April 2021 Ken Larson KJ6RZ

# Origin of the Sun

Literary Hub

Future Chapter

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# 6 The Beginning of Everything

## 6.1 Formation of the Universe

About 13.8 billion years ago, for reasons we do not yet understand, the universe came into existence. At that instant there was no such thing as time, space, or matter. At time $t = 0^+ \ll 10^{-100}$ seconds, the universe existed as a single point of incredible energy far beyond our comprehension. All of time, space, and matter rapidly expanded out of that single point. How rapidly? It is estimated that the universe expanded from about the size of an electron, $\sim 4\ (10^{-15}$ km), to over a light year in size, $9.46\ (10^{+12}$ km), is roughly a picosecond ($10^{-12}$ seconds). We call the rapid emergence of the universe the “big bang” because time, space, matter, everything that we are aware of “explode” into existence. There was nothing “before” the big band. The big bang 13.8 billion years ago is the beginning of time.

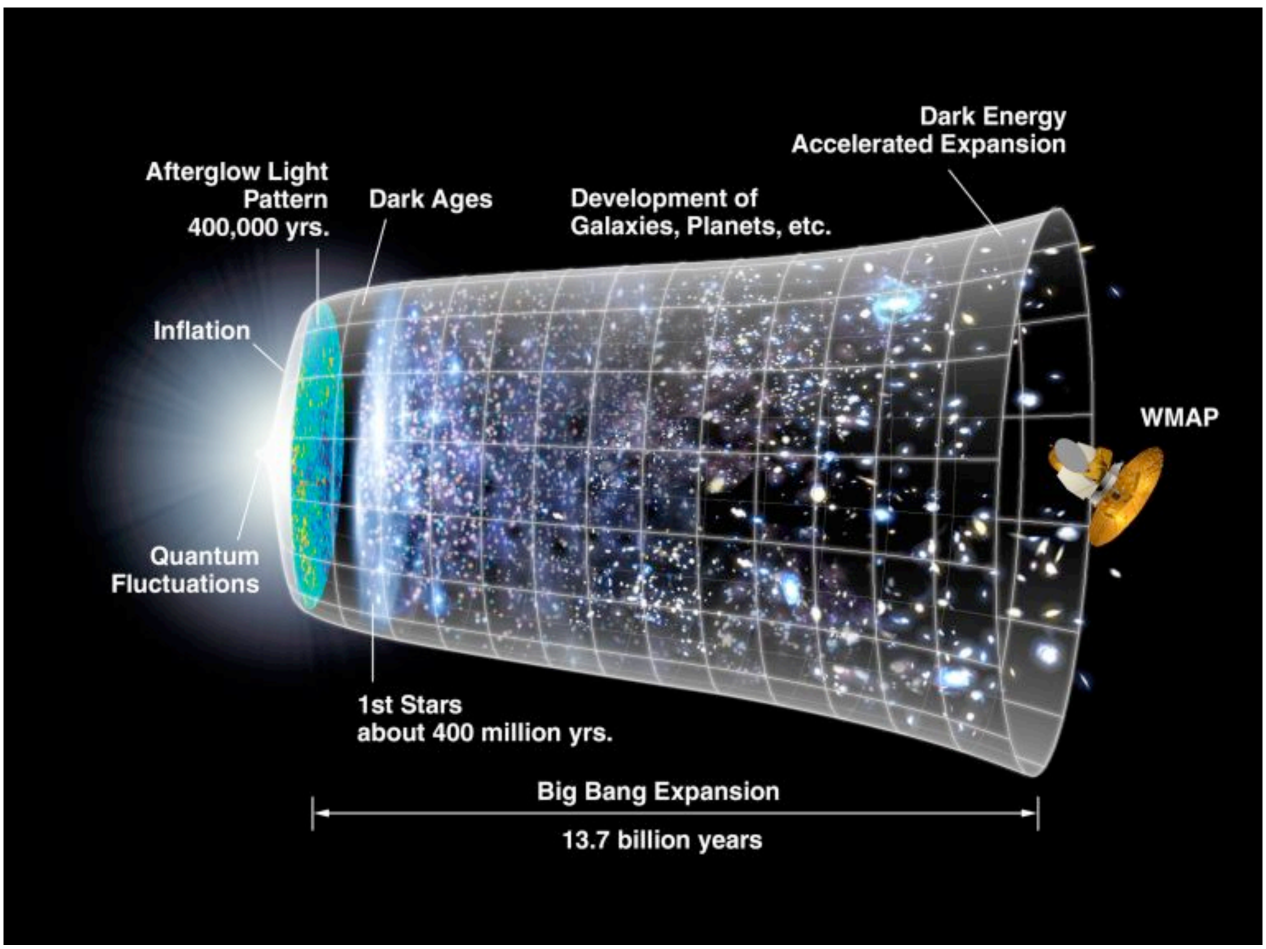


Figure 1 Expansion of the Universe (source: NASA)

We have no problem relating to the beginning of time. The beginning of time is a common every day experience, the beginning of a race, the beginning of a project, etc. Similarly, the formation of matter is something that we can easily deal with. We are always building things out of other things, making cloths out of fabric, building tall sky-scrapers, etc. But the creation of space out of nothing is something that conceptually we have trouble grappling with. We try. Figure 1 is a drawing illustrating the expansion of the universe over time. In nature there is nothing beyond the universe. But in Figure 1 the rest of the page is beyond the universe. In the drawing the universe began at a point on the left side of the page. In fact, the universe expanded out of nothing. There is no such thing as a place at which creation began. Another analogy that sometimes helps is visualizing the universe expanding like a rapidly inflating balloon in which the entire universe exists only on the the balloon's surface. Here to the analogy falls short. In terms of the universe there is no such thing as inside the balloon or above the balloon. Everything in the universe exists only on the surface of an ever expanding surface. We can think of the surface as having a thickness which is incredibly thin compared the surface itself. The thickness representing local up and down. All other directions stretch out across the surface. Because the universe is expanding, growing ever larger, the stars and galaxies are slowly drifting apart. In fact, that is how we know that the universe is still expanding.

While we do not understand what happened at the beginning of the big band (at time $t = 0^{+}$), but our knowledge of physics is good enough to determine, with a fair degree of confidence, what happened from that point on. In fact, we are pretty sure that we understand what happened from $10^{-45}$ seconds onward.

### 6.1.1 Fundamental Forces of Nature

The four fundamental forces responsible for creating the universe, and everything in it, came into existence within the first picoseconds of time. These forces are:

- The strong force,
- Electromagnetic force,
- The weak force, and
- Gravitational force.

The relative strengths of the four forces is shown in the following table in which the weak force has been arbitrarily assigned a force of 1.

| Force | Relative Strength |
|---|---|
| Strong | 10,000 |
| Electromagnetic | 100 |
| Weak | 1 |
| Gravity | $7 \cdot 10^{-34}$ |

Table 1 Fundamental Forces of Nature

The strong force is the strongest force in nature. It holds together the subatomic particles, including up quarks and down quarks, that make up protons and neutrons. The strong force also holds protons and neutrons together in the nuclei of an atoms. The strong force operates over an extremely short distance which is about the diameter of a proton. Two particles must be almost touching to be affected by the strong force. However, when two particles get close enough, the strong force "kicks in" dominating all other forces in nature. Since the strong force is one hundred times stronger than the electromagnetic force, it is able to hold together protons within a nucleus even though the positively charged protons, under the influence of the electromagnetic force, try to repel one an other.

The electromagnetic force is the next strongest force. The electromagnetic force holds together atoms binding the cloud of negatively charged electrons to the positively charged nucleus. The electromagnetic force also binds together atoms into molecules and molecules into all of the more complex structures that we are accustom to including trees, oceans, and our human body. The electromagnetic force is the primary force underlying most of engineering, physics, chemistry, and biology. The electromagnetic force has an infinite range. The electromagnet force between two electrically charged objects is inversely proportional to the square of the distance separating them, but never goes to zero. Two electrons on opposite sides of a galaxy still repel each other even though the force between them is infinitesimally small. The electromagnetic force causes most large objects in the universe to be electrically neutral. If an object is electrically positive, it will over time attract and capture a sufficient number of electrons to become electrically neutral. A negatively charged object will eventually eject enough electrons to become electrically neutral.

The weak force has the shortest range of all the forces. Its range of influence is only about 1% the diameter of a proton. It is extremely unlikely that two particles will get close enough to interact via the weak force. Thus reactions that occur as a result of the weak force occur at an extremely slow rate. However, the weak force is responsible for radioactive decay and, under certain conditions, the transformation of a proton into a neutron and the conversion of a neutron into a proton. This conversion process between protons and neutrons enables the production of all elements other than hydrogen. Radioactive decay provides much of the heat required to keep the Earth's nickle-iron core molten. A molten nickle-iron core is extremely important since it is responsible for Earth's significant magnetic field that largely shields Earth's atmosphere from erosion by the solar winds emanating from the Sun.

Gravity is incredibly weak in comparison to the other three forces, and yet it is the most important. In relative terms, the strength of gravity is only $7 \cdot 10^{-34}$ compared to the weak force, the next smallest force. However, the range of gravity is infinite and it attracts **all** types of mater. Thus gravity accumulates! The gravity associated with a small particle attracts other particles and they attract it, forming a larger body. The gravitational force associated with a large body is the sum of the gravitational force of each of its component particles. As a body grows in size, so does its gravitational force pulling in more and more material, leading eventually to the development of planets, stars, and galaxies. Gravity holds together galaxies, galactic clusters, and solar systems. It makes stars and planets rounds. It holds us, the oceans, and most other things that we are familiar with in our daily lives to the surface of the Earth. It causes weaken buildings to collapse, mountains to erode, and ultimately determines the fate of the universe. Thus, despite its intrinsic weakness, the infinite range of gravity and its attraction force exerted on all forms of matter cause gravity to dominate all other forces on a large scale.

### 6.1.2 The Radiation Era

The creation of light (photons or packets of energy) formed before the creation of matter. The background radiation that we see filling the universe today originatged at this time.

### 6.1.3 Formation of Matter

The initial temperature of the universe at time zero is estimated at $10^{32}$ degrees kalvin ($^{o}K$). The flegeling universe cooled as it expanded. At around 1 microsecond it had cooled to $10^{15}$ $^{o}K$, cool enough to allow formation of subatomic particles including electrons and the various types of quarks as illustrated in Figure 1. Unlike protons and neutrons, subatomic particles have no internal structure. The most important subatomic particles are shown in Table 2.

| Subatomic Particle | Electrical Charge |
|---|---|
| | |
| Up Quark | + 2/3 |
| Down Quark | - 1/3 |
| Electron | - 1 |

Table 2 Subatomic Particles

About 100 microseconds later the universe had cooled to around 20 billion degrees kelvin permitting protons and neutrons to form. Protons and neutrons are composed of the following subatomic particles

| Particle | # Up Quarks: Charge = +2/3 | # Down Quarks: Charge = -1/3 | Total Charge |
|---|---|---|---|
| Proton | 2 | 1 | +1 |
| Neutron | 1 | 2 | 0 |
| Electron | Electron is subatomic particle | | -1 |

Table 3 Atomic Particles

Neutrons are slightly heavier than protons. Because of its lower mass more protons formed than neutrons.

The formation of protons and neutrons stopped as the universe cooled below 10 billion degrees with a resulting concentration of 7 protons for every neutron.

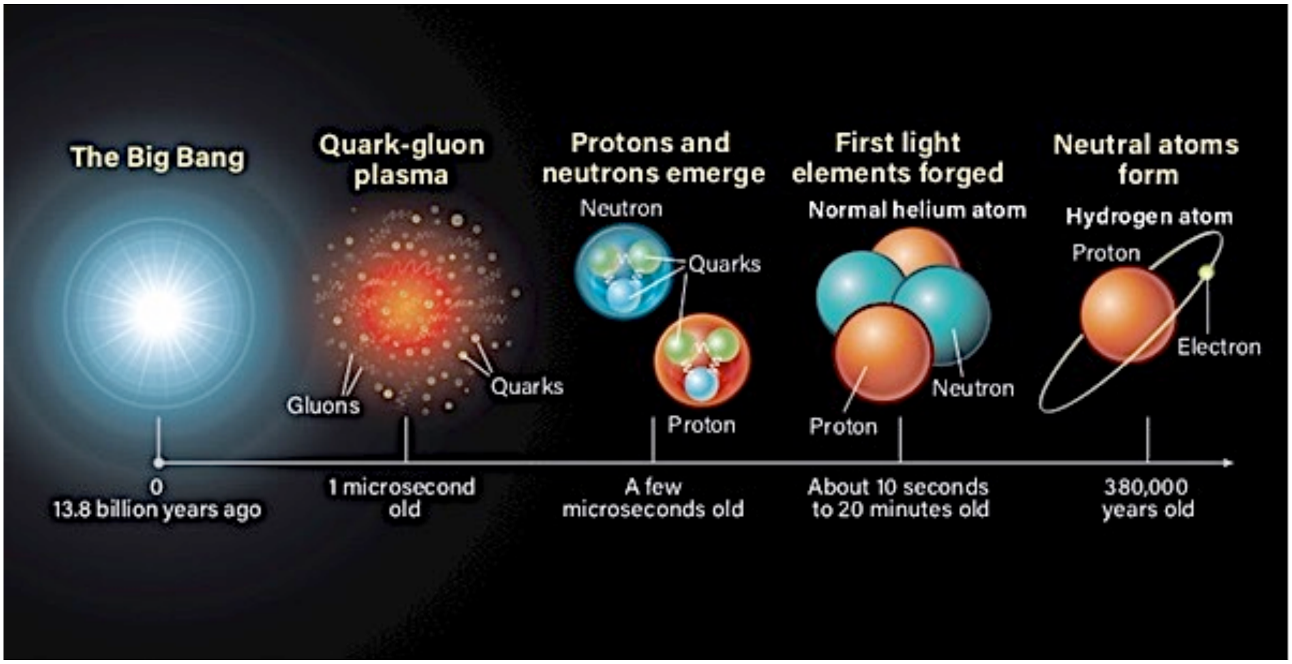


Figure 1 Creation of Matter (source: Astronomy)

At about 1 billion degrees kelvin protons and neutrons had cooled down enough to begin sticking together forming the first simple atomic nuclei, a process called nucleosynthesis. This occurred in the first few minute of time. Since the number of protons considerably out numbered neutrons, only 1 proton in 7 could unite with a neutron to form deuterium. In atomic form a deuterium atom, also known as heavy hydrogen, consists of a single electron orbiting a nucleas composed of one proton and one neutron. However, at this point the universe was too hot to form complete atoms. That occurred later.

Only a small fraction of deuterium nuclei, about one in ten thousand or so, remained as deuterium. The rest quickly combine in pairs to form helium nuclei. A helium nuclei consists of 2 protons and 2 neutrons. Consequently out of every 16 nucleons (14 protons + 2 neutron) four nucleons (2 protons + 2 neutrons) became a helium nuclei while the remaining 12 protons became hydrogen nuclei (a hydrogen atom consists of one electron orbiting a nucleas containing a single proton).

After about 20 minutes, nucleosynthesis ended and no further nuclei could form. At the end of nucleosynthesis three-quarters of the universe by mass was hydrogen and one-quarter helium. In addition to hydrogen and helium very small amounts of lithium (several parts in ten billion compared to hydrogen) and small amounts of remaining deuterium (one part in ten thousand) were produced by the big band. The remaining 90 or so chemical elements, including increasing concentrations of helium and lithium, are produced in stars but constitute only a few percent of the overall mass in the universe. Over 98% of the universe today is still composed mostly of hydrogen (71 % by mass) and helium (27 %).

380,000 years after the big bang, at a temperature around 3,000 $^{o}$K, the universe had cooled enough for the electromagnetic force to join negatively charged electrons with positively charged nuclei to form neutral hydrogen and helium atoms plus very small traces of lithum.

### 6.1.4 Dark Matter

In addition to normal matter, a dark matter also formed. Dark matter accounts for approximately 85% of the matter in the universe. Its presence is implied by gravitational effects that can not be explained unless more matter exists than can be seen. This evidence includes calculations showing that many galaxies would fly apart if they did not contain large amounts of an unseen matter. Other evidence inclued:

- Astronomical observations of the universe’s current structure,
- Formation and evolution of galaxies,
- Motion of galaxies within galaxy clusters, and
- Gravitational lensing.

Dark matter is called dark because it does not appear to interact with electromagneitc fields. Consequently, it does not absorb, reflect, or emit electromagnetic radiation making it difficult to detect. Current theories are that dark matter is compoosed of some as yet undiscovered subatomic particles which do not interact with ordinary matter.

### 6.1.5 Local Universe

The local universe is the part of the universe in which we live. It is a region approximately 1 billion light years in radius. Most of our knowledge about the structures and internal evolutionarily processes of galaxies and systems of galaxies comes from our study of the local universe.

### 6.1.6 Galaxies

Under the influencce of gravity stars began forming from hydrogen and helium gas clouds about 200 million years after the big bang. Around 300 to 500 million years after the big bang collections of stars were pulled by gravity into the first galaxies. It is currently estimated that there are over 200 billion galaxies in the universe, each galaxy containing billions upon billions of stars. Throughout the universe there are more stars than grains of sand on Earth. Figure 2 is a small segment of sky imaged by the Hubble spacecraft showing hundreds of galaxies.

The original stars that formed were composed entirely of hydrogen, helium and trace amounts of lithium, the only material in existance at the time. Since then all of the elements in the chemical periodic table (Figure 3), other than hydrogen and the initial helium, have been produced through nuclear fusion within the cores of stars (converting hydrogen into helium, helium into carbon, etc.).

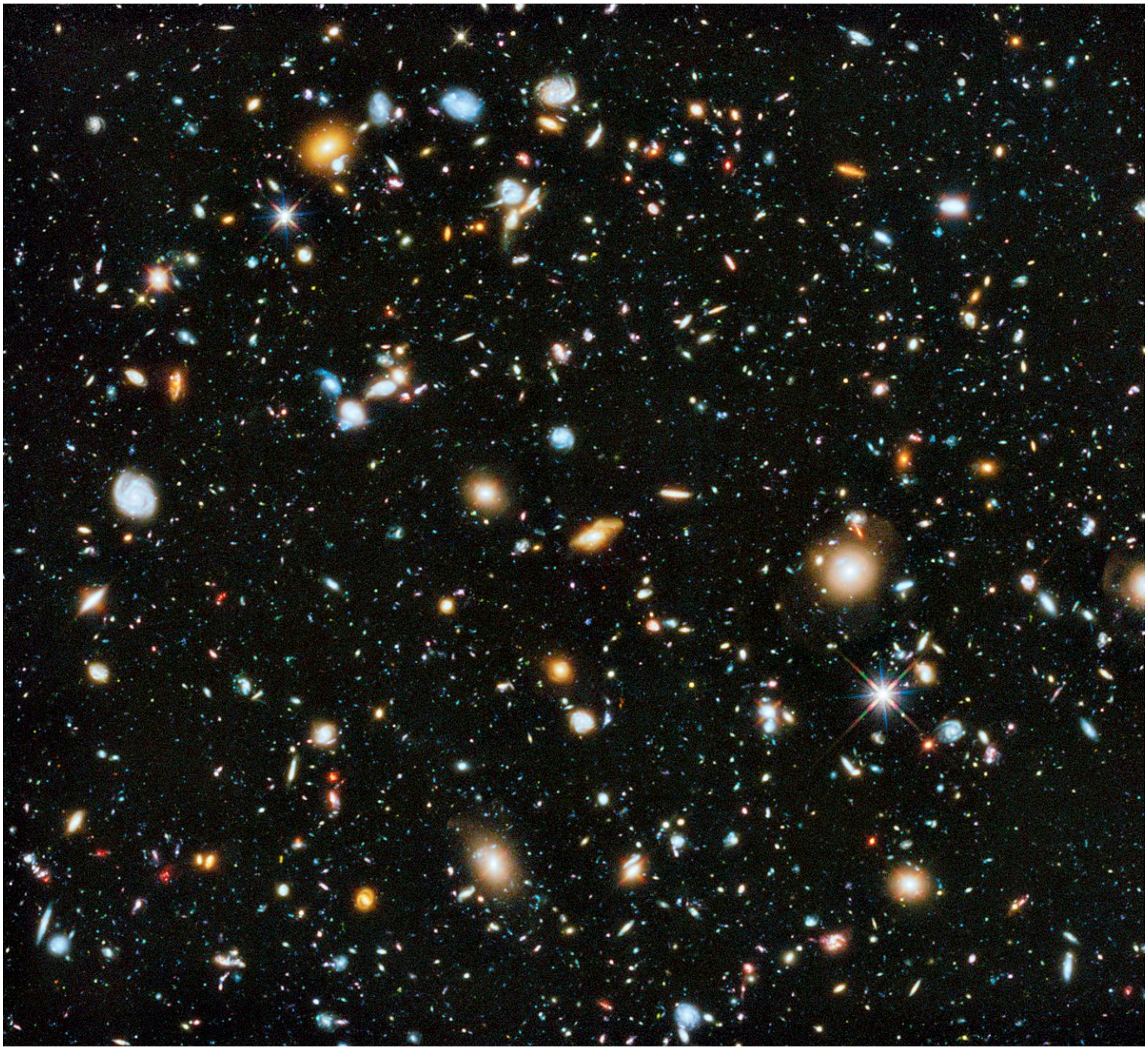

Figure 2 A universe filled with galaxies (source: NASA)

The heaviest elements were, and continue to be, formed in the violent deaths of very large stars (in supernova). Astronomers refer to the elements beyond hydrogen and helium as metals and the proportions of them found in interstellar gas and stars as metallicity. Metallicity is continuously increasing in the universe as one generation of stars evolves from the previous generation. Hence the proportion of metals found in a star can be an indication of its age, with older stars having a lower metallicity.

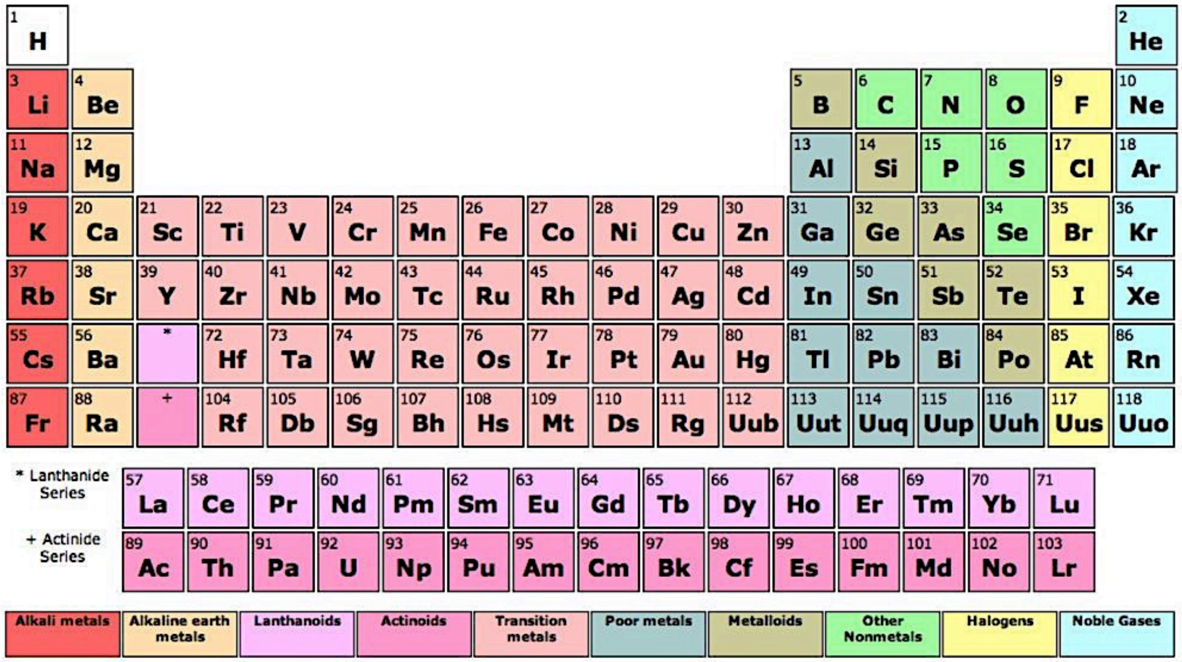


Figure 3 Chemical Period Table of the Elements

Astronomers group stars into three main populations accoringe to their metallicty.

- **Population I:** Metal rich stars that tend to be yound and are found primarily in the disks of galaxies. The Sun is a Population I star.

- **Population II:** Metal poor stars that are older and found in galactic bulges and halos. A halo is the spherical region surround a galaxy.

- **Population III:** The first generation of stars made primarily of primordial gas (hydrogen and helium) with almost no metals at all.

Most galaxies are 3,000 to 300,000 light years in diameter and are separated by distanaces on the order of millions of light years. For example, the Milky Way galaxy is around 100,000 light years in diameter and separated from the Andromeda Galaxy, our nearest large neighbor, by around 2.5 million light years. The space between galaxies is filled with intergallic gas that is so tenuous that its density is less than 1 atom per cubic meter.

Many galaxies are thought to have massive black holes at their centers. A black hole is an astromical object so massive that nothing can escape from it, not even light. The black hole at the center of the Wilky Way galaxy is 4 million times the mass of the Sun.

The majority of galaxies are gravitationally organized into groups, clusters, and superclusters. The Milky Way and Adromeda galaxies dominate the Local Group of galaxies, which also includes manky smaller galaxies. The Local Group is part of the Virgo Supercluster.

Galaxies span a wide range of sizes and shapes from dwarf galaxies containing as few as 100 million stars to giant galaxies with over a 100 trillion stars. Based on their shapes galaxies are catorgized as:

- Elliptical,
- Spiral, or
- Irregular

#### 6.1.6.1 Elliptical Galaxies

Elliptical galaxies are believed to make up approximately 10–15% of the galaxies in the Virgo Supercluster. Approximately one third of the galaxies in the universe overall are ellipticals. They vary in shape from nearly circular to highly elongated with little visible structure as illustrated in Figure 4.

Elliptical galaxies consists mainly of older low mass stars with little remaining gas and dust in the galaxies to form new stars. In fact, most of the stars in elliptical galaxies are much older than the stars in spiral galaxies. Consequently, elliptical galaxies typically appear yellow-red, which is in contrast to the distinct blue tinge of most spiral galaxies. In spirals, this blue color emanates largely from the young hot stars in their spiral arms. In addition, most of the stars in elliptical galaxies have a low abundance of heavy elements because star formation ceased after the initial stars were formed. Heavy elements are produced through the birth, life, and death of many generations of stars, a process that did not occur in ellipticals. It is believed that black holes at the center of most ellipticals played an important role in limiting the growth of elliptical galaxies in the early universe by inhibiting star formation.

The stars in elliptical galaxies orbit a common center of gravity but in random directions giving the galaxies their fuzzy elliptical shapes. The number of stars in elliptical galaxies range from tens of millions to over one hundred trillion stars. The most common ellipticals are dwarf galaxies only a few light years wide. The largest are giant elliptical galaxies that are about 300,000 light years across. These are relatively rare. It is widely accepted that merging of galaxies through gravitational attraction, which was common in the early universe, played a major role in shaping the growth and evolution of elliptical galaxies, particularly the largest ellipticals.

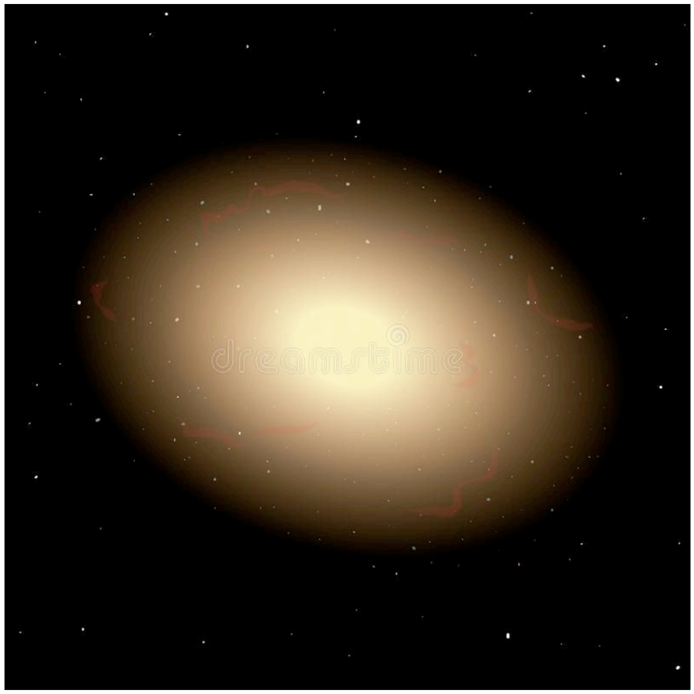

Figure 4 Elliptic Galaxy (source: Printerest)

### 6.1.6.2 Spiral Galaxies

Spiral galaxies are relatively flat rotating disks of blue white stars with a yellowish bulge at their centers. Two examples of spiral galaxies are shown in Figures 5 and 6. The central bulge is generally composed of older red Population II stars with low metal content. Extending outward from the central bulge are bright arms generally containing vast quantities of gas and dust from which Population I stars are being actively formed. Active star formation gives the arms their bluish white color. Spiral galaxies range in size from 16,000 to over 300,000 light years across. It is believed that the central bulge of most spiral galaxies contains a supermassive black holes.

Both stars and the spiral arms rotate around the center of the galaxy. The speed of each star system is modified by gravitational forces as it moves through an arm. A star systems returns to its normal quiescent speed as it emerges from an arm. The flatness of the galactic spiral depends on its speed of rotation. Slower rotating galaxies tending to have thicker bulges while faster rotating galaxies are thin and flatter. Today spiral galaxies make up nearly two-thirds of the galaxies in the universe.

Spiral galaxies are divided into two groups: normal spirals, Figure 5, and barred spirals Figure 6. An elliptical shaped region of stars (a bar) runs through the central bulge of a barred spiral. The arms of a barred spiral begin at the ends of the bar instead of at the central bulge. It is believed that only about 10% of the spiral galaxies in the early universe were barred. Today roughly two-thirds of all spiral galaxies are barred spirals.

Our own Milky Way galaxy, illustrated in Figure 7, is a barred spiral galaxy approximately 260,000 light years in diameter with 100 to 400 billion stars. It is the second largest galaxy in our Local Group of galaxies, the Adromeda galaxy being the largest. The central bulge of the Milk Way galaxy is around 12,000 light years in diameter while the spiral arms are only about 1,000 light years thick. Our Solar System is located at a radius approximately 27,000 light-years from the galactic center and is on the inner edge of the Orion Arm as shown in Figure 7. Surrounding the galactic disk is a spherical galactic halo of stars and globular clusters extending out over 300,000 light years from the center of the galaxy. The galactic bulge and halo contain primarily Population II stars while the spiral arms are home to predominately Population I stars. A massive black hole 4 million times the mass of the Sun is located at the center of the galaxy.

Figure 5 Spiral Galaxy (source: Wikipedia)

Figure 6 Barred Spiral Galaxy

Figure 7

Figure 7 Milky Way Galaxy (source Astronomy) page 27

### 6.1.6.3 Irregular Galaxies

Irregular galaxies do not have a distinct shape. They are often chaotic in appearance without a central bulge or spiral arms. An example of an irregular galaxy is shown in Figure 8. These galaxies were abundant in the early universe before elliptical and spiral galaxies developed. Today irregular galaxies are thought to make up about one quarter of the galaxies in the universe. Some irregular galaxies may have once been spiral or elliptical galaxies that were deformed by uneven external gravitation forces such as a close encounter with a much larger galaxy. Irregular galaxies are often small, about one tenth the mass of the Milky Way galaxy, and are easily distorted by such encounters.

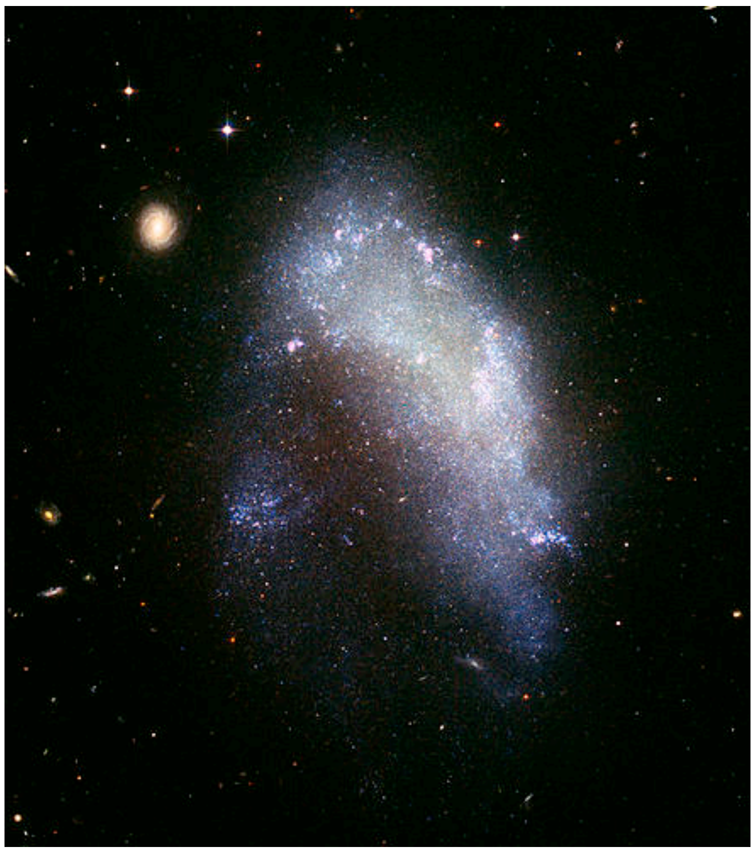

Figure 8 An Irregular Galaxy (source: Wikipedia)

### 6.1.6.4 Globular Clusters

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A globular cluster is a spherical collection of stars. Globular clusters are very tightly bound by gravity, which gives them their spherical shapes and high stellar densities toward their centers.

Globular clusters are generally composed of hundreds of thousands of low-metal, old stars.

Globular clusters normally consist of Population II stars, which have a low proportion of elements other than hydrogen and helium when compared with Population I stars such as the Sun.

They are free of gas and dust and it is presumed that all of the gas and dust was long ago either turned into stars or blown out of the cluster during the initial burst of star formation.

The type of stars found in a globular cluster are similar to those in the bulge of a spiral galaxy but confined to a volume of only a few million cubic parsecs.

Globular clusters can contain a high density of stars; on average about 0.4 stars per cubic parsec, increasing to 100 or 1000 stars per cubic parsec in the core of the cluster.[35] The typical distance between stars in a globular cluster is about 1 light year,[36] but at its core, the separation is comparable to the size of the Solar System (100 to 1000 times closer than stars near the Solar System).[37]

Globular clusters are fairly common; there are over 150[2][3] known in the Milky Way, with possibly many more still to be found.[4] The Andromeda Galaxy, comparable in size to the Milky Way, may have as many as 500.[5] Some giant elliptical galaxies (particularly those at the centers of galaxy clusters), such as M87, have as many as 13,000 globular clusters.

Globular clusters in spiral galaxies are mostly found in the galactic halo. Globular clusters tend to be older, more massive, denser, and contain fewer heavy elements than open clusters, which are generally found in the disks of spiral galaxies.

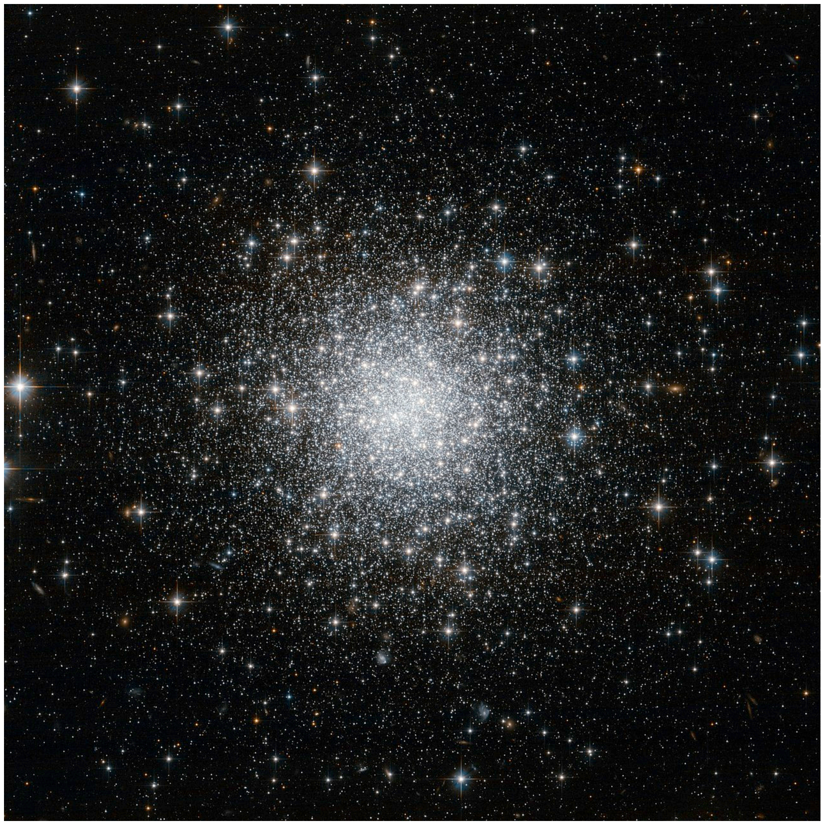


Figure 9 Globular Cluster (source: NASA Hubble)

#### 6.1.6.5 Open Clusters

### 6.1.6.6 Molecular Clouds

### 6.1.6.7 Galactic Groups

A collection of neighboring galaxies is defined as a group. Typically a group contains less than 60 galaxies in a region 6 to 12 million light years across. At least 50 % of the galaxies in the local universe belong to groups.

A compact group is a small number of galaxies, typically around five, in close proximity and relatively isolated from other galaxies and formations. The visible mass of many compact groups is significantly less than that needed to gravitationally hold the group together. The missing mass is composed of dark matter which seems to be abundant throughout a compact group.

The Local Group is the galaxy group that includes our Milky Way galaxy. It is roughly 10 million light years across and is believed to contain around 54 galaxies. The Andromeda and the Milky Way galaxies are the two largest galaxies in the group, both being spiral galaxies with their own systems of small satellite galaxies. The Andromeda and the Milky Way galaxies are separated by 3 million light years and are moving toward one and other at a speed of about 123 km/sec. The Triangulum Galaxy, also a spiral galaxy, is the third largest member of the Local Group. It and Andromeda may be companion galaxies. The two galaxies experienced a close passage 2 – 4 billion years ago which triggered star formation across the Andromeda disk. The Local Group is part of the larger Virgo Supercluster.

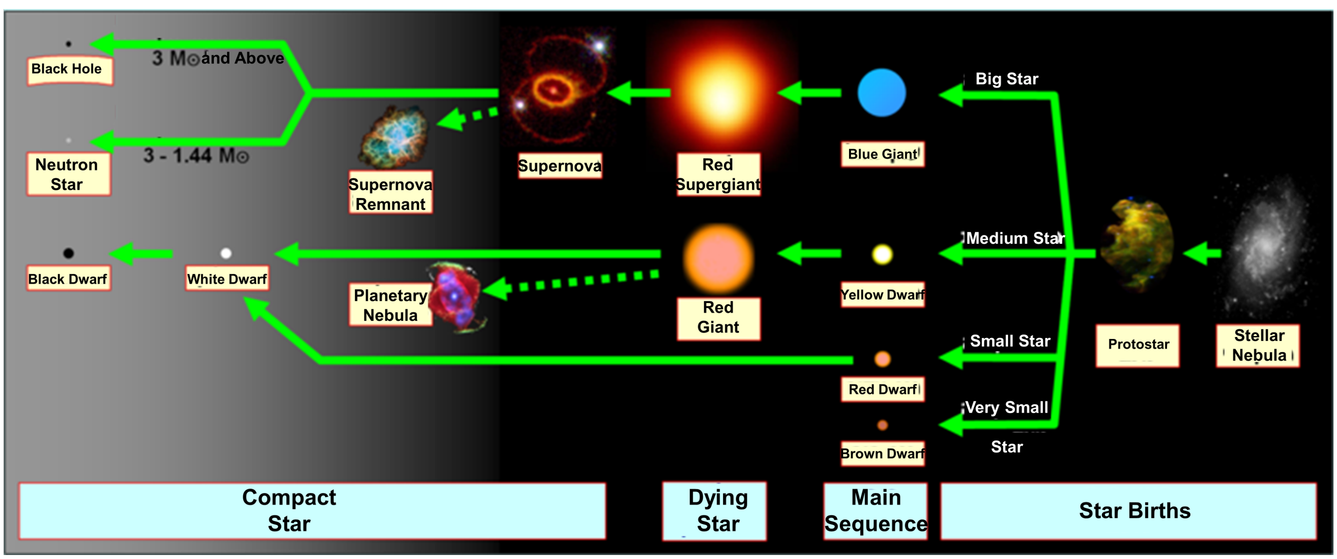
### 6.1.6.8 Galactic Clusters and Super-clusters

A cluster is made up of hundreds, or even thousands, of galaxies that are bound together by gravity.

Superclusters are even larger. A supercluster typically contains a large number of both clusters and galactic groups all of which are held together by gravity. Superclusters are the largest known structures in the universe. It is estimated that around 10 million supergroups exist.

The gas that exists between the galaxies of a galactic cluster is called the intracluster medium (ICM). The intracluster medium is composed primarily of ionized hydrogen and helium enriched with small amounts of heavier elements including iron. The ICM density is only about $10^{-3}$ particles per cubic centimeter with a mean free path of roughly one lightyear. Mean free path is the distance a particle travels before colliding with an other particle. Roughly 10% of a cluster's mass is compostd of ICM with its galaxies and stars account for only 1% of the total mass. It is believed that most of the mass in a galactic cluster consists of dark matter.

## 6.2 Evolution of Stars




The above picture, developed by NASA, illustrates the evolution of stars from their birth as protostars, through their main sequence of life, into old age, and finally death.

Stars are classified by their size:

- Very Small Brown Dwarf Stars,
- Small Red Dwarf Stars,
- Medium Yellow Dwarf (like our Sun) Stars, and

- Large Blue Giant Stars

The life span of a star depends on its size. Small stars live a very long time. Giant stars have a relatively short life, as illustrated in the following table.

| Mass (solar masses) | Time (years) | Spectral Type |
|---|---|---|
| 60 | 3 million | O3 |
| 30 | 11 million | O7 |
| 10 | 32 million | B4 |
| 3 | 370 million | A5 |
| 1.5 | 3 billion | F5 |
| 1 | 10 billion | G2 (our Sun) |
| 0.1 | 6 trillion | M7 |

### 6.2.1 Protostar

Gas Nebula

Gas nebula are the birth place of stars. A gas nebula is composed almost entirely of hydrogen gas with small quantities of helium, oxygen, and carbon. Trace amounts of all other elements may also be present. The composition of the universe and most nebula is shown in the following chart.

| Element | Atoms | Atomic Mass |
|---|---|---|
| Hydrogen | 92% | 74% |
| Helium | 7.5% | 24% |

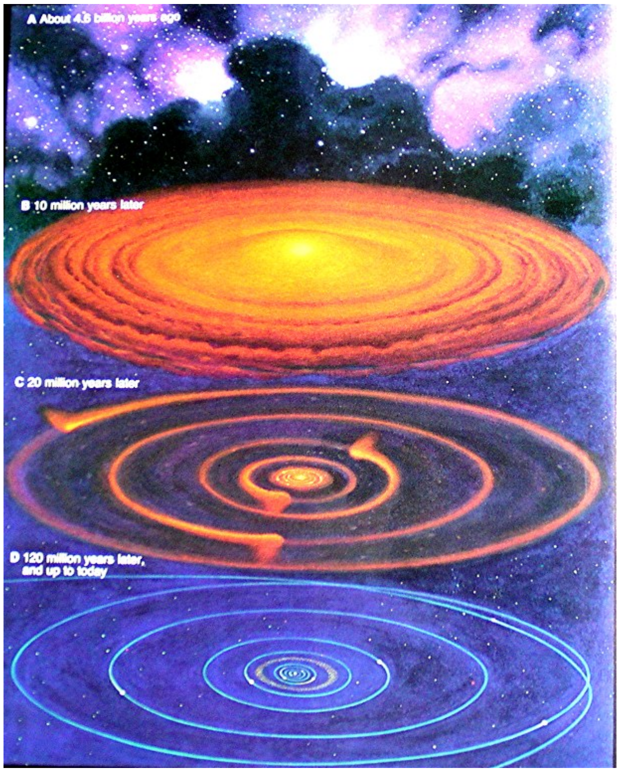
| | | |
|---|---|---|
| Oxygen | | 1% |
| Carbon | | 0.5% |
| All other elements | | 0.5% |

Composition Of The Universe

Virtually all of the hydrogen in the universe was produced in the first few minutes following the massive conversion of energy into light and primitive matter that marked creation of the universe. This massive conversion, known as the Big Bang, occurred around 13.8 billion years ago. Small amounts of helium were also produced at the same time. The first stars are believed to have formed about 400 million years later, that is, around 13.4 billion years ago. All the remaining helium in the universe, plus all other elements, were created in these old stars and their successors as they formed, lived, and finally died.

Under the right set of circumstances some of the gas in a nebula begins to rotate and collapse under its own gravitational force, perhaps as the result of a shock wave from a near by super nova. As the collapse continues, a high concentration of gas forms at the center of the rotating cloud. The gravity associated with this central bulge draws in more gas. The bulge grows in size, its gravity increases, the bulge is compressed in size, and the gas at its center heats up. A protostar is formed.
The process continues until one of two things happen. All of the available gas has been drawn into the protostar ending its growth. Or, if the temperature and pressure within its core is high enough, thermonuclear fusion of hydrogen gas into helium will occur. Energy released by this reaction counter acts the pull of gravity stabilizing the protostar at a particular size and mass. A star is born.

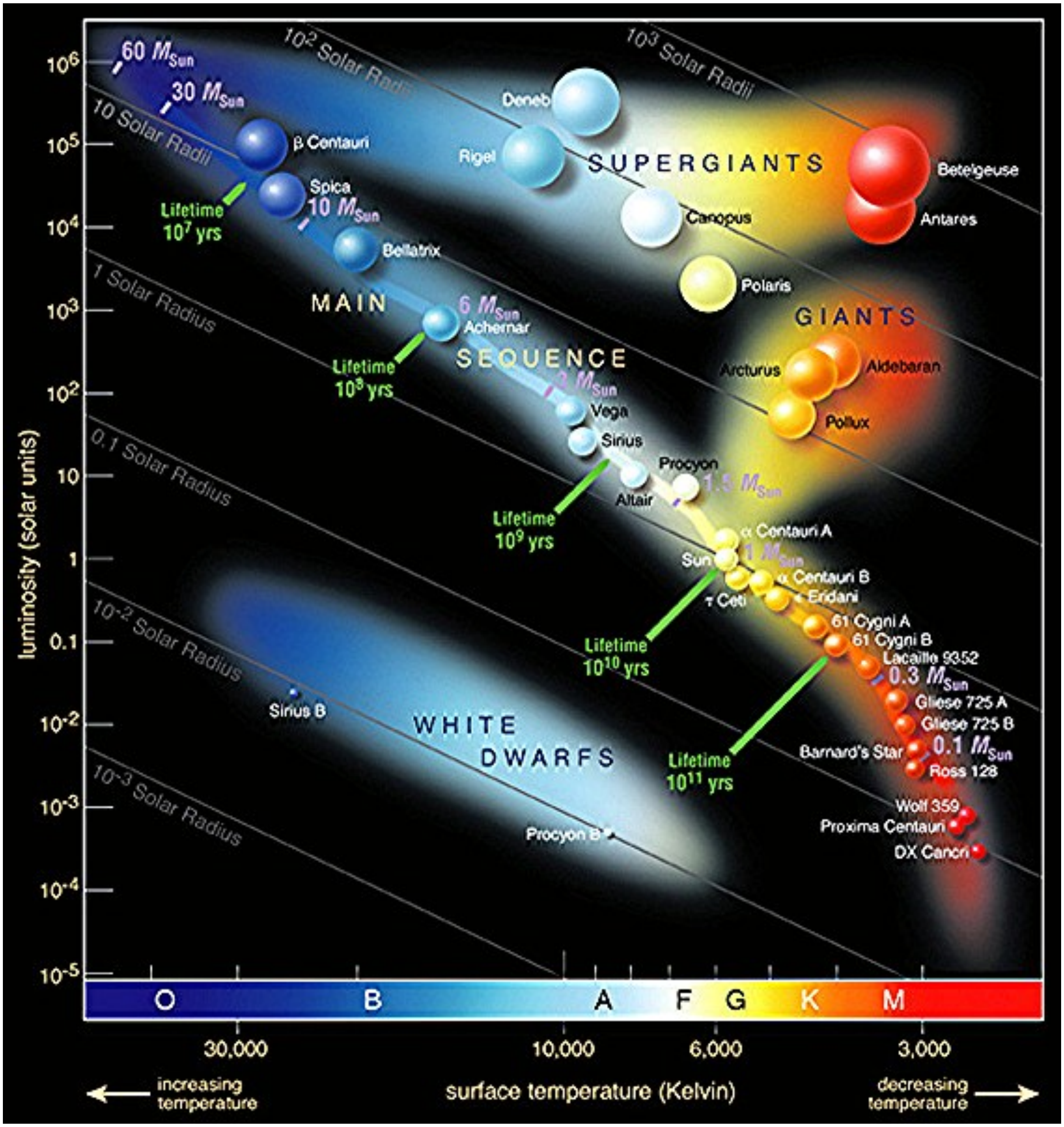
The figure below illustrations the formation of our solar system from a gas cloud around 4.5 billion years ago. Gravitational forces coupled with external forces caused the cloud to rotate and collapse inward. About 10 million years later the cloud had flattened into a hot rotating disk with a central bulge. After an other 20 million years the central bulge had collapsed into a protostar and planets began to form in the outer regions of the disk. Finally, 120 million years later the protostar had ignited into a yellow dwarf star (our Sun) and formation of the solar system was complete.




### 6.2.2 Main Sequence H-R Diagram

The Hertzsprung – Russell (H-R) diagram in the figure below shows the relationship between the absolute magnitudes (luminosities) of stars and their classifications (temperature). The diagram was created around 1910 by Ejnar Hertzsprung and Henry Russell.

The string of stars from the lower right to upper left hand corners of the diagram represents stars during their hydrogen burning Main Sequence of their lives. Stars in the upper right corner are red giant stars nearing the end of their lives. The white dwarf stars in the lower left part of the graph are the remnants of previous stars. The scale along the bottom indicates a star's surface temperature and its approximate color when viewed through a telescope. The letters along the bottom of the chart represent temperature/color classifications. For example, our Sun is classified as a Class G yellow dwarf star with a surface temperature of approximately 6,000 degrees Kelvin. The vertical scale is the luminosity of a star. Our Sun is the reference point with a luminosity of 1.



### 6.2.3 Brown Dwarf

A protostar that is less than roughly 0.08 the mass of the Sun does not produce a high enough temperature or pressure in its core to ignite thermonuclear reaction. Protostars in the range of 0.01 to 0.08 solar masses are classified as brown dwarfs. In comparison, the mass of Jupiter is 0.000954 the mass of the Sun. Thus the smallest brown dwarf is 13 times the mass of Jupiter. A protostar smaller than 0.01 solar masses is classified as either a sub-brown dwarf or a planet.

### 6.2.4 Red Dwarf

Red dwarf stars range in size from roughly 0.1 to 0.5 solar masses. A red dwarf is large enough to produce a temperature of over 10 million degrees in its core, sufficient to ignite thermonuclear fusion. A red dwarf lives an extremely long life on the order of six to twelve trillion years. However, a red dwarf does not have sufficient mass to generate the pressure and temperatures necessary to fuse helium into carbon. When the thermonuclear fusion of the hydrogen in its core is complete, it collapses slowly over several hundred billion years into a white dwarf star.

### 6.2.5 Yellow Dwarf Star

A yellow dwarf star, like our Sun, lives for 10 billion years or more as the thermonuclear reaction within its core slowly proceeds fusing hydrogen into helium. The star reaches the end of its life as the hydrogen within its core becomes depleted. Gravitational forces, no longer balanced by the energy released from its thermonuclear reaction, compresses its core. Temperature and pressure rise within the core until thermonuclear fusion of helium into carbon ignites. The energy released by this second thermonuclear reaction expands the star into a red giant. Despite its now bloated size, the star is not massive enough for thermonuclear fusion of carbon to occur. When the helium fuel within its core is consumed, the star collapses into an extremely dense white dwarf star about the size of Earth. The outer layers of the previous red giant dissipate into space forming a planetary nebula surrounding the white dwarf.

### 6.2.6 Blue Giant Star

A blue giant star, with a mass more than 8 times that of our Sun, lives a very short life typically less than a 100 million years. A blue giant that formed about the time of the last dinosaurs on Earth is probably no longer in existence. The thermonuclear fusion of hydrogen within its core must “burn” at a ferocious rate to release enough energy to balance the enormous gravitational force created by its huge size. When the hydrogen in its core is consumed, the core compresses, temperature and pressure rise quickly, and thermonuclear fusion of helium into carbon ignites. As the helium diminishes, the core compresses more, core temperature reaches 600 million degrees, and fusion of carbon into oxygen, neon, and magnesium begins. The energy released by the thermonuclear reactions cause the star to expand into a super red giant. The cycle continues until at temperatures of several billion degrees iron, cobalt, and nickel form. Even though the star is massive, the core is now so dense that it simply can not be compressed any more. The thermonuclear reaction stops, the outer regions of the star come crashing down onto the core, and the star implodes into a supernova. In the process, atomic nuclei are ripped apart forming free protons and neutrons which are captured by existing nuclei forming heavy elements like gold, lead, and uranium. Depending on the size of the original star, the remaining core degenerates into either a neutron star of a black hole.

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