

Cosmology

Cosmology is the study of the history of the Universe as a whole, both its structure and evolution. The study assumes that over large distances the Universe looks essentially the same from any location (the Universe is homogeneous) and that the Universe looks essentially the same in all directions (the Universe is isotropic). The assumptions are known as the **cosmological principle**. In addition, it is assumed that the same laws of physics hold everywhere in the Universe.

Reliable astronomical records are available for the last 100 years or so. This time interval is minute by astronomical scales, which are typically on the order of 10 billion years. To study the evolution of the Universe, astronomers rely on observations of distant objects. For example, the Andromeda Galaxy (M31) is about 2 million light years away. This means that our photographs of M31 show the galaxy as it was 2 million years ago. The Virgo cluster of galaxies is about 50 million light years away, and the information presently received by our telescopes describe the state of the cluster as it was 50 million years ago. Information received from galaxies that are billions of light years away pertains to the state of these objects as they were billions of years ago, when they were much younger, possibly just forming. Receiving information from distant objects is equivalent to receiving information from the past. This information is vital in reconstructing the evolutionary stages of the galaxies, and the Universe as a whole. As the development of testable hypotheses is limited by our present instrumental capabilities, the theories proposed are speculative.

Hubble's Law

Edwin Hubble determined that there is a relation between the distance of various galaxies and their radial velocity, derived from the Doppler shift of absorption lines in the spectrum of the galaxies. The spectral lines appear red-shifted for all galaxies. This result is very significant: all galaxies are moving away from us, i.e.,

they are receding. The amount of red shift in the absorption is proportional to the distance of the galaxy. The relation, known as Hubble's Law, is given by

$$v = Hd$$

where v is the radial recession velocity, d is the distance, and H is the Hubble constant. Current best estimates of H are around 65 km/s/Mpc. Note that the units of H are actually inverse time. The only galaxies that deviate from Hubble's Law are those so close that gravity dominates their behavior.

Hubble's Law and the Expansion of the Universe

If the galaxies are just moving randomly through space, some near ones would move rapidly and some distant ones would move slowly. About half as many would approach as recede. The fact that all the galaxies are moving away from us does not mean that we are in a special place in the Universe. Hubble's Law could be measured at any location in the Universe, with the same result. This means that space itself is expanding, because the more distant the galaxies are, the faster they are moving away. A two-dimensional analog is the surface of an expanding balloon. If you blow up a balloon part way, and mark little dots on it to indicate galaxies, then continue to blow it up, you will find that the distance between the dots that were most separated increased more than the distance between dots that were close together. In the same way, more distant galaxies move away faster, and so we know that the space in between grew. Fortunately, there is more evidence than simply the Hubble Law, and this evidence has convinced astronomers that the Universe is expanding. This evidence will be discussed later in this chapter.

Hubble's Law and the Age of the Universe

According to Hubble's Law, the recession velocity v divided by the distance d is equal to the constant $1/H$, the same for all galaxies. The ratio v/d gives the time it took for the Universe to expand to the present state. This implies that $1/H$ is the age of the Universe. Using $H = 65$ km/s/Mpc, and values from Appendix 2, we can estimate the age of the Universe to be about 15 billion years.

An important assumption in this estimate is that the rate of expansion is constant. The gravitational interaction between galaxies would tend to slow down the expansion. On the other hand, observations of Type Ia supernovae in very distant galaxies indicate recession speeds lower than predicted by Hubble's Law. But for very distant galaxies, the measured speed corresponds to their speeds in the distant past when the observed spectrum was emitted, i.e., the speeds in the past were slower, so the expansion has accelerated. The expansion age of the Universe is often referred to as the Hubble Time, and depends on the value of Hubble's constant, which may include significant uncertainty.

The uncertainties lead to some paradoxical results. For example, some globular clusters and white dwarfs seem to be older than 15 billion years, which is inconsistent with the Hubble Time. The error may result either from stellar evolution calculations, or in the determinations of distances and velocities, or in the assumptions. The Universe is probably not younger than 15 billion years old. Though it may be older, it's probably not very much older.

Hubble's Law and the Size of the Universe

Using the Hubble Time we can use conversions from Appendix 2 to estimate the size of the Universe as

$$R = ct = 15 \text{ billion light years}$$

The Big Bang

One implication of Hubble's Law is that the entire Universe was once much denser than it is now, so that all the mass was much closer together. But Hubble's Law is not the only piece of evidence.

1. **The Universe contains mass, and gravity is the only force acting on the large scale of distances, and tends to pull mass together.** This observation implies that at least one of three things is true:
 - (i) The Universe is of finite age. Gravity hasn't had enough time yet to collapse the Universe.
 - (ii) The Universe is infinite in extent. There's no center for all of the mass to fall to.
 - (iii) The Universe is expanding faster than its own escape velocity. All the galaxies have enough speed to overcome their mutual gravitational attraction.
2. **The night sky is dark.** This is also known as **Olbers' paradox**. Given an infinite Universe, the night sky ought to be as bright as the day. This is analogous to standing in the forest and looking through the trees. If the forest is large enough, then you observe nothing through the trees but more trees. This implies that at least one of four things is true:
 - (i) The Universe is of finite age. Light hasn't had enough time yet to get here from the most distant places.
 - (ii) The Universe is of finite extent. There aren't actually enough objects out there to fill up the sky.

- (iii) The Universe is expanding/contracting so fast that the light is getting Doppler shifted out of any band of the electromagnetic spectrum we can observe.
 - (iv) Stars are a “new” phenomenon. The Universe only recently started to produce light.
3. **The Universe is expanding.** This implies that
 - (i) The Universe is of finite age.
 - (ii) Because we can measure this, we know that 1(iii) and 2(iii) above are incorrect.
 4. **The cosmic microwave background radiation (CMBR) exists.** It is a perfect blackbody spectrum at 2.74 K. The CMBR is the same (isotropic) to a fairly high degree of precision in every direction in the sky, with only very small deviations (anisotropies). The existence of this background implies that at one time the whole Universe was the same temperature.
 5. **The helium abundance.** The amount of helium in the Universe is about 25% of the total amount of matter. By stellar nucleosynthesis alone, it should be only about 10%. This implies that, at some time, there was a massive burning of H into He.

In summary, the Universe is finite in age. It may or may not be finite in extent. At one time, the Universe was hot, compressed, and all the same temperature. Thus, the Big Bang: a hot beginning.

The Big Bang was the beginning of time and space. Asking what happened before the Big Bang is a lot like asking “Where is north from the North Pole?” Anywhere from the North Pole is south. Any when from the Big Bang is later in time. The Big Bang is the beginning of time. There is no “before.” Where did the Big Bang happen is a similarly impossible question. Space itself was created in the Big Bang. There was no where “before” that. In a sense, the Big Bang happened everywhere. This is why the CMBR is the same everywhere. All the points in the Universe were the same point, and all of them were the same temperature.

The Universe does not have a “center,” whether or not it is infinite. A two-dimensional analog to the finite Universe is the surface of a balloon: all points on the surface are equivalent. There are no edges, and there is no center. Note also that this means that there is no “outside.”

1. There is no center. The Universe is not expanding “away” from anything.
2. There is no “before.” Time began at the Big Bang.
3. The Universe is not expanding “into” anything. Space is created by the expansion of the Universe.

THE RADIATION-DOMINATED UNIVERSE

Astronomers have a good understanding of the beginning of the Universe, all the way back to about 10^{-34} seconds after it began. The grand unified theories (GUT) that describe the ways that the known forces of physics operated in the very early

Universe are not experimentally verifiable by present means. The radiation-dominated era lasted from about 10^{-34} seconds to about 10^5 years. The temperature of the Universe cooled during this time from about 10^{32} K to 10^3 K. The energy of the Universe during this era was mainly in the form of photons; hence the name radiation era. Photons of high energy (gamma rays) can create pairs of particles of matter–antimatter, e.g., electron–positron pairs. The energy of the gamma ray required to produce a particle–antiparticle pair can be calculated from Einstein’s mass–energy formula: $E = mc^2$, where m is the mass of the particle (also the antiparticle) and c is the speed of light. We can use this equation to estimate the energy and the temperature required for the creation of particle–antiparticle pairs. For example, the gamma ray required to produce an electron–positron pair should be at least equal to $2(m_e c^2)$ plus the kinetic energy of the particles (m_e is the mass of the electron). The factor 2 accounts for the fact that two particles are created. Neglecting the kinetic energy of the particles, and using values from Appendix 2, we can estimate the energy required to be $E = 1.6 \times 10^{-13}$ joules. From Wien’s Law (Chapter 1), a blackbody (the Universe) at temperature T has a wavelength maximum of $\lambda_{\max} \text{ (m)} = 0.0029/T$. Using this value in Planck’s relation for the energy of a gamma-ray photon, we find

$$E = hf = \frac{hc}{\lambda}$$

$$E = \frac{hcT}{0.0029}$$

Solving for the temperature, T , we have

$$T = 0.0029 \frac{E}{hc}$$

$$T = 0.0029 \frac{1.6 \times 10^{-13}}{(6.6 \times 10^{-34} \cdot 3 \times 10^8)} \text{ K}$$

$$T = 2.3 \times 10^9 \text{ K}$$

A similar estimate for protons–antiprotons gives $T = 5 \times 10^{12}$ K.

10^{-6} seconds after the Big Bang. The Universe cooled enough so that the gamma rays no longer had enough energy to make protons, and a few seconds later, the temperature was too low for the creation of electron/positron pairs. Pair annihilation continued. The density of the Universe decreased enough that neutrinos stopped interacting with matter, and propagated almost freely.

1 to > 300 seconds after the Big Bang. The protons and neutrons fused to form deuterium nuclei (heavy hydrogen). The photons still had enough energy to break deuterium apart. At about 100 seconds, the temperature had dropped to 1 billion K, and the deuterons began to survive, since a typical photon no longer had enough energy to tear them apart. Deuterium nuclei fused to form helium (see the proton–proton chain, Fig. 8-1). In addition, minute amounts of lithium and beryllium were formed. The observed abundances of these elements in primordial matter is one of the most important pieces of evidence in support of the Big Bang.

THE MATTER-DOMINATED UNIVERSE

Until 100,000 years after the Big Bang, the amount of energy in the form of radiation far exceeded the amount of energy in the form of mass. Once the temperature falls to a few thousand K, however, two things happen: matter begins to dominate, and the Universe becomes transparent to radiation. Until this time, the Universe was opaque. Astronomers can never observe the first 100,000 years, no matter what technical improvements in telescopes occur. This is the “current” epoch of the Universe. Once the temperature was low enough for atoms to survive, the Universe became transparent. The time when this happened is called the “decoupling epoch” (because the radiation and the matter become mostly decoupled from each other), or the “recombination epoch” (because the electrons and the nuclei “recombine”). Nearly all of the radiation that existed at this time is still traveling through the Universe. This is what we see when we observe the cosmic background radiation—very strongly red-shifted light, which has been traveling through the Universe since about 100,000 years after the Big Bang, and is just now reaching us. Galaxies and stars began to form at about 1 billion years after the Big Bang.

THE CURVATURE OF SPACE-TIME

Space is bent, not just locally by gravity, but possibly in a larger sense, as the entire Universe may have a curvature. There are three possibilities for the curvature of the Universe. Visualizing these curvatures is far easier in two dimensions than in four.

1. **0 curvature (flat).** In two dimensions, this can be visualized as a piece of paper. A flat Universe is infinite. Someone traveling in one direction, just keeps going that way forever and ever, and never comes back around to where they started. But still, there are no boundaries, and therefore no center. Angles in triangles add up to 180° . The circumference of a circle is always $2\pi R$. All of the Euclidean geometry rules apply.
2. **Positively curved.** In two dimensions, this can be visualized as the surface of a sphere. In this case, the Universe is finite, yet unbounded. Someone traveling in one direction long enough comes back to where they started. In positively curved space, there are no straight lines. The shortest distance between two points is along a great circle. The circumference of circles is $< 2\pi R$. The sum of the angles in a triangle adds up to more than 180° .
3. **Negatively curved.** In two dimensions, this is often called saddle shaped. Like flat space, negatively curved space is infinite in extent, and has no boundaries. In this kind of space, the angles of a triangle add up to **less** than 180° and the circumference of a circle is $> 2\pi R$.

General relativity says that space is curved by the presence of matter. Therefore, the density determines the curvature. If the actual density of the Universe, ρ , is larger than a critical density, ρ_c , then the Universe will have positive curvature. If

$\rho < \rho_c$, then the Universe will have negative curvature. If $\rho = \rho_c$, then the Universe will be flat. The critical density is extremely small ($\sim 10^{-26}$ kg/m³). The most recent results indicate that the density of the Universe is pretty close to flat, and ρ/ρ_c is between 0.1 and 2. That is, the density is close to the critical density. ρ/ρ_c is also known as Ω_0 (pronounced “omega-naught”).

The future of the Universe depends on the density, and therefore on the curvature. If astronomers can determine either the density or the curvature, then they can predict how the Universe will end. Hubble’s constant determines the expansion rate of the Universe, and the average density describes the self-gravitation and curvature. If H is small, and the density is large, the Universe will recollapse. If H is large, and the density is small, the Universe will keep expanding indefinitely. The dividing line between the two occurs when $\Omega_0 = 1$, where the Universe expands until it reaches equilibrium, then stops.

THE BIG CRUNCH

If $\Omega_0 > 1$, then the Universe will slow down, stop expanding, and begin to contract. As this occurs, the nearby galaxies will become blue-shifted. The more distant galaxies will still appear as they were in the past, before contraction began. However, as time passes, more and more distant galaxies will begin to be blue-shifted, until we are observing the Hubble Law in reverse.

Gravity accelerates the collapse, and the density and the temperature of the Universe rise. Eventually, the density and temperature get so high that the Universe can “re-explode,” forming a new Big Bang.

THE BIG FREEZE

If $\Omega_0 < 1$, the Universe will expand indefinitely. Binary stars and galaxy clusters collapse into each other, and the stars gradually burn out, and form black holes. On time scales of 10^{32} years, protons in the Universe will decay into radiation. All particles and black holes will “evaporate” over time. Eventually, all the mass in the Universe disappears. All that is left is radiation, which reddens and weakens forever.

INFLATION

While the Big Bang model is successful in explaining many things about the Universe, it fails to explain three major observations:

1. The extreme uniformity of the CMBR in different regions of space, which were widely separated even when the Universe first became transparent. If these regions were widely separated, how did they come to the same temperature? This is the horizon problem.
2. The value of Ω_0 should remain either greater than or less than 1. The $\Omega_0 = 1$ case is sensitive to small perturbations, and is unstable. Any deviation

from flatness should have grown to noticeable extremes by now. This is the flatness problem.

3. The existence of large-scale structure, like walls of clusters of galaxies and voids, which are unexplained in the basic Big Bang theory. This is the structure problem.

Inflation is an adjustment to the basic Big Bang which has been proposed in order to solve these problems. Essentially, inflation removes the assumption that the Universe has always expanded at the same rate. Inflation says that between about 10^{-34} seconds and 10^{-32} seconds after the Big Bang, the Universe underwent an extremely accelerated expansion, caused by the separation of various fundamental forces into individual forces. Prior to this time, these three forces (called electromagnetic, strong, and weak) were unified at the higher temperatures and pressures, and indistinguishable from one another, because they have precisely the same strengths. This rapid period of expansion solves the three problems remaining in the Big Bang.

Adding inflation to the Big Bang theory means that the Universe prior to 10^{-34} seconds was much denser than previously thought. This solves the horizon problem. With inflation, the regions of space that emitted the CMBR were actually quite close together when the Universe became transparent. Therefore it is reasonable that they might have been the same temperature, since they could exchange heat quite easily.

The flatness problem is solved by inflation because during that rapid expansion, the Universe expanded faster than the speed of light, so a large fraction of the Universe now exists beyond what will ever be observable. Consider yourself on the Earth. You can see about 1 mile all around you, and the Earth looks pretty flat on that scale. However, if the Earth were smaller, you would see significant curvature over the same 1 mile scale. In the same way, because our view of the Universe is limited, we see that it is locally quite flat, even if on larger scales (or when the whole Universe was smaller), it had noticeable positive or negative curvature.

Minute deviations from uniformity that existed prior to inflation were magnified during inflation. The process occurred so quickly that the non-uniformities would not have had time to become “smoothed out,” and imprinted themselves on the large-scale structure of the Universe.



Solved Problems

- 11.1. Suppose that the Hubble constant is found to be 70 km/s/Mpc. What is the Hubble time for this value of the Hubble constant?

The Hubble Time is given by $1/H$. First, let's convert H into units of time. (Recall that $1 \text{ pc} = 3.09 \times 10^{13} \text{ km}$.)

$$\begin{aligned} H &= 70 \text{ km/s/Mpc} \\ H &= 70 \text{ km/s/Mpc} \cdot (1 \text{ Mpc}/10^6 \text{ pc}) = 70 \times 10^{-6} \text{ km/s/pc} \\ H &= 70 \times 10^{-6} \text{ km/s/pc} \cdot (1 \text{ pc}/3.09 \times 10^{13} \text{ km}) \\ H &= 22.65 \times 10^{-19} \text{ s}^{-1} \end{aligned}$$

Now, invert to find the Hubble Time.

$$\begin{aligned} \frac{1}{H} &= \frac{1}{70 \text{ km/s/Mpc}} \\ \frac{1}{H} &= \frac{1}{22.65 \times 10^{-19} \text{ s}^{-1}} \\ \frac{1}{H} &= \frac{1}{22.65} \times 10^{19} \text{ s} \\ \frac{1}{H} &= 0.04414 \times 10^{19} \text{ s} \\ \frac{1}{H} &= 4.414 \times 10^{17} \text{ s} \end{aligned}$$

Convert the seconds to years, and truncate to the correct number of significant figures (recall that $1 \text{ yr} = 3.16 \times 10^7 \text{ s}$).

$$\begin{aligned} \frac{1}{H} &= 4.414 \times 10^{17} \text{ s} \cdot (1 \text{ yr}/3.16 \times 10^7 \text{ s}) \\ \frac{1}{H} &= 1.397 \times 10^{10} \text{ yr} \\ \frac{1}{H} &= 13.97 \times 10^9 \text{ yr} = 13.97 \text{ billion years} \\ \frac{1}{H} &= 14 \text{ billion years} \end{aligned}$$

A value of 70 km/s/Mpc gives a Hubble Time of 14 billion years.

11.2. Using the Hubble Law, we can derive an age of the Universe of about 15 billion years. But this assumes the Universe is empty, so that gravity is not slowing the expansion. If the Universe is flat, and the density is the same as the critical density, the age of the Universe is about two-thirds of the Hubble Time. What is the value of the Hubble constant in a flat, critical density Universe?

$$\begin{aligned} \text{Age} &= 2/3 \cdot \frac{1}{H} \\ H &= 2/3 \cdot \frac{1}{\text{Age}} \\ H &= 2/3 \cdot \frac{1}{15 \times 10^9 \text{ yr}} \\ H &= \frac{2 \times 10^{-9}}{3 \cdot 15 \text{ yr}} \\ H &= 0.0444 \times 10^{-9} \text{ yr}^{-1} \end{aligned}$$

Fix the units:

$$H = 0.0444 \times 10^{-9} \text{ yr}^{-1}$$

$$H = 0.0444 \times 10^{-9} \text{ yr}^{-1} \cdot (1 \text{ yr}/3.16 \times 10^7 \text{ s})$$

$$H = 0.0141 \times 10^{-16} \text{ s}^{-1}$$

$$H = 0.0141 \times 10^{-16} \text{ s}^{-1} \cdot (3.09 \times 10^{19} \text{ km/Mpc})$$

$$H = 0.0434 \times 10^3 \text{ km/s/Mpc}$$

$$H = 43.4 \text{ km/s/Mpc}$$

For a 15-billion-year-old flat, critical density Universe, the Hubble constant has a value of 43 km/s/Mpc. This is at the low end of current estimates of the Hubble constant.

- 11.3.** Suppose we observe a galaxy 500 Mpc away, which is moving away from us with a velocity of 30,000 km/s. If the speed has been constant throughout time, when did the Big Bang happen?

The key point is that when the Big Bang happened, the galaxy would have been at 0 distance from the Milky Way. We begin with the basic equation:

$$t = \frac{d}{v}$$

$$t = \frac{500 \text{ Mpc}}{30,000 \text{ km/s}}$$

$$t = 0.01667 \text{ Mpc} \cdot \text{s/km}$$

Now fix the units:

$$t = 0.01667 \text{ Mpc} \cdot \text{s/km} \cdot (3.09 \times 10^{19} \text{ km/Mpc})$$

$$t = 0.0515 \times 10^{19} \text{ s}$$

$$t = 0.0515 \times 10^{19} \text{ s} \cdot (1 \text{ yr}/3.16 \times 10^7 \text{ s})$$

$$t = 0.0163 \times 10^{12} \text{ yr}$$

$$t = 16 \times 10^9 \text{ yr} = 16 \text{ billion years}$$

If a galaxy like this were observed, it would imply that the Big Bang happened approximately 16 billion years ago. This is comparable to current estimates of the age of the Universe, so it would not be unusual to observe a galaxy at this distance with this recession velocity.

- 11.4.** If $H = 65 \text{ km/s/Mpc}$, the critical density is $8 \times 10^{-27} \text{ kg/m}^3$. How much mass would be enclosed in a sphere with the radius of the Earth's orbit ($R = 1 \text{ AU}$)? Assume a flat Universe.

$$V = \frac{4}{3} \cdot \pi \cdot R^3$$

$$V = \frac{4}{3} \cdot \pi \cdot (1.5 \times 10^{11} \text{ m})^3$$

$$V = 14.137 \times 10^{33} \text{ m}^3$$

Multiply the density by the volume to get the mass enclosed ($\rho = \rho_c$ in a flat Universe):

$$m = \rho \cdot V$$

$$m = (8 \times 10^{-27} \text{ kg/m}^3) \cdot (14.137 \times 10^{33} \text{ m}^3)$$

$$m = 113 \times 10^6 \text{ kg}$$

The mass enclosed in a sphere of radius 1 AU is 100 million kilograms. This mass is quite small when compared to the mass of the Earth ($M_E \sim 6 \times 10^{24}$ kg). This means that the Universe has a **really** low density.

- 11.5.** Compare flat universes with positively curved universes. Are they closed? finite? do they have centers?

A flat universe is infinite, and open. Because it is infinite, it doesn't make sense to ask whether it has a center.

Conversely, a positively curved universe is finite and closed. But it also has no center, and is unbounded (has no edges).

- 11.6.** If the density of the Universe is less than critical ($\rho < \rho_c$), what is the curvature? What is the ultimate fate of the Universe in this case?

If the density is less than the critical density, then $\Omega_0 < 1$, so the curvature is negative. Since there is not enough gravity to reverse the expansion, the Universe will continue expanding forever.

- 11.7.** Explain how to use globular clusters to put a lower limit on the age of the Universe (see also Problem 8.19 in Chapter 8).

Globular clusters are made of stars that were all born at the same time. In addition, all the stars are approximately the same distance away, so that differences in their apparent magnitudes represent differences in their absolute magnitudes. Therefore, we can make an H-R diagram, plotting the magnitude of the stars versus their color or spectral type. From the location of the main sequence turn-off, we can find the age of the globular cluster. Since the globular clusters could not have been created before the Universe, the Universe must be at least as old as the oldest globular clusters.

- 11.8.** Why were no significant amounts of elements heavier than lithium or beryllium formed in the Big Bang?

In the Big Bang, conditions were very hot. It was too hot for elements heavier than lithium to live very long (they were almost immediately torn apart by photons). Then the Universe cooled very quickly, over just a few hundred seconds. As soon as it was cool enough for the elements to survive, it was too cool to make them.

- 11.9.** If a gas of temperature 3000 K emitted CMBR, why does the CMBR have the spectrum of a 2.728 K blackbody?

Since the radiation was emitted, space has expanded, red-shifting the radiation, so that it now represents a much cooler blackbody.

- 11.10.** Astronomers observe several galaxies in the Local Group that actually approach the Milky Way. The Andromeda Galaxy is the largest of these. Does this mean that the Hubble Law is incorrect? Why or why not?

No, this does not disprove the Hubble Law. On small scales, such as the size of the Local Group, the behavior of space is dominated by gravity, rather than by expansion.

Life in the Universe

WHAT IS LIFE?

1. **Organization.** Life is organized and structured. This is true at all levels: molecular, cellular, organ, individual, etc. To maintain this organization requires the use of energy (metabolism).
2. **Reproduction.** Things that are alive reproduce.
3. **Responds.** Life responds to stimuli, such as excessive heat or cold, light or darkness, etc.

FAVORABLE CONDITIONS FOR LIFE

Life on Earth is based on amino acids, which are carbon-based molecules. Water seems also to be a crucial factor. Water is an excellent solvent. It can dissolve materials so that they can move and interact. Water is also a liquid at a wide range of temperatures (0–100°C), and it can act as a temperature regulator as it absorbs heat on evaporation and releases heat on condensation. Other liquids might serve these functions for life elsewhere, such as ammonia and methyl alcohol. Ammonia, however, has a smaller range of temperatures over which it is a liquid, and methyl alcohol has a low heat of vaporization, which means that methyl alcohol is not a good temperature regulator. Thus, abundance of carbon and water would indicate conditions favorable to life.

Planets and moons have lots of carbon. Mars may at one time have had liquid water, and so it seems a good place to look for fossils of life. Europa currently has lots of liquid water, so it might be a good place to look for current life.

MARS

The first attempt to find life on Mars, carried out by the Viking lander, was inconclusive. The lander carried out three tests, two of which had negative results, and the third of which had a positive result. This has been interpreted to mean that there is some sort of chemical (non-biological) process occurring that we do not understand.

On the other hand, in 1996, scientists announced that they may have found evidence of life in a Martian meteorite. Inside, they found organic compounds, which increased in number closer to the center of the meteorite. This is unusual. Organic compounds are often found in space, and in meteorites, but in most meteorites the number decreases near the center. Also, some tube-like structures were seen near the organic compounds that resemble fossils of living organisms. However, there are other, non-biological processes that can form similar tubules, and the organic compounds are the same as those found elsewhere.

EUROPA

Voyager images of Europa show cracks and distortions that look much like the patterns seen in the cracked ice over the Arctic Ocean. There are objects that look like icebergs tilted on their sides, and Europa's density profile (mapped out by Voyager and Galileo) is consistent with a liquid water ocean under a crust of ice. The cracks may persist for centuries before the ice fills them in again, allowing sunlight to penetrate to the water below. Also, Europa is heated from within by tidal interactions, which also provide a source of energy.

ELSEWHERE

The Drake equation gives an estimate of the number of civilizations, N , in our galaxy that are able to communicate with others:

$$N = R_* f_p n_e f_i f_c L$$

- R_* is the rate at which stars form in the galaxy: a few per year.
- f_p is the fraction of stars with planets. This number is probably about 0.1.
- n_e is the number of Earth-like planets (or moons) per planetary system where life can survive. This number is probably in the range from 0.1 to 1.
- f_i is the fraction of these planets on which life actually arises. Estimates range from 10^{-3} to 1.
- f_i is the fraction of life species on a planet that develop some form of intelligence. Estimates range from 10^{-6} to 1.
- f_c is the fraction of intelligent life forms that actually develop communication across space. On the Earth, this fraction is a number close to 1.
- L is the length of time the communicating society exists. For Earth, this number is at least 100 years. Guesses for the maximum of this number go up to 10^9 years.

Obviously, our limited knowledge of the factors in the Drake equation introduce substantial uncertainty in the result. The minimum number N must be 1, since we are here.

LOOKING FOR LIFE

From another star, the Sun would look like a variable radio source, since the Earth and the Sun would be indistinguishable from that distance. The signal would vary with a period of 24 hours, as the Earth rotates on its axis. So, we look for life in a similar way. The Arecibo Radio Telescope is used to look for periodic radio signals from stars.

The Arecibo Radio Telescope was also used to send signals to other stars, but the light travel time is so long that a response is not expected for at least several thousand years. It is important to note that the entire discussion above relates only to our own galaxy. Even if the probability of life in the Galaxy turns out to be small, the probability of life in the Universe may still be large, since there are so many galaxies.



Solved Problems

- 11.11.** Suppose that R_* is 5/year, f_p is 0.5, n_e is 2, f_1 is 1/1,000, f_i is 1/1,000, f_c is 1, and L is 1,000 years. What is N ? Is this reasonable?

Drake's equation is the product of all these values,

$$\begin{aligned} N &= R_* f_p n_e f_1 f_i f_c L \\ N &= 5 \cdot 0.5 \cdot 2 \cdot \frac{1}{1,000} \cdot \frac{1}{1,000} \cdot 1 \cdot 1,000 \\ N &= 5 \times 10^{-3} \end{aligned}$$

Using these values, N is a completely unreasonable 5×10^{-3} . N must be at least 1 to account for the fact that humans exist.

- 11.12.** Of the values in Problem 11.11, the most uncertain values are f_1 and f_i . How much must these number be changed in order to make $N > 1$?

If each of these quantities increased to 1/10, then $N = 50$, which is greater than 1, and therefore acceptable in principle.

- 11.13.** Proxima Centauri is the closest star to the Sun. It is 1.3 pc away. How long would it take for us to receive a reply to a message sent to Proxima Centauri?

The light would have to travel to Proxima Centauri, and return, so it would have to travel 2.6 pc all together. Using the relationship between time, distance, and velocity gives

$$\begin{aligned} t &= \frac{d}{v} \\ t &= \frac{2.6 \cdot 3 \times 10^{16} \text{ m}}{3 \times 10^8 \text{ m/s}} \\ t &= 2.6 \times 10^8 \text{ s} \\ t &= 8.2 \text{ yr} \end{aligned}$$

It would take 8.2 years for a message to be sent and replied to from Proxima Centauri.



Supplementary Problems

- 11.14.** Suppose that $H = 65 \text{ km/s/Mpc}$, so that $\rho_c = 8 \times 10^{-27} \text{ kg/m}^3$. You observe the density of the Universe to be $7.9 \times 10^{-27} \text{ kg/m}^3$. What is the curvature?

Ans. Negative

11.15. Suppose the density of the Universe is 10^{-26} kg/m³. How many hydrogen atoms are in a box 1 m on a side?

Ans. Nearly 6

11.16. What is the peak wavelength of radiation produced by a 3,000 K blackbody? What type of radiation is this?

Ans. 9.66×10^{-7} m, infrared

11.17. What is the speed of protons in the early moments after the Big Bang, when the temperature was 10 billion K? (Use thermal speed from Chapter 1.)

Ans. 1.4×10^7 m/s

11.18. How much kinetic energy does the proton in Problem 11.17 have?

Ans. 1.7×10^{-13} J

11.19. When the proton in Problems 11.17 and 11.18 meets an antiproton, what is the frequency of the radiation production?

Ans. 4.6×10^{23} Hz

11.20. What is the wavelength of a typical photon produced by a gas of 1 billion K? What is the frequency of this photon?

Ans. 2.9×10^{-12} m, 1×10^{20} Hz

11.21. How much energy does the typical photon of Problem 11.20 have?

Ans. 6.85×10^{-14} J

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APPENDIX 1

Physical and Astronomical Constants

Symbol	Value	Meaning or other name
π	3.1415926	pi
c	2.9979×10^8 m/s	speed of light in vacuum
G	6.67×10^{-11} m ³ /kg/s ²	gravitational constant
h	6.6261×10^{-34} W · s ² (W · s ² = J · s)	Planck's constant
m_e	9.1094×10^{-31} kg	mass of electron
m_H	1.6735×10^{-27} kg	mass of hydrogen atom
σ	5.6705×10^{-8} W/m ² /K ⁴	Stefan-Boltzmann constant
k	1.3805×10^{-23} W · s/K	Boltzmann constant
M_{Earth}	5.9742×10^{24} kg	mass of Earth
M_{Sun}	1.9891×10^{30} kg	mass of Sun
R_{Earth}	6.378×10^6 m	radius of Earth (at equator)
R_{Sun}	6.9599×10^8 m	radius of Sun
L_{Sun}	3.8268×10^{26} W	luminosity of Sun
AU	1.496×10^{11} m	astronomical unit
pc	3.0857×10^{16} m	parsec
ly	9.4605×10^{15} m	light year

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APPENDIX 2

Units and Unit Conversions

Symbol	Equivalent unit	Name, What does it measure?
nm	1×10^{-9} m	nanometer, length
μm	1×10^{-6} m	micrometer (micron), length
cm	1×10^{-2} m; 0.3937 inches	centimeter, length
m	3.28 feet	meter, length
km	1×10^3 m; 0.6214 miles	kilometer, length
AU	1.496×10^{11} m	astronomical unit, length
ly	9.4605×10^{15} m	light year, length
pc	3.0857×10^{16} m; 3.26 ly; 206,265 AU	parsec, length
Mpc	10^6 pc	megaparsec, length
kg	2.2046 pounds (on Earth)	kilogram, mass
yr	3.16×10^7 s	year, time
M_{Earth}	5.9742×10^{24} kg	mass of Earth
M_{Sun}	1.9891×10^{30} kg	mass of Sun
R_{Earth}	6.378×10^6 m	radius of Earth (at equator)
R_{Sun}	6.9599×10^8 m	radius of Sun
L_{Sun}	3.8268×10^{26} W	luminosity of Sun

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Algebra Rules

SCIENTIFIC NOTATION

Scientific notation is a way of writing numbers in shorthand. For example, $300 = 3 \times 10^2$ (to make the number 300, multiply 3 by 10 twice). Combining numbers in scientific notation means following three rules.

1. **Adding and subtracting.** Numbers written in scientific notation can only be added and subtracted if the exponent on the 10 is the same. Then, simply add or subtract the numbers before the \times . For example,

$$3 \times 10^8 + 4 \times 10^8 = 7 \times 10^8$$

$$3 \times 10^8 - 4 \times 10^8 = -1 \times 10^8$$

and

$$\begin{aligned} 3 \times 10^8 + 4 \times 10^9 &= 3 \times 10^8 + 40 \times 10^8 \\ &= 43 \times 10^8 \\ &= 4.3 \times 10^9 \end{aligned}$$

2. **Multiplying.** Multiply the numbers before the \times and add the exponents.

$$(3 \times 10^8) \cdot (4 \times 10^7) = 12 \times 10^{15}$$

3. **Dividing.** Divide the numbers before the \times and subtract the exponents.

$$\begin{aligned} (3 \times 10^8)/(4 \times 10^7) &= 0.75 \times 10^1 \\ &= 7.5 \end{aligned}$$

SIGNIFICANT DIGITS

The final answer should always have only as many significant digits as the measurement with the **least** number of significant digits.

$$(2.81 \times 10^2) \cdot (8 \times 10^5) = 2 \times 10^8$$

ORDER OF OPERATIONS

Powers are performed first, then multiplications and divisions, and finally additions and subtractions. (Operations in parentheses are carried out first.)

$$5 + 6 \cdot 7 = 47$$

$$(5 + 6) \cdot 7 = 77$$

$$(5 + 6)^7 = 2 \times 10^7$$

$$5 + 6^7 = 3 \times 10^5$$

UNITS

Just as numbers which appear in both the numerator and denominator of a fraction cancel, so do units.

$$(N \cdot m/m) = N$$

$$(km/s) \cdot (Hz/km) = 1/s^2$$

LOGARITHMS

Any number can be written as 10^x , if we allow x to be a non-integer:

$$4 = 10^{0.6}$$

To invert this, use the log function on your calculator:

$$0.6 = \log(4)$$

or

$$42 = 10^{1.62}$$

$$1.62 = \log(42)$$

History of Astronomy Timeline

Period	Dates	Who	What
Ancient	35,000 BC	Lascaux Caves	Include Sun/star symbols
	7,000 BC	Abris de las Vinas (Spain)	First known lunar phase diagram
	3,500 BC	Proto-Europeans	Began building megalithic stone structures such as Stonehenge
	3,000 BC	Babylonians/Egyptians	Identified constellations
	2,000 BC	Babylonians	Recorded motions of planets
		Babylonians/Egyptians	Identified ecliptic
	500 BC	Greeks	Widely understood that the Earth and Moon are spherical
	293–273 BC	Eratosthenes	Measured circumference of the Earth
	200 BC	Babylonians	Predicted lunar/solar eclipses
	200 BC	Babylonians/Egyptians	Clearly recognized precession of Earth's poles
Medieval	4th–11th century	Arabs and Persians	Intensive development of astronomy; star charts and catalogues, planets, and the Moon movement; better estimations of the Earth size and calendar improvement
	813	Al Mamon	Founded the Baghdad school of astronomy
	813	Ptolemy	<i>Mathematike Syntaxis</i> by Ptolemy is translated into Arabic as al-Majisti (Great Work), later called by Latin scholars <i>Almagest</i>
	903	Al-Sufi	Constructed his star catalog
	1054	Chinese astronomers	Observe supernova in Taurus (now this supernova remnant is known as the Crab Nebula (M1))
Renaissance	1543	Copernicus	Published <i>De Revolutionibus Orbium Coelestium</i> in which he provided mathematical evidence for the heliocentric theory of the Universe
	1572	Tycho Brahe	Discovered a supernova in the constellation Cassiopeia
	1576	Tycho Brahe	Founded the observatory at Uraniborg

Period	Dates	Who	What
	1582	Pope Gregory XIII	Introduced the Gregorian calendar
	1595	David Fabricius	Discovered the long-period variable star in the constellation Cetus, named Mira Ceti
	1600 (Feb. 17)	Giordano Bruno	After 8 years of imprisonment, was charged with blasphemy, immoral conduct, and heresy for challenging the official church doctrine on the origin and structure of the universe and burned at the stake in Campo dei Fiori
	1603	Johann Bayer	Published his star catalog, <i>Uranometria</i> . Introduced the Bayer system of assigning Greek letters to stars—still widely used by astronomers
	1604	Kepler	Discovered supernova in Ophiuchus
	1608	Lippershey	Dutch spectacle maker invented the first telescope
	1609	Galileo	First used the telescope for astronomical purposes: discovered four Jovian moons, observed Lunar craters and the Milky Way
		Kepler	Announced first two laws of planetary motion
	1611	Galileo, Scheiner, and Fabricius	Observed sunspots
	1612	Peiresc	Discovered the Orion Nebula (M42)
	1619	Kepler	Published the Third Law of Planetary Motion in his <i>Harmonice Mundi (Harmony of the World)</i>
	1631	Kepler	Predicted the transit of Mercury, which was subsequently observed by Gassendi
	1632	Galileo	Published his Dialogue on the Two Chief World Systems—the discussion of Ptolemaic and Copernican hypotheses in relation to the physics of tides (the original version, <i>Dialogue on the Tides</i> , was licensed and altered by the Roman Catholic censors in Rome)
	1633	Galileo	Was forced by the Inquisition to recant his theories
	1639	Horrocks	Observed the transit of Venus
	1647	Hevelius	Published a map of the Moon
	1656	Huygens	Discovered the nature of Saturn's rings and Titan—the largest satellite of Saturn
	1659	Huygens	Observed markings on the planet Mars
	1666	Cassini	Observed the polar caps on Mars
	1668	Newton	Built the first reflecting telescope (Newtonian)
	1669	Montanari	Discovered the variable nature of Algol
	1671	Paris Observatory	Founded
	1675	Greenwich Observatory	Founded
		Romer	Measured the velocity of light
		Cassini	Discovered the main division in Saturn's rings
	1683	Cassini	Observed the zodiacal light
Modern	1687	Newton	Published <i>Philosophiæ Naturalis Principia Mathematica</i> establishing the theory of universal gravitation
	1705	Halley	Predicted the return of Halley's comet in 1758
	1725	Flamsteed	The first Astronomer Royal of England, published his star catalog. He introduced star numbering in each constellation in order of increasing right ascension

Period	Dates	Who	What
	1728	Halley	Discovered proper motion
		Bradley	Proposed the theory of the aberration of the fixed stars, including the aberration of light
	1729	Hall	Proposed the principle of the achromatic refractor
	1750	Wright	Speculated about the origin of the solar system
	1755	Kant	Proposed the hypothesis of the origin of celestial bodies
	1758	Palitzsch	Observed previously predicted Halley's comet return.
	1761	Lomonosov	Discovered the atmosphere of Venus
	1781	Messier	Searching for comets, Messier discovered dozens of deep sky objects (galaxies, nebulae, and star clusters) which he compiled in his catalog
	1781	Herschel	Discovered Uranus
	1784	Goodricke	Discovered the variable nature of Delta Cephei
	1789	Herschel	Built a telescope at Slough with a 48-in mirror. Using this telescope he resolved stars in different galaxies
	1796	Laplace	Proposed the Nebular Hypothesis of the origin of the solar system based on the theory of stellar evolution
	1801	Piazzi	Discovered the first asteroid, Ceres
	1802	Herschel	Announced the discovery of binary star systems
		Wollaston	Observed absorption lines in the solar spectrum
	1803		Fall of meteorites at L'Aigle. The explanation of the nature of meteorites is established
	1811	Olber	Proposed the theory of comet tails
	1814	Fraunhofer	Provided a detailed description of the solar spectrum
	1834	Bessel	Inferred that the irregularity of proper motion of Sirius is due to the presence of an invisible companion
	1837	Beer and Madler	Published the first accurate map of the moon
	1838	Bessel	Determined the distance of 61 Cygni. This was the first determination of a stellar distance
	1839–40	Draper	The first application of photography to astronomy—Draper photographed the Moon
	1842	Doppler	Discovered the Doppler effect
	1843	Schwabe	Described the sunspot cycle
	1846	Galle	Discovered the planet Neptune based on its position calculated by the French astronomer Leverrier
	1851	Foucault	Provided evidence for the rotation of the Earth by suspending a pendulum on a long wire from the dome of the Pantheon in Paris
	1859	Kirchoff	Interpreted the dark lines in the Sun's spectrum
	1859–62	Argelander	Published <i>Bonner Durchmusterung</i> (BD)—a catalog of over 300,000 stars
	1862	Clark	Discovered Sirius B based on calculations by Bessel
	1860–63	Huggins	Began the spectral analysis of stars
	1868	Jansen and Lockyer	Observed solar prominences
	1877	Hall	Discovered the Martian satellites Phobos and Deimos
		Schiaparelli	Observed the Martian canals

Period	Dates	Who	What
	1890	Lockyer	Announced his theory of stellar evolution
		Vogel	Discovered spectroscopic binaries
	1894	Percival Lowell	Founded the Flagstaff Observatory in Arizona
	1897	Yerkes Obs.	Founded
20th century	1900	Chaberlin and Moulton	Proposed the new theory of the solar system origin
	1905	Mt. Wilson Obs.	Established exclusively for the study of the Sun
	1905	Einstein	Proposed the basis of the Special Theory of Relativity, first described in his paper <i>On the Electrodynamics of Moving Bodies</i>
	1908	Hertzsprung	Described giant and dwarf stars
		Leavitt	Discovered the period–luminosity relation for Cepheids
	1911–14	Hertzsprung and Russell	Discovered the relationship between spectral type and absolute magnitude (H-R diagram)
	1914	Goddard	Began practical experiments with rockets
	1915	Adams	Discovered White Dwarfs (Sirius B)
	1916	Eddington	Proposed the first premises of the theory of stellar structure
		Einstein	Proposed his General Theory of Relativity
	1918	Shapley	Provided the first model of the Galaxy structure
	1918–24	Cannon	Published the fundamental catalog of star spectra
	1919	Barnard	Published the catalog of dark nebulae
	1920	Slipher	Discovered red shifts in the spectra of galaxies
	1923	Hubble	Proved that the galaxies lie beyond the Milky Way
	1926	Goddard	Fired the first liquid fuel rocket
	1927	Oort	Proved that the center of the galaxy lies in the direction of Sagittarius
	1929	Hubble	Discovered linear relationships between the galaxy distance and its radial velocity, the Hubble Law
	1930	Tombaugh	Discovered Pluto based on Lowell's predictions
	1931	Jansky	Discovered cosmic radio waves
	1937	Reber	Constructed the first radio telescope
	1937–40	Gamow	Proposed the first theory of stellar evolution
	1942	Strand	Speculated that 61 Cygni is attended by a planet.
	1944	Van de Hulst	Suggested that interstellar hydrogen must emit radio waves at 21.1 cm
	1946	Bay	Obtained the first radar images of the Moon
	1947	Ambarcumian	Discovered star associations
	1949	Hale 200-inch	Completed at Mount Palomar
	1951	Ewen and Purcell	Discovered the 21.1 cm hydrogen emission predicted by van de Hulst
	1951–54		Spiral structure of our galaxy determined
	1955		250-foot radio telescope at Jodrell Bank is completed
	1957	Russia	The first artificial satellite launched
	1958	USA	The first American satellite launched
	1959	Russia	Lunik I passes the Moon; Lunik II lands on the Moon

Period	Dates	Who	What
	1961	Gagarin	The first man in space
	1962	Glenn	First American orbital flight
		Russia/USA	Planetary probes: Mars I (Russia) and Mariner II (USA)
			First galactic source of X-ray radiation (Sco X-1) detected
			First quasar (3C273) discovered
	1965	Penzias and Wilson	Discovered cosmic background radiation, providing direct evidence to support the Big Bang Theory
	1966	Russia/USA	First soft landing on the Moon (Luna 9—Russia and Surveyor I—USA). Russian probe lands on Venus
	1967	Bell, Hewish	Discovered pulsars
	1968	Apollo 8: Borman, Lovell, and Anders	First manned flight around the Moon
	1969	Apollo 11: Armstrong and Aldrin	July 20–21: First man on the Moon
	1970	Uhuru	Satellite Uhuru scans the sky in the X-ray range
	1971	Russia	First probes in orbit around Mars and first soft landing on Mars (Mars 3—Russia)
	1971	USA	First manned mechanical vehicle on the Moon (Apollo 15—USA)
	1972		Satellite Copernicus conducts spectroscopic ultraviolet observations of stars and interstellar matter with high resolution The first observations in gamma-radiation range Launch of Pioneer 10—the first probe to Jupiter (USA)
	1973	USA	First images of Jupiter transmitted from close vicinity by Pioneer 10
	1977		Discovery of Uranian rings
	1978		Discovery of Pluto's moon, Charon
	1980	USA	First images of Saturn and its rings transmitted from close vicinity by Voyager 1
	1983		InfraRed Astronomical Satellite scans the sky in the infrared
	1986		January 24: Voyager 2 approaches the planet Uranus January 28: Space shuttle Challenger disaster March: Space probes Vega 1, Vega 2, and Giotto pass near Halley's comet
	1987		February 23: Supernova 1987a in the Large Magellanic Cloud was visible to naked eye
	1988		Discovery of quasars 17 billion light years away
	1989		May 4: Magellan mission to radar map the surface of Venus August 24: Voyager 2 approaches the planet Neptune November 18: NASA launches Cosmic Background Explorer (COBE) satellite
	1990		April 24: space shuttle Discovery puts the Hubble Space Telescope into orbit December 5: the first picture (galaxy NGC 1232 in Eridanus) taken with Keck Telescope is published in the <i>Los Angeles Times</i>
	1991		April 5: Compton Gamma Ray Observatory (GRO) launched October: Galileo passes by the asteroid Gaspra

Period	Dates	Who	What
	1992		<p>April: the Hubble Space Telescope photographs in the Large Magellanic Cloud the hottest star ever recorded (temp. 360,000°F)</p> <p>April 24: COBE proves the existence of temperature fluctuations in the background radiation, which is strong evidence supporting the Big Bang theory.</p> <p>September 16: the discovery of the first object orbiting the Sun beyond the planet Pluto, in the Kuiper Belt</p> <p>September 25: NASA launches the Mars Observer spacecraft to study the atmosphere and surface of Mars</p> <p>October 31: the Vatican (Pope John Paul II) announce that the Catholic Church erred in condemning Galileo's beliefs</p>
	1993		<p>January 31: The Gamma Ray Observatory (GRO) detects the brightest burst of gamma rays ever recorded</p> <p>December: Astronauts aboard space shuttle Endeavour correct the defects in the Hubble Space Telescope</p>
	1994		July 20: Comet Shoemaker-Levy crashes into Jupiter
	1995		December 7: Galileo reaches the planet Jupiter

INDEX

- Absolute magnitude, 127
Absorption lines, 19
Accretion disks, 50
Active galactic nuclei, 196
Active galaxies, 196
Active region, 136
Albedo, 21
Altitude, 31
Amino acids, 214
Angles, measuring, 25
Angular diameter, 25
Angular momentum, 4
Angular resolution, 43
Annihilation of matter, 154
Antiparticles, 154
Apparent brightness, 127
Apparent magnitude, 127
Arcminute, 25
Arcsecond, 25
Asteroids, 99
Asymptotic Giant Branch (AGB), 160
Atmosphere:
 of Earth, 65
 of Jupiter, 78
 of Mars, 71
 of Mercury, 56
 of Moon, 67
 of Neptune, 80
 of Pluto, 103
 of Saturn, 79
 of Uranus, 80
 of Venus, 59
 planetary, 54
Aurorae, 63
Autumnal equinox, 31
Azimuth, 31

Balmer series, 129
Barred spirals, 190
Big Bang:
 background radiation from, 206
 time of occurrence, 204
Blackbody emission, 117
Black hole, 179
Blueshift, 20
Bombardment era, 51
Brightness:
 measuring, 127
 of stars, 127

Broad line regions, 198
Butterfly diagram, 140

Callisto, 83
Carbonaceous chondrites, 96
Celestial coordinate system, 31
Celestial equator, 31
Cepheid variables, 159
Chondrites, 96
Chondrules, 96
Chromosphere, 128
Circular velocity, 4
Clouds:
 of interstellar gas, 109
 on Jupiter, 78
 on Mars, 71
 on Neptune, 80
 on Venus, 60
Clusters of galaxies, 192
Collisions between galaxies, 192
Comet:
 defined, 91
 and meteor showers, 96
 origins of, 92
 parts of, 91
 properties of, 91
Condensation, 50
Continuous emission, 17
Convection zone, 137
Core:
 of Earth, 62
 of Jupiter, 78
 of Mars, 72
 of molecular clouds, 117
 of stars, 153
 of supernovae, 162
Corona, 142
Coronal holes, 142
Coronal mass ejections, 140
Cosmic background radiation, 19
Cosmological principle, 203
Cosmology, 203
Craters, 54
 on Mercury, 56
 on Moon, 67
Crescent phase, 34
Critical density, 208
Crust, 53
 of Earth, 62

Crust (*Cont.*)
 of Mars, 72
 of Moon, 69
Curvature of space, 208
Curved spacetime, 208

Dark matter, 186
Dark nebulae, 110
Day:
 lengthening of, 33
 lunar, 33
 sidereal, 32
 solar, 32
Declination, 31
Decoupling epoch, 208
Density:
 critical, 208
 and curvature, 208
 definition of, 2
Differential rotation, 140
Differentiation, 53
Diffusion, radiative, 137
Disks, 183
Distance:
 calculating, 25
 to galaxies, 191
 to stars, 126
Doppler effect:
 defined, 20
 and stellar spectra, 128
Doppler equation, 20
Dust:
 in comet tails, 91
 interstellar, 110
 in Seyfert galaxies, 198
Dwarfs, 156

Earth:
 atmosphere of, 65
 evolution of, 53
 interior of, 62
 properties of, 49
Eccentricity, 2
Eclipse:
 lunar, 35
 solar, 35
Ecliptic, 32
Eddington luminosity, 198
Electromagnetic radiation, 16

- Electromagnetic spectrum, 16
 Electrons, 19
 Ellipses, 2
 Elliptical galaxies, 190
 Elliptical orbits, 2
 Emission lines, 19
 Energy:
 gravitational potential, 5
 kinetic, 4
 and mass, 154
 in photons, 16
 produced in stars, 153
 and Stefan-Boltzmann law, 18
 Energy level, 19
 Equinox:
 autumnal and vernal, 31
 precession of, 35
 Escape velocity, 4
 Europa, 83
 Event horizon, 179
 Evolution of stars, 153
 Expansion of universe, 204
 Extinction by interstellar dust, 111
- Filaments, solar, 140
 Flares, solar, 140
 Flat space, 208
 Flatness problem, 209
 Flux, 18
 Foci, of ellipse, 2
 Frequency, 15
 Full phase, 34
 Fusion:
 described, 153
 and energy, 154
 hydrogen, 153
- Galactic bulge, 184
 Galactic disk, 183
 Galactic halo, 184
 Galactic nucleus, 184
 Galaxies:
 active, 196
 classification of, 189
 clusters of, 192
 distance to, 191
 elliptical, 190
 formation of, 192
 irregular, 191
 radial velocity of, 191
 rotation of, 185
 spiral, 189
 Galilean satellites, 82
 Gamma rays:
 creation of matter from, 154
 energy of, 16
 in stars, 154
 Ganymede, 83
- Gases:
 degenerate, 173
 density and pressure of, 13
 escape of, 13
 interstellar, 109
 neutral, 13
 Giant molecular clouds, 107
 Giants, 158
 Gibbous phase, 34
 Granulation of Sun, 138
 Gravitational contraction, 117, 155
 Gravity, 2
 effect on expansion, 205
 and space, 208
 and tides, 33
 Greenhouse effect, 65
- Helioseismology, 143
 Helium:
 abundance, 164
 formation in primordial universe, 165
 fusion of, 153
 from hydrogen in stars, 153
 Helium flash, 158
 Hertzsprung-Russell diagram, 156
 HII regions, 109
 Horizon, 31
 Horizon problem, 209
 Hubble's constant, 204
 Hubble's Law, 191, 203
 Hubble time, 204
 Hydrogen:
 absorption and emission, 129
 abundance, 164
 conversion to helium, 153
 21 cm line of, 110
 Hydrostatic equilibrium, 126
- Ideal gas law, 13
 Impact cratering, 54
 Inflation of universe, 209
 Infrared radiation:
 defined, 16
 from interstellar dust, 110
 Interstellar matter:
 dust, 110
 gas, 109
 Interstellar reddening, 111
 Inverse square law, 25
 Io, 82
- Jets, 198
 Jovian planets, 76
 Jupiter, 78
- Kepler's Laws, 3
 Kinetic energy, 4
 Kuiper belt, 92
- Latitude, 31
 Law of gravitation, 2
 Life, 214
 Light:
 absorption and reflection of, 19
 measuring devices for, 44
 speed of, 16
 Light curve, 101
 Light-gathering power, 42
 Line emission, 19
 Linear diameter, 25
 Lithosphere, 53
 Local Group, 192
 Long-period comets, 92
 Luminosity:
 of active galactic nuclei, 196
 classifying, in stars, 130
 and mass, 131
 of stars, 127
 Lunar eclipse, 35
 Lunar phases, 33
- Magnetic field:
 of Earth, 63
 of neutron stars, 176
 in star formation, 117
 of Sun, 139
 Magnification of telescope, 44
 Main-sequence stars:
 evolution of, 157
 lifetime of, 131
 Mantle, 53
 Maria, of Moon, 67
 Mars, 71
 Mass:
 defined, 1
 and energy, 154
 of stars, 131
 and stellar luminosity, 131
 of white dwarfs, 161
 Mass-luminosity relation, 131
 Massive stars:
 collapse of, 162
 life cycle of, 162
 Matter, creation from radiation, 154
 Mercury, 56
 Meridian, 31
 Metallic hydrogen, 78
 Meteorites, 95
 Meteoroids, 95
 Meteors, 95
 Milky Way, 183
 Moon, 67

- Motion:
 proper, 128
 of stars, 128
- Narrow line region, 198
- Neap tides, 33
- Nebulae:
 dark, 111
 HII regions, 109
 planetary, 161
 reflection, 111
- Negative curvature, 208
- Neptune, 80
- Neutral gases, 13
- Neutrinos, 137, 154
- Neutron capture, 165
- Neutron stars, 176
- New phase, 34
- Normal spirals, 189
- North celestial pole, 31
- Northern lights, 63
- Nuclear reactions, 153, 155
- Opacity, 156
- Orbits, 3
- Outgassing, 54
- Parallax, stellar, 126
- Penumbra, 139
- Perihelion, 3
- Period–luminosity relation, 159
- Photons:
 creation from matter, 154
 effect on energy levels, 19
- Photosphere, 128
- Planetary nebulae, 161
- Planetesimals, 50
- Planets, 49, 77
- Plasma, 13
- Plasma tail of comet, 91
- Plate tectonics, 53
- Pluto, 103
- Polarity:
 of Sun's magnetic field, 140
 of sunspots, 139
- Positive curvature, 208
- Positrons, 154
- Precession, 35
- Pressure, 13
- Prominences, solar, 140
- Proper motion, 128
- Proton–proton chain, 153
- Protostars, 117
- Pulsars, 176
- Quarter phase, 34
- Quasars, 198
- Radial velocity, 128
- Radiant of meteor shower, 97
- Radiation:
 absorption and reflection of, 19
 cosmic background, 206
 and matter, 154
 from quasars, 198
- Radiation era, 206
- Radio waves, 16
- Recombination epoch, 208
- Reddening, interstellar, 111
- Red giant stars, 158
- Red shift, 20
- Reflecting telescopes, 42
- Reflection nebulae, 111
- Refracting telescopes, 42
- Resolution of telescopes, 43
- Right ascension, 31
- Rings, 87
- Rotation:
 differential, 140
 of Milky Way, 185
 of neutron stars, 176
 synchronous, 33
- Rotation curve, 185
- r-process, 165
- RR Lyrae stars, 160
- Saturn, 79
- Scattering by interstellar dust, 111
- Seasons, 34
- Semimajor axis, 2
- Short-period comets, 92
- Small angle equation, 25
- Solar eclipse, 35
- Solar flares, 140
- Solar prominences, 140
- Solar system, origin of, 50, 77
- Solar wind, 143
- Solstices, 34–35
- South celestial pole, 31
- Spectra, 17
- Spiral galaxies, 189
- Spring tides, 33
- s-process, 165
- Stars:
 brightness of, 127
 distances to, 126
 energy generation in, 154
 formation of, 117
 main sequence, 131
 mass of, 131
 motions of, 128
 post-main sequence, 158
 red giant, 158
 spectra of, 128
 spectral class of, 128
 white dwarf, 161
- Stefan-Boltzmann Law, 18
- Stellar parallax, 126
- Stony-iron meteorites, 96
- Stony meteorites, 96
- Structure problem, 210
- S-type asteroids, 100
- Summer solstice, 35
- Sun:
 chromosphere of, 141
 corona of, 142
 interior of, 137
 photosphere of, 138
 sunspots in, 139
- Sunspots, 139
- Superclusters, 192
- Supergranulation, 138
- Supernovas, 162
- Synchronous rotation, 33
- Tails of comets, 91
- Tectonics, 54
- Telescopes, 42
- Temperature:
 of gases, 13
 of stars, 128
 of terrestrial planets, 49
- Terrestrial planets, 49
- Tidal bulges, 33
- Tidal forces, 33
- Tides, 33
- Titan, 85
- Triton, 85
- Type I supernovae, 163
- Type II supernovae, 162
- Ultraviolet radiation, 16
- Universe:
 age of, 204
 contraction of, 209
 end of, 209
 expansion of, 204
 inflation of, 209
 measuring curvature of, 208
- Uranus, 79
- Van Allen belts, 63
- Velocity:
 of atoms and molecules in a gas, 13
 circular, 4
 escape, 4
 of light, 16
 of orbiting bodies, 3, 4
- Venus, 59
- Vernal equinox, 31
- Volcanism, 54
- Volume, 1

Waning, of Moon, 34
Wavelength, 15
Waves, electromagnetic, 15
Waxing, of Moon, 34
White dwarfs:
 age of, 174
 evolution of, 174

Wien's Law, 18
Winds:
 in AGB stars, 160
 on Jupiter, 78
 solar, 143
 in young stars, 118

X-rays, 16

Zenith, 31
Zero curvature, 208