiard ball placed in the middle, where the billiard ball represents a massive object and the surface of the sheet represents curved space (Figure 3). The presence of the ball causes a dimple in the center of the sheet analogous to the curvature of space. As a smaller ping pong ball rolls across the sheet, toward the billiard ball, but not straight at it, it will curve toward the billiard ball as it approaches it, and then continue in a straight line as it leaves. A ping pong ball rolled close enough to the billiard ball will spiral into the larger ball colliding with it.

Web Animation - Film Clip of a Ball Rolling Across a Flexible Sheet

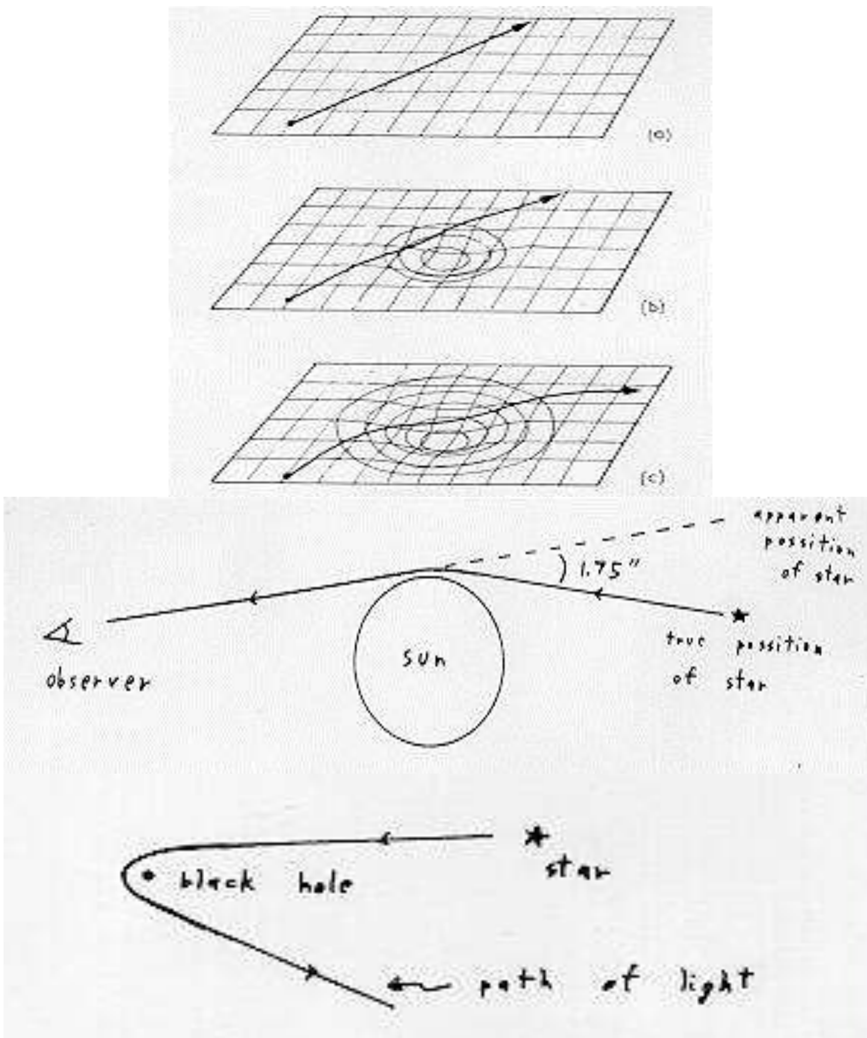


**Figure 3.** ***Panel A.*** *Gravitational deflection of starlight is analogous to a billiard ball being rolled across a rubber sheet. Starlight is bent by the gravitational attraction of the Sun.* ***Nicolson. Gravity, Black Holes, and the Universe. Panel B.*** *A star's apparent position on the sky is predicted to undergo a 1.75-arcsecond change, as its light passes near the edge of the Sun.* ***Original. Panel C.*** *Starlight passing near a black hole would undergo a dramatic deviation from a straight line.* ***Original.***

In 1916 Einstein predicted that starlight passing near the surface of the sun would undergo a slight deflection. This deflection is difficult to measure because of the dazzling brilliance of the nearby sun. It wasn't until the total solar eclipse of 1919 that astronomers could test this prediction of the General Theory of Relativity. Similar measurements have been made several times since. The deflection of radio waves from cosmic sources has verified the theory to within 1 percent.

*B. Thought Experiment 2 - Gravitational Red Shift & Slowing of Clocks*

Another interesting phenomenon predicted by the Principle of Equivalence is the gravitational red shift of light (for a discussion of red shift/Doppler shift, also see the discussion in Chapter 13, Section IV). Imagine a laser mounted on the floor of the rocket cabin pointed upward with a detector mounted on the ceiling of the cabin pointed downward (Figure 4). The detector is used to precisely measure the wavelength of light that has moved upward and hit the detector. Suppose that a burst of light is emitted from the laser just when the elevator begins to accelerate upward. By the time the light hits the detector, time t later, the rocket has accelerated to a velocity equal to the rate of acceleration times t. Since the detector is receding from the light, it will appear red shifted to the detector. The Principle of Equivalence tells us that an equivalent amount of gravity should produce the same amount of red shift. Light moving upward against the force of gravity is red shifted, and is therefore also losing energy, *even though light has no mass!* This is a unique prediction of General Relativity and cannot be explained by Newton's Universal Law of Gravitation.

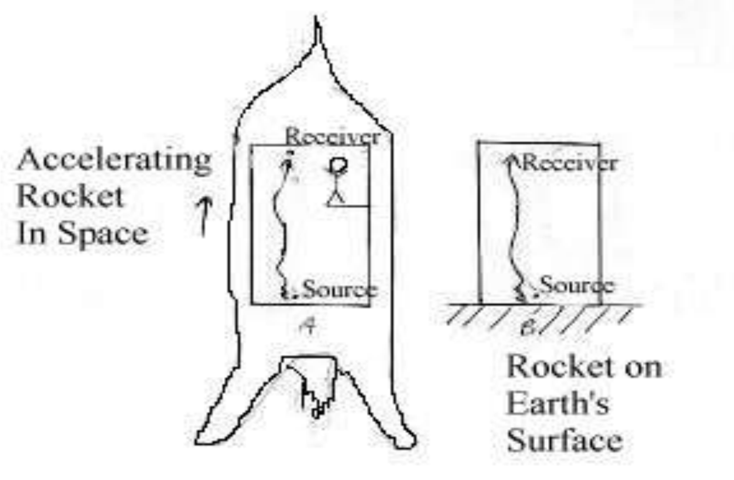


**Figure 4.** *The Principle of Equivalence dictates that an experiment on the Earth and the same experiment inside a rocket accelerating at 9.8 m/s$^2$ will produce the same results. A light wave traveling upward in an upward-accelerating rocket undergoes a red shift as it approaches the ceiling of the cabin. The Principle of Equivalence predicts that light will appear red shifted by gravity, even through it has no mass.* ***Original.***

Web Animation - Gravitational Redshift

If the laser and detector are switched, with the laser on the ceiling of the accelerating elevator, pointing down, the detected light is blue shifted. Light emitted as the rocket begins moving upward, moves down toward a detector that is being accelerated upward toward the oncoming beam of light. Since the detector is advancing toward the light, the light will be measured as blue shifted, and therefore gaining in energy. In other words, light moving toward a massive object will gain energy, as would a small mass falling onto a more massive object, not due to gravitational attraction (remember, light has no mass) but because of the Principle of Equivalence.

Now we have a second dilemma. How do we define the passage of time? Crudely speaking, we can use the ticking of a clock, a beating heart, the motion of the Sun in the sky, or the falling of grains of sand in an hourglass. But, as you can imagine, none of these techniques is precise enough for the physicist. One precise way of measuring time is to measure the period of vibration of light at a well-determined wavelength, for example the wavelength corresponding to light emitted from a red helium/neon laser. This wavelength is defined by the atomic structures of helium and neon. Consider this as the ticking of an atomic helium/neon clock. Now think about how our clock would be operated when accelerated, and what the Principle of Equivalence says about the behavior of our clock. Let's use the same lasers that we used for the gravitational red shift experiment for our atomic clock, and the same detector to measure the ticking rate. But we have a problem. Where do we measure the ticking period of this clock, at the bottom of the elevator or the top? We find that the ticking rate depends on where we make our measurements. As light travels upward in our cabin, it is red shifted, meaning that it experiences an increase in wavelength and increase in period (or decrease in frequency). This means that the measured ticking rate decreases as light moves upward against gravity. Similarly, the measured ticking rate increases as light is blue shifted, moving downward. For an accelerating cabin we have time dilation due to acceleration. When caused by gravity, this effect is called **gravitational time dilation**. It means that the rate of the passage of time is not the same everywhere, but is dependent on the influence of gravity. Suppose we could observe a clock on the surface of a distant star collapsing into a 3 solar mass black hole. When the star is 1000 miles in diameter the clock would appear to run 7 minutes slow each day, at 30 miles diameter it would lag by 5 hours per day, and at the 11-mile diameter the clock would appear to have stopped.

In 1960, two American physicists, R.V. Pound and G.A. Rebka verified the gravitational time dilation prediction of the General Theory of Relativity for the first time. They found that light shined up a 72-foot tower at Harvard University was red shifted by 15 parts in $10^{15}$, and blue shifted by the same amount if it traveled down the tower toward the Earth's surface. This experiment was remarkable in that these wavelength shifts were measured to a few parts in a million billion ($10^{15}$).

The effects of gravity, warping of space (i.e., bending of light), dilation of time, and red shift of light, occur in the neighborhood of any mass, but are only significant in regions of space where gravitational forces are exceptionally high. White dwarfs, neutron stars, and black holes are all dense enough to produce significant effects on time and space.

Black holes are singularly dense stars defined by their ability to warp space to such a high degree that light emitted from these objects can never leave the vicinity; it can orbit the collapsed star or fall back to the surface, but it cannot escape.

## III. Properties of Black Holes

### *A. The Event Horizon*

Consider a hot, glowing object such as a star being crushed under its own weight, in the last throes of stellar death. As collapse occurs gravity dominates all other forces. If the Earth were to collapse from its current diameter of 8,000 miles, by Newton's Universal Law of Gravitation, a 175-pound person on the surface would weight one ton at an Earth diameter of 2000 miles, one million tons at two miles, and at a diameter of 2/3 inch the Earth would become a black hole. For a star, light is being emitted from its photosphere, but as it collapses and the force of gravity grows correspondingly greater at its surface, the trajectories of the emitted starlight begin to deviate more and more from straight lines as predicted by General Relativity (Figure 5). As a star shrinks within a certain radius, light can no longer escape from the surface of the star to shine into the outside Universe. We call this the **event horizon** or **Schwarzschild radius** for that star, or for an object of that mass (named for the astronomer Karl Schwarzschild). Schwarzschild showed that the event horizon radius is given by the formula:

$$R_s = 2GM/c^2,$$

where $R_s$ is the so-called Schwarzschild radius, G is the gravitational constant ($6.67 \times 10^{-11}$ $m^3/kg\ s^2$), M is the mass of the star, and c is the speed of light ($3.0 \times 10^8$ m/s). A clock at the Schwarzschild radius to an outside observer as if time has stopped.

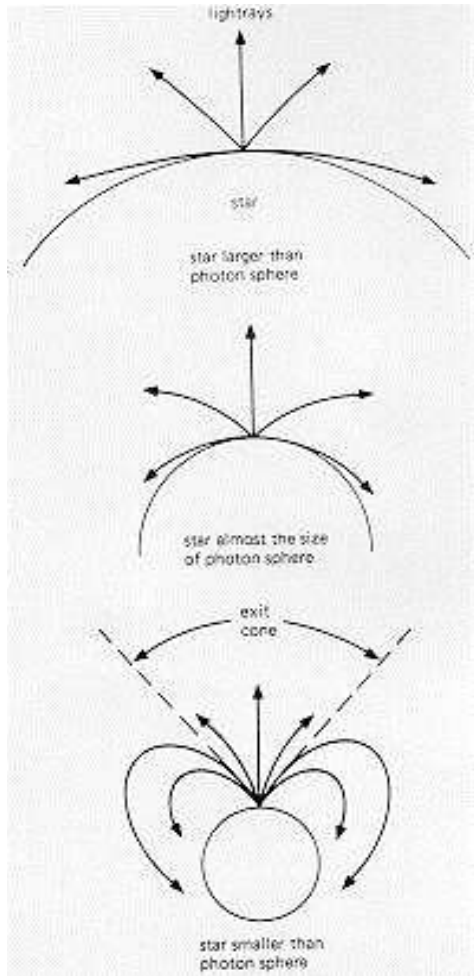


**Figure 5.** *A collapsing star experiences greater and greater surface gravity as it shrinks. As it collapses toward its event horizon, light is more dramatically bent, until it finally penetrates its event horizon, and light can no longer escape****. Harrison.***

**Derivation of the Schwarzschild Radius:**

The Schwarzschild radius $R_s$ of a black hole can be derived from the equation for the escape velocity of a projectile from a star or planet of mass M (see Chapter 4, Section 9):

$$(17.1)\ v^2_{esc} = 2GM/R.$$

If at a certain distance from a star, the escape velocity for an object is equal to the speed of light, then that radius is called the Schwarzschild Radius. Setting $v_{esc}$ equal to c, the speed of light, in Equation (17.1), we have,

$$(17.2)\ c^2 = 2GM/R.$$

Rearranging Equation 17.2, we obtain Equation 17.3, the equation for the Schwarzschild radius,

$$(17.3)\ \ R_s = 2GM/c^2.$$

Using Equation 17.3 we can compute the Schwarzschild Radius for a black hole of any mass. This equation assumes that the black hole under consideration is a nonrotating black hole. Otherwise centrifugal effects must also be considered. For a non-rotating black hole, Equation 17.3 is precise. For an arbitrary black hole with an unknown rotation rate, it can be used as an approximation.

**What is the Schwarzschild Radius of a 30 solar mass black hole?**

Using Equation 17.3 we get,

$\mathbf{R_s}$ = (2.0) x ($6.7\text{x}10^{-11}$ $m^3$/kg $s^2$) x (30. solar masses) x (2.0 x $10^{30}$ kg/solar mass)/ (3.0 x $10^8$ m/s$)^2$ = **8.9 x $10^4$ m, for a non-rotating black hole.**

The event horizon defines a black hole: a black hole is any object contained within its event horizon, that is, any object with a high enough density so that light cannot escape from the gravity surrounding that object. There is an event horizon radius for objects of any mass, not simply objects of many solar masses (Table 2).

*Table 2: Black holes do not have to be formed from dense matter.*

| Object | $R_s$ | Density |
|---|---|---|
| Person | $10^{-23}$ m | $10^{73}$ gm/cm$^3$ |
| the Sun | 3 km | 2 x $10^{16}$ gm/cm$^3$ |
| $10^8$ Solar Mass Black Hole | 2 A.U. | 1 gm/cm$^3$ |

Theoretically, one could form a black hole from ordinary objects, such as pencils, chairs, or automobiles by compressing them inside a radius given by the event horizon radius calculated for that mass (Figures 6 and 7). Once compressed within its event horizon, nothing, neither light nor matter, can escape the gravitational pull of the black hole. The escape velocity of matter exceeds the speed of light. Light and matter can penetrate the event horizon of the black hole, but once inside, they may never reappear. This matter has reached the point of no return. Not only is this matter and light irretrievable, but also no communications exist between the interior of the black hole and the outside world. Communications are based on the exchange of signals from light - radio waves, microwaves, visible light, etc., or from matter. We can neither look into the black hole, and see whatever exists inside, nor receive light emitted from within the event horizon. The black hole interior appears black indeed.

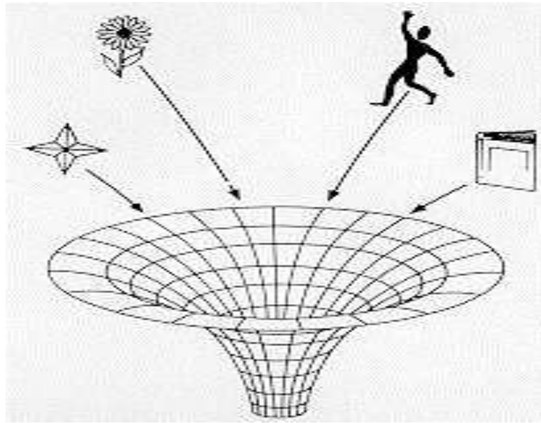

**Figure 6.** *Matter falling into a black hole becomes one with the black hole, and loses all of its individual characteristics. The black hole itself has only three properties: mass, electrical charge, and spin.* ***Harrison.***

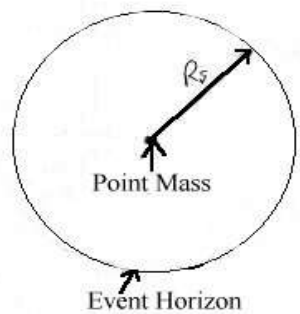


**Figure 7.** *Structure of a black hole. A non-rotating black hole has an extremely simple structure with only two components: a point-mass at the center and an event horizon, an imaginary sphere at the Schwarzschild radius indicating the boundary of the black hole - from within which light cannot escape.* ***Original.***

Can black holes much smaller than 3 solar masses exist? Black holes that are small in mass are not ordinarily expected to be found in nature, for we know of no natural way that an object under 3 solar masses can collapse under their own weight with sufficient force to be compressed into a size smaller than the Schwarzschild radius, other than in the creation of the Universe. However, for objects of very large mass, the required density becomes less and less, until at masses of 3-5 solar masses, stars are expected to collapse within their Schwarzschild radius when they run out of nuclear fuels, cool off, and collapse under their own weight. At very large masses, a black hole can form out of matter with a density less than that of ordinary water (Figure 8).

Let's examine some properties of black holes, by performing a set of imaginary experiments based on results of the Principle of Equivalence.

*B. Thought Experiment 3 - Dropping a Flashlight into a Black Hole*

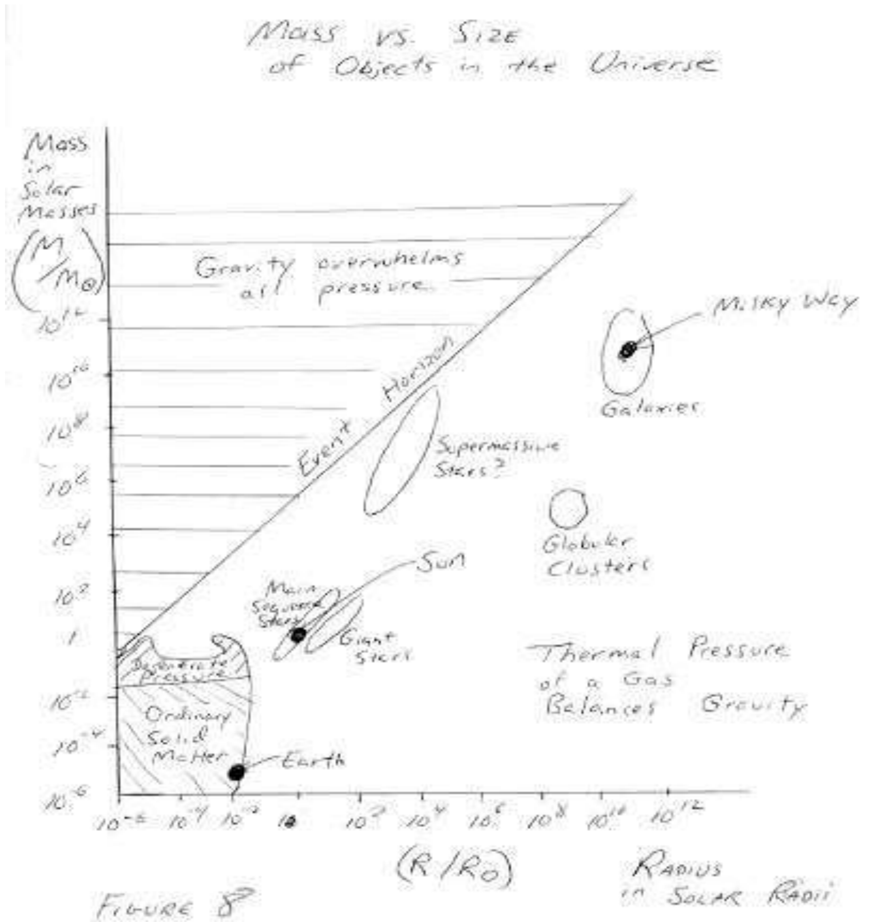


**Figure 8.** *Mass vs. radius of astronomical objects. All mass on a cosmic scale can be divided into two groups - black holes: objects with a high enough density that they are contained within their event horizon - and conventional objects: where catastrophic collapse is prevented by pressure of an ordinary solid (e.g., the Earth), ordinary gas (e.g., our Sun), or a degenerate gas (for neutron stars and white dwarfs).* ***Add lines of constant density. Original.***

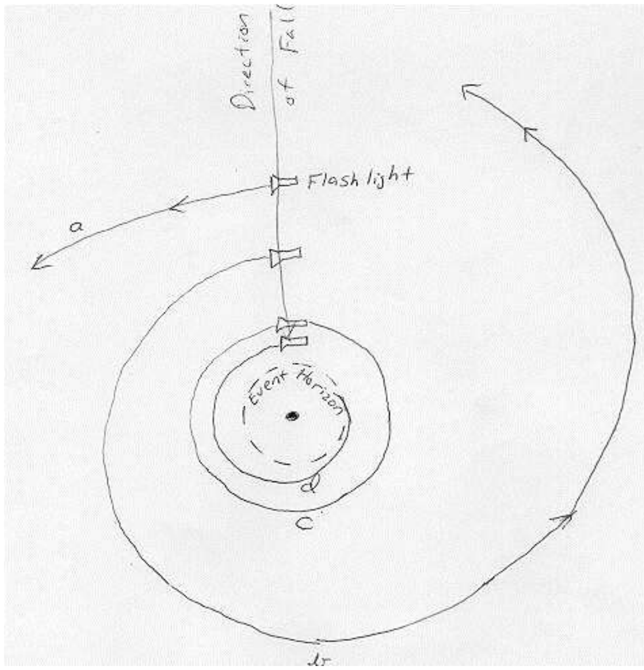


**Figure 9.** *A flashlight dropped into a black hole. As the flashlight approaches the event horizon, the light is bent more severely. On a sphere of radius 1.5 times the radius of the event horizon, light can orbit the black hole in a circular path. Inside this sphere, light will spiral into the black hole, penetrating the event horizon, never to exit.* ***Original.***

In the first experiment we drop a flashlight into the black hole, so that the light is pointed perpendicular to the line of travel (Figure 9). At first the light travels from the flashlight in nearly a straight line. As the flashlight falls closer to the black hole the force of gravity becomes stronger and the curvature of the light path becomes greater. At a distance of 1.5 times the event horizon radius the light can orbit the black hole in a circular path. Inside the event horizon the light can never leave the vicinity of the black hole.

Web Animation - Bending of Light Near a Black Hole

*C. Thought Experiment 4 - Mission into a Black Hole*

Imagine two astronauts, Buzz and Liz, determined to explore the neighborhood of a black hole (Figure 10). Buzz, the more reckless of the two, decides to travel into the black hole and communicate his experiences to Liz, who will orbit the black hole at a safe distance. As Buzz allows his craft to fall into the black hole he communicates to Liz by sending a light signal. Liz acknowledges the communications by returning a light signal to Buzz. As Buzz approaches the event horizon several things happen. As Buzz's light travels to Liz it is red shifted whereas light emitted from orbiting Liz to Buzz would be blue shifted. But Buzz's light is a measure of the passage of time in his own spacecraft and ticks in time to Buzz's clock and heartbeat. So Liz sees Buzz slowing as Buzz approaches the event horizon. Buzz doesn't notice anything funny about his own clock, but does notice that Buzz's light is blue shifted, indicating that Liz's clock is running fast. If they could read each other's watches with their telescopes, Buzz would think that Liz's watch was running too fast and Liz would think that Buzz's watch was running too slow. As Buzz accelerates and passes through the event horizon, Liz sees Buzz's clock slow to a stop, so that Buzz appears on the surface of the event horizon forever (although at this point Liz can't really see Buzz anyway, Buzz's light is red shifted to extremely low energies) and Buzz sees Liz's clock sped up infinitely. For Liz, Buzz's clock is frozen in time, hence black holes are called frozen stars. But, unfortunately, our courageous but reckless Buzz zips through the event horizon, is rapidly pulled apart by fierce tidal forces[1], and crashes into the black hole point mass, becoming one with the black hole.

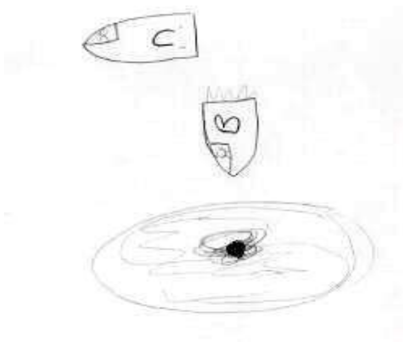

**Figure 10.** *Astronauts probing a black hole. Liz orbits the black hole while observing Buzz, who has unwisely ventured into the event horizon.* ***Original.***

## IV. Detecting a Black Hole

Obviously, black holes, by virtue of their "blackness", have unique problems being detected. How does one detect an object from which light cannot escape? One can search for the gravitational effects of black holes on the matter outside their event horizon. Astronomers look to binary star systems for the answer. Over half the stars in the sky are members of double, or binary, star systems. The orbital period observed for a binary system allows us to estimate the mass of the pair (Chapter 17, Section 6). If one of the pair is invisible, but has a mass over 3 solar masses, it becomes a black hole candidate. (Collapsed stars less than 3 solar masses become white dwarfs or neutron stars.) In addition, it is expected that X-ray emitting accretion disks will be found surrounding the event horizons of black holes combined with giant or supergiant companions (Figure 11). An accretion disk is a bottleneck for matter streaming out of the outer atmosphere of a giant star onto its collapsed companion. The matter is attracted to the black hole by its strong gravitational pull, but as it nears the black hole the matter is flattened into a thin disk the centrifugal forces that this material acquired from the spinning and orbiting giant companion. Then it is backed up outside the Schwarzschild radius, swirling around the black hole before it falls in, much like water spinning around

[1] On the Earth the tidal force, the difference in gravitational force between a person's head and feet, tending to pull them apart, is only one part in $10^{14}$. At the event horizon of a 3 solar mass black hole it is 100 million times greater. A person there would experience a 10 million pound tidal force pulling their head away from their feet.

a bathtub drain. As the matter piles up in a disk outside the black hole, called an accretion disk, friction within the disk of compressed gas heats the inner portion of the disk to temperatures of millions of Kelvins. At these temperatures the accretion disk will emit large amounts of energy in the X-ray part of the electromagnetic spectrum.

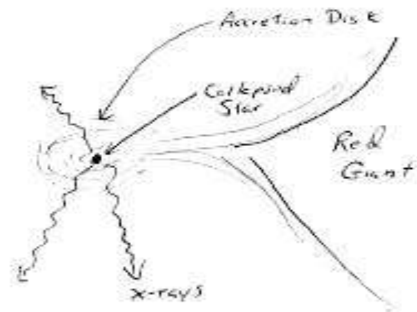


**Figure 11.** *A black hole/red giant binary star system. As the giant star evolves it expands, with its outer atmosphere spilling onto its collapsed companion in a thin accretion disk. The gas swirls around the black hole, until it is swallowed by the event horizon. As it becomes compressed it increases in temperature to millions of degrees Kelvin. This ultra-hot gas radiates much of its energy in the X-ray part of the spectrum.* ***Original.***

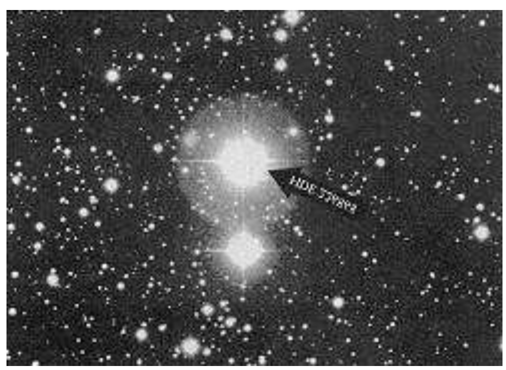

**Figure 12.** *Cygnus X-1. The star designated with the arrow is the supergiant companion of the black hole and X-ray source known as Cygnus X-1.* ***Arny.***

Cygnus X-1 is one such black hole candidate (Figure 12). Discovered in the 1970's by the Uhuru X-ray satellite as a strong X-ray emitter (the brightest X-ray source in the constellation Cygnus) it has been found to correspond to the position of a visible B0 star (with a temperature of 31,000K) named HDE226868. HDE226868 has no visible companion, but the Doppler shift of its lines indicates that it is orbiting around an unseen companion with a period of 5.6 days. A B0 star is not expected to emit significant X-ray radiation, so this emission is thought to arise from the accretion disk surrounding a collapsed companion (white dwarf, neutron star, or black hole). The B0 supergiant is estimated to have a mass of 15-40 solar masses. In order for the binary system to have a period of 5.6 days the companion should then have a mass greater than about 7 solar masses. This would indicate that Cygnus X-1 must be a black hole. Also, the X-ray emission of the system varies in intensity over a timescale of about 0.01 seconds as the temperature and density of the accretion disk varies. If the region of the accretion disk producing X-rays varies with a time scale of 0.01 seconds or less, then it must be about 3000 km across (smaller than the Earth) (the light travel time across the object). This is further indication that Cygnus X-1 can only be a black hole.

Other black hole candidates are given in Table 3 below.

*Table 3: Black Hole Candidates*.

| Black Hole Name | Companion Star | Orbital Period | Est. Mass of Black Hole |
|---|---|---|---|
| LMC X-3 | B3 main sequence | 1.7 days | 6 solar masses |
| A0620-00 | K5 main sequence | 7.75 hours | > 3.2 solar masses |
| V404 Cygni | G or K main sequence | 6.4 days | > 6.2 solar masses |

It is also expected that supermassive black holes could form at the centers of galaxies, as gas left over from the collapse and formation of the galaxy condensed in the center. One example is M87 (Figures 13 and 14). This galaxy has a small luminous source at the galactic center. By measuring the velocities of gas orbiting the center of M87 it has been estimated that 3 billion solar masses reside in an object about the size of our solar system, easily satisfying the minimum density required for a black hole. Other supermassive black holes are thought to be seen in Andromeda, M106, and even our own Milky Way.

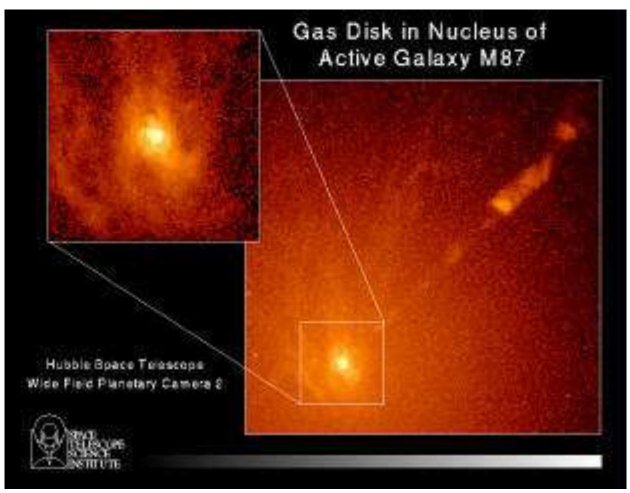


**Figure 13.** *A Hubble Space Telescope image of M87, a galaxy 50 million light-years away in the constellation Virgo. At the center of M87 (see the inset) is seen a spiral accretion disk outside a black hole with a mass of 3 billion suns and a size approximately equal to that of our solar system.* ***HST. NASA.***

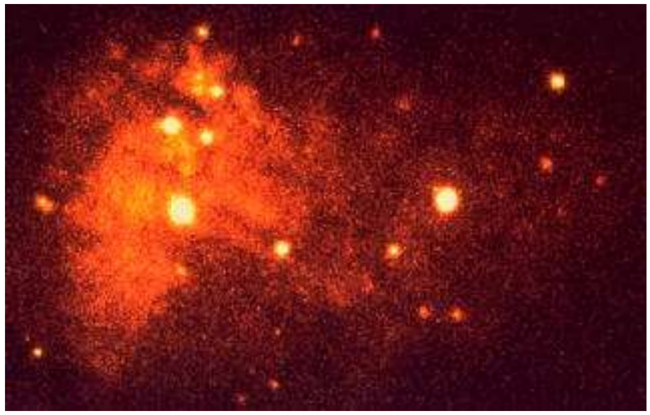

**Figure 14.** *LMCX-1. A ROSAT (Roentgen Satellite) X-ray image of the Large Magellanic Cloud, a nearby galaxy, showing an X-ray bright nucleus indicating the accretion of matter into a massive black hole.* ***NASA, APOD.***

The third type of black hole predicted to occur in nature is the primordial black hole, created in pockets of dense matter compressed shortly after the creation of the Universe, when all matter was undergoing explosive expansion. Such black holes could have almost any mass, even a few grams! However, small black holes require an external compressing force to overcome electron and neutron degenerate gas pressure.

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**Summary**

Although any mass can theoretically become a black hole by being squeezed inside its event horizon - inside of which the escape velocity is greater than the speed of light - this is the natural state of affairs for any star of mass greater than three solar masses after nuclear fusion has ceased. Einstein's General Theory of Relativity predicted the existence of the black hole in 1916, which seems to be confirmed by the detection of unseen companions in X-ray emitting, binary star systems. The General Theory of Relativity is based on the Principle of Equivalence: the effects of gravity and acceleration are equivalent. The result is the bending of light and the dilation of time due to gravity. These effects are significant where gravity is uncommonly strong, particularly near a black hole.

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**Key Words & Phrases**

1. **Black Hole** - A black hole is a collapsed star with a gravitational pull that is so great that neither light nor matter can escape it.
2. **Escape Velocity** - The velocity that an object must achieve to escape the gravitational pull on another object.
3. **General Theory of Relativity** - Einstein's theory that predicts the effects of gravity on space and time, based on the Principle of Equivalence.
4. **Principle of Equivalence** - The effects of gravity and acceleration are equivalent, that is, there is no experiment that can differentiate between the two.

5. **Schwarzschild Radius (or event horizon)** – When a mass is compressed within this radius, its escape velocity exceeds the speed of light and it becomes a black hole.

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**Review for Understanding**

1. How can light be bent by gravity if it has no mass?
2. What is the Principle of Equivalence? What does it predict?
3. Would a standard clock, placed anywhere in the universe, be perceived by us to always run at the same rate?
4. What is the diameter of the event horizon for a 10 solar mass black hole?
5. To within what diameter would your body mass have to be compressed to form a black hole?
6. How could one verify that an X-ray source is a black hole?
7. How has Einstein's General Theory of Relativity been experimentally verified?
8. Are all black holes found in binary star systems?
9. Must all black holes have a high density of matter?

**Essay Questions**

1. Under what conditions could the Universe be considered a black hole?
2. If the Sun suddenly collapsed into a black hole without changing its mass, would the planets be sucked within its event horizon?
3. Compare and contrast the properties of white dwarfs, neutron stars, and black holes.
4. Why can't a black hole gobble up more and more mass, becoming larger and larger, eventually swallowing up the entire Universe?