CHAPTER 1

Origin of the Universe

Whereas the focus of this text is the origin of life and the evolution of the biosphere we call Earth, it is appropriate to discuss some of the events that preceded. We begin with a brief discussion of occurrences from the time of the origin of the Universe to the establishment of a habitable planet.

NEWTON'S UNIVERSE WAS INFINITE AND STATIC

In Newton's time the Universe was pictured as an infinite sea of stars in fixed positions. The only movements that astronomers were aware of were those of the planets about the Sun and satellites about the planets. Rejection of this static view of the Universe required sophisticated astronomical measurements that could not be made until the 20th century.

Newton argued that the stars were scattered across an infinite expanse of space in more or less fixed positions. In proposing this model for the Universe, Newton's attention was focused on the balance of gravitational forces. If the Universe were only finite or if the stars were clustered in only one part of the Universe, the gravitational forces should cause these stars to be drawn together into one huge mass. Because Newton was not aware of any movement between the stars, it seemed most likely that the gravitational forces must be in balance.

Concern over this model was first expressed by Johannes Kepler in the 1600s and subsequently by Heinrich Olbers in the 1800s. If the Universe were truly infinite and contained stars more or less uniformity distributed throughout space, then we would expect it to be filled with stars and light in every direction. As a result the sky should be bright at all times and there would be no darkness at nighttime. This dilemma, known as Olbers' paradox, was not resolved until the 20th century when an entirely new dynamic model was proposed for the Universe.

HUBBLE'S UNIVERSE WAS FINITE AND EXPANDING

In the early part of the 20th century, Einstein's theory of relativity changed our thinking about space and time but even Einstein did not reject the concept of an infinite static Universe despite the inconsistency of this model with his own theory. In his later years Einstein said that this was the biggest mistake he had ever made. The point is that no matter how attractive a theory may seem, it is difficult to make much progress without experimental observations. The experiments that were to provide us with the currently accepted model for the Universe were performed by Edwin Hubble in the 1920s. In Hubble's model the Universe began with all the mass and the energy concentrated at a point; an explosion known as the Big Bang followed. Current indications are that this explosion occurred about 20 billion years ago and that all matter powered by the force of this explosion is still being propelled outward in all directions from the center of this explosion.

THE DOPPLER EFFECT SHOWS THAT ALMOST ALL GALAXIES ARE MOVING AWAY FROM US

Hubble's model for the Universe was the outcome of research that permitted him to estimate the movement of the stars relative to Earth. The main way such studies are made is by analyzing the light they emit. One of the important facts we can determine from such an analysis is the speed at which a stellar body is moving relative to our observation point on Earth. To appreciate how this is done, we must understand some of the basic properties of light.

Light is an electromagnetic field that oscillates in space and time. It interacts with matter in packets called *photons*, each of which contains a fixed amount of energy, which is a function of its frequency of oscillation. The relationship between the energy of a photon ϵ and the frequency ν of its oscillating field is given by

$$\epsilon = h\nu, \tag{1}$$

where h is known as Planck's constant. The frequency ν is the number of oscillations

BOX 1A Explaining Exponentials

In astronomy we often deal with very small or very large numbers. It is convenient to express these numbers as the product of a simple number and 10 raised to a power indicated by a superscript. For example, we have stated that 1 nm is equal to 10^{-9} m. This is the same as saying 1×0.000000001 m. In this case the superscript has a minus sign so that the number is very small. An example of a very large number is speed of light, which we have indicated is 3×10^{10} cm/s in a vacuum. This is equivalent to 30,000,000,000 cm/s.

per second at a given point in space. The wavelength λ of the oscillations is conveniently expressed in nanometers (1 nm = 10^{-9} m). It depends on both ν and the velocity v with which light travels through space:

$$\lambda = \frac{\nu}{v}. \tag{2}$$

Light travels with a velocity c of 3×10^{10} cm/s in a perfect vacuum (Box 1A). This speed is reduced when it is passes through space that is occupied by matter. Blue light has a wavelength in the region of 450 nm ($\nu = 6.7 \times 10^{14}$/s) and an energy per photon of about 2.8 electron volts (eV). Red light has a wavelength of about 650 nm. Radiation with wavelengths much below 400 nm or above 750 nm is invisible to the human eye, and some prefer not to call this light. However, all radiation obeys essentially the same laws.

The light we observe from a distant star or galaxy is a composite of different frequencies. This fact can be demonstrated with a prism that permits resolution of light of different wavelengths. For example, when visible white light is passed through a prism, it is bent according to its frequency; blue light is bent less than red light and so on (Fig. 1).

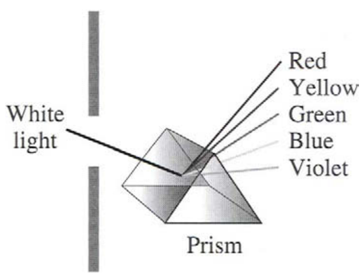

FIGURE 1 When white light is passed through a prism, it breaks up into a characteristic pattern of light with many colors.

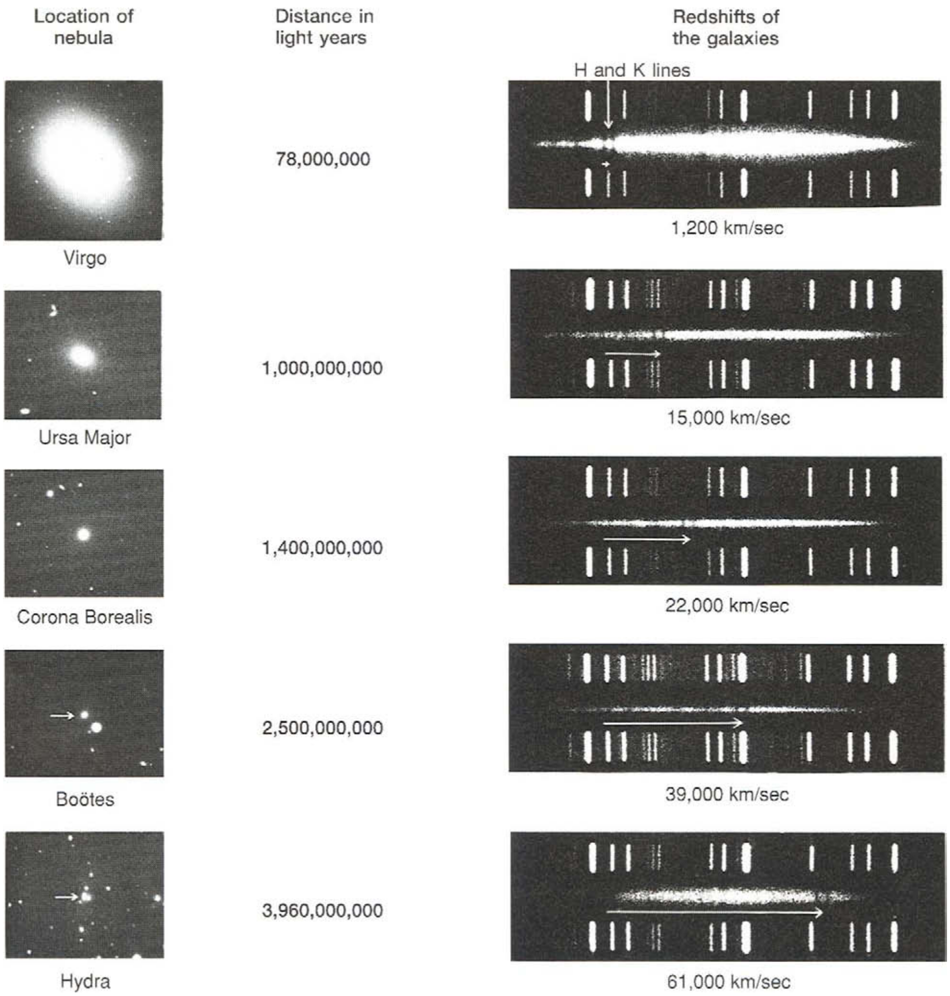

FIGURE 2 Galaxies and their light spectra. On the left are shown photos of five galaxies taken with the Hale Observatory telescope. Because these objects are probably similar in size, Virgo must be located much closer to Earth than to Hydra. Also shown, on the right, are light spectra from these galaxies. The white arrows show the displacement of an easily identified pair of dark lines from its position in a light spectrum for the Sun (or for a laboratory arc). The recession velocities corresponding to these arrow lengths are given. As can be seen, the more distant the object, the greater its recession velocity.

In observing light from any particular star, astronomers noted that superimposed on an almost continuous spectrum of light of different frequencies was a series of sharp dark bands (Fig. 2). They concluded that these dark bands must correspond to the wavelengths of light that are absorbed by the elements surrounding that body. Each element has a particular set of frequencies that it absorbs preferentially. This selective absorption is due to the interaction of the photons with the electrons of the element. When a photon is absorbed by an electron, the electron is catapulted from an orbit of relatively low energy to an orbit with a higher energy level. Because each element contains electrons at different energy levels, the frequency of absorbed light is characteristic of the element. As a result, the frequency of the absorbed light identifies the element and the intensity of the absorption indicates the amount of the element.

For a great many stars the spectra of absorbed bands are quite similar in their general patterns, an indication that most of the elements associated with different stars are quite similar. Quantitative differences in the extent of absorption at different frequencies permit the assessment of the relative concentrations of different elements for a particular star. When spectra are examined in detail, thousands of these bands become apparent. Thus a spectral analysis of absorption bands gives a detailed accounting of the relative amounts of the different elements in the solar gases that surround different stellar bodies.

For a long time astronomers used these absorption patterns to measure the relative abundance of the elements making up the atmospheres of neighboring stars. As more powerful telescopes became available, astronomers were able to extend their spectral analyses to more distant objects. To their surprise they found that, although the general pattern of absorption bands remained quite similar, for these more distance objects there was a shift in the location of the dark lines on the otherwise continuous spectrum. For example, a line that appeared in the blue part of the spectrum from the Sun or a nearby star was found in the green part of a spectrum of a very distant star, a line that appeared in the yellow part of the Sun's spectrum was present in the orange part of another more distant galaxy's spectrum, and so on. For any particular galaxy the pattern of dark lines always shifted to longer wavelengths. The extent of the shift was a characteristic of the galaxy. This effect was very puzzling to astronomers when it was first discovered, and a great deal of effort was made to correlate the extent of the shift with other characteristics of the galaxies. The most striking correlation was found with respect to the distance of the galaxy. The greater the spectral shift of the pattern of darkened lines, the farther away the galaxy appeared to be (see Fig. 2).

To understand the significance of the spectral shifts it was necessary to have a theory explaining their cause. This theory was provided by a 19th-century Viennese scientist named Doppler. The Doppler effect related the apparent frequency of a wave motion to the relative velocity between source and observer.

We find examples of the Doppler effect in our daily lives. For example, the engine of a high-speed racing car makes a high-pitched sound on approaching a stationary observer and shifts to a low-pitched sound once it has passed. Sound is a wave motion that travels through air at a velocity of 740 miles per hour. If the racing car is moving at the rate of 148 miles per hour the frequency of sound impulses reaching a stationary observer's ears will be 20% higher as the car approaches and 20% lower after it has passed. This frequency change accounts for the considerable variation in the pitch heard by a stationary observer. By contrast, the racing car driver hears a sound with a constant, intermediate pitch. This is because the onboard listener is traveling at the same rate as the vehicle that is producing the sound. Thus the sound heard is a function of the relative velocity between the source of the sound and the listener.

Could the Doppler effect explain the shift in frequency of the absorption bands in the observed stellar spectra from different galaxies? If so, the calculated speeds would have to be much higher than that of a racing car. Because light travels at the rate of 670 million miles an hour, a shift in the spectrum of the light reaching us from a distant galaxy corresponding to a 10% reduction in frequency would mean that the galaxy must be speeding away from us at a recessional velocity one-tenth the speed of light, or 67 million miles an hour (3×10^{10} cm/s). The general picture of the recessional velocities that has been obtained by comparing the shifts in spectra from observed galaxies is that all galaxies are speeding away from us and that the farther away they are, the faster is the rate at which their distance is increasing. This pattern can be explained if all matter is moving out from a point source at approximately the same speed from an explosion that occurred a long time ago.

RATE OF SEPARATION AND DISTANCE DATA SUGGEST THAT THE UNIVERSE ORIGINATED ABOUT 20 BILLION YEARS AGO

The relationship between distance in galaxies and their redshifts has led to one of the most important astronomical discoveries of the 20th century. The finding that virtually all objects are receding from us can most likely be explained by the fact that we live in an expanding Universe. To take full advantage of this relationship, it is necessary that more precise measurements of recessional velocity and distance be made.

The recessional velocity is relatively easy to measure precisely. The redshift z is defined as

$$z = \frac{\lambda - \lambda_0}{\lambda_0}, \tag{3}$$

where λ_0 is unshifted wavelength and λ is the observed wavelength. The recessional velocity v may be calculated from z because $z = v/c$, where c is the velocity of light. For z value of 0.05 we calculate that $v = 0.05\ c$. For a large value of z we must use the relativistic equation

$$\frac{v}{c} = \frac{(z + 1)^2 - 1}{(z + 1)^2 + 1}. \tag{4}$$

In contrast to recessional velocities, distances are most difficult to estimate. In fact, there is no way that they can be measured with certainty for stars and galaxies that are very far away. The problem of measuring the distance of an object without actually measuring it directly has been solved by surveyors using the method of triangulation. This is illustrated in Fig. 3. Imagine that the goal is to determine the exact distance of

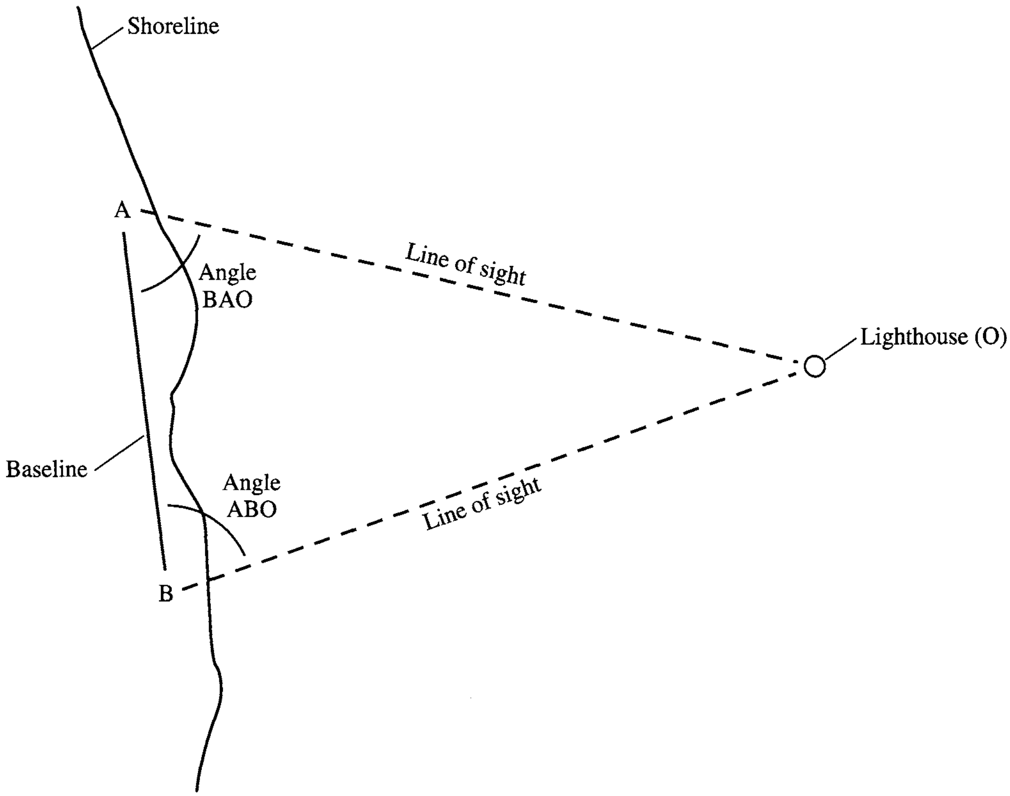

FIGURE 3 Surveyors method of measuring distance by trigonometry. From the measured distance AB and the angles BAO and ABO, the distance AO and BO may be calculated by trigonometry.

a lighthouse from either point A or point B in the shoreline. The surveyor would measure the distance between A and B directly and then determine the angle between the line of light of the lighthouse (AO or BO) and the line AB. From this information the distances AO and BO can be calculated by trigonometry. The known distance of Earth on either side of the Sun can be used in the same way to determine the distances to nearby stars. However, nearby stars are not of great interest to us because they have very small recessional velocities. For very distant objects in the Universe, the angle subtended by the object of interest to the two reference points is so close to zero that it does not give us a perceptible triangle. For the purpose of estimating distances to far away stars or galaxies, brightness is the main criterion used. For stars that are close enough to resolve as individual stars, one compares the brightest stars in the galaxies. For more distant stellar objects where it is impossible to resolve individual stars, the brightness of the galaxies themselves is compared; the hope is that there is not too much variation in brightness so that the distance will be reciprocally related to the brightness. By making many measurements on different galaxies, one hopes to obtain a reasonably accurate assessment of the ratio of the recessional velocities as a function of the distance.

Astronomers have estimated the distance of dozens of galactic clusters as a function of recessional velocity. When these data are plotted, the straight line relationship displayed in Fig. 4 is produced. The slope of this line is a constant called the Hubble constant. Hubble's law is most easily stated as a formula,

$$v_r = H_0 r, \tag{5}$$

where v_r is the recessional velocity, r is the distance, and H_0 is the hubble constant. From the data plotted on this graph we find that

$$H_0 = 15\ \mathrm{km/s/Mly}, \tag{6}$$

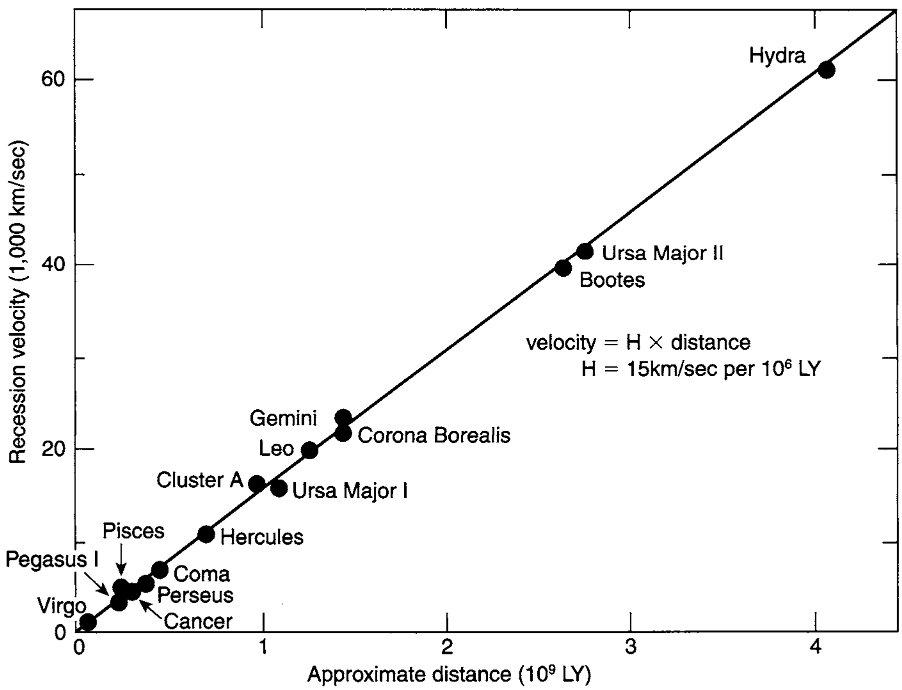

FIGURE 4 Hubble velocity–distance relation of 15 clusters of galaxies. The alignment of the data along a nearly straight line implies that recession velocity varies regularly with distance. For instance, galaxies at 1 billion light years (LY) have a recession velocity of 15,000 km/s, those at 2 billion LY have a recession velocity of 30,000 km/s. and so forth. (From Kutter, G. S. *The Universe and Life,* 1987, Sudbury, MA: Jones & Bartlett publishers. www.jbpub.com. Reprinted with permission.)

where Mly stands for 10^6 light years. In other words, for each million light years to a galaxy, the galaxy's recessional velocity increases by 15 km/s. For example, a galaxy located 100 million light years from Earth should be rushing away from us at a speed of 1500 km/s. Most astronomers prefer to speak in units of millions of parsecs, termed megaparsecs (Mpc), instead of millions of light years (Mly). By using that unit,

$$H_0 = 50\ \text{km/s/Mpc}. \tag{7}$$

Units of the Hubble constant sometimes are written with exponents instead of slashes:

$$H_0 = 15\ \text{km s}^{-1}\ \text{Mly}^{-1} = 50\ \text{km s}^{-1}\ \text{Mpc}^{-1}. \tag{8}$$

As one might suspect, the exact value of the Hubble constant is a topic of heated debate among astronomers today, simply because of the uncertainty in determining distances.

To calculate the time elapsed since the Big Bang, imagine watching a movie of any two galaxies separated by a distance r receding from each other with a velocity v. Now run the film backward, and observe the two galaxies approaching each other as time runs in reverse. We can calculate the time to T_0 it will take for the galaxies to collide by using the simple equation

$$T_0 = \frac{r}{v}. \tag{9}$$

Employing the Hubble law, $v = \mathrm{H}_o r$, to replace the velocity, v in this equation, we get

$$T_0 = \frac{1}{H^0} = \frac{1}{50\ \text{km/s/Mpc}} = 20\ \text{billion years}. \tag{10}$$

Because the separation r has canceled, T_0 is the same for all galaxies. This is the time in the past when all galaxies were crushed together, the time the Big Bang occurred.

The true age of the Universe may be somewhat greater than this because the speed at which galaxies have been separating probably has been gradually increasing since the time of the Big Bang.

QUASARS HAVE ANOMALOUSLY HIGH REDSHIFTS

Whereas all matter is being propelled by the Big Bang that occurred about 20 billion years ago, there is also movement that results from other mostly gravitational factors. A most obvious example is the orbital motion of the planets around the Sun. The sun and all the planets are subject to a translational motion that resulted from the Big Bang. However, relative to one another, the planets have movement of a different sort.

A more puzzling type of movement is observed by unusually luminous stellar bodies that are located at great distances from us but show recessional velocities of a much greater magnitude than is consistent with their brightness. The redshifts recorded for so-called *quasars* frequently have z values greater than 1, indicating relativistic speeds. For example, the quasar known as OH 471 has a redshift of $z = 1.4$, which corresponds to a recessional velocity of greater than 90% of the speed of light. The highest recorded redshift for a quasar is $z = 4.7$. Based on their brightness, quasars are believed to be much closer to us than would be suggested by Hubble's law. Current opinion favors the notion that quasars are being accelerated by very dense bodies in their vicinity known as *black holes*. For the present all that we need to know about black holes is that they are objects whose gravity is so strong that the escape velocity

BOX 1B Properties of Blackbody Radiation

The amount of energy radiated by an object depends on its temperature. The hotter the object, the more energy it emits in the form of electromagnetic radiation. The dominant wavelength of the emitted radiation also depends on the temperature of the object. A hot object emits most of its energy at short wavelengths, whereas a cool object emits most of its energy at long wavelengths.

While a white body reflects a great deal of the incident radiation that comes on it, a blackbody absorbs most of the incident radiation. An idealized blackbody absorbs all the radiation falling on it and emits a continuous spectrum of radiation at equilibrim. Because a blackbody reflects no electromagnetic radiation, the radiation that it emits is entirely the result of its temperature. The temperature of a blackbody and the dominant wavelength (λ_{max}) of the energy it emits are inversely related by the equation

$$\lambda_{max} = \frac{2.9 \times 10^{-3}}{T},$$

where λ_{max} is measured in meters, and T is measured in degrees Kelvin. This relation is called Wien's law.

To a first approximation the Sun and most stars are good examples of blackbodies because they absorb almost all the radiation falling on them. Consequently, we may estimate the Sun's surface temperature from Wien's law. The maximum intensity of sunlight is at a wavelength of about 500 nm = 10^{-7} m. From Wien's law, we find the Sun's surface temperature to be $T_{\odot} = \dfrac{2.9 \times 10^{-3}}{5 \times 10^{-7}} = 5800$ K. A subscript with a circle and a center dot refers to the Sun.

BOX 1C Black Holes

A black hole is a region of space in which matter is so concentrated and the pull of gravity is so powerful that nothing, not even light, can emerge from it. Black holes represent the ultimate triumph of gravity over all other forces.

By definition, a black hole cannot be seen. Its presence must be detected through indirect evidence: the vast whirlpools of matter being sucked in by consuming gravity at ever increasing velocities.

Scientists have uncovered evidence that supermassive black holes probably lurk at the core of nearly all galaxies. They also have detected for the first time confirming evidence for the existence of the boundary of no return that surrounds a black hole—an event horizon across which matter and energy pass in one direction only, falling in but never coming back out.

exceeds the speed of light (Box 1B). Hence they emit no visible radiation and can be detected only by their gravitational effects. One may wonder why we do not see quasars with blueshifts. Probably the light of a quasar oriented in this way would be absorbed by the black hole (Box 1C) before it reached us.

ISOTROPIC BACKGROUND RADIATION IS BELIEVED TO BE A REMNANT OF THE BIG BANG

In the early 1960s, Arno Penzias from Princeton University and Robert Wilson from Bell Telephone Labs were experimenting with a new microwave horn antenna designed to relay telephone calls. Initially they were annoyed by the fact that no matter in what direction they pointed their horn they picked up a weak background radiation with a wavelength of about 1 mm. Eventually they realized that this radiation was coming from outer space with approximately equal intensity in all directions. For a blackbody a wavelength of 1 mm corresponds to a temperature of about 2.7°C (see Box 1B). The detection of this radiation was considered so important that Penzias and Wilson were eventually awarded the Nobel Prize for its detection. This cosmic background radiation is believed to be a vestige of very high energy photons that existed shortly after the big bang. As the Universe expanded these very short wavelength photons become stretched. This stretching process is referred to as a cosmological redshift to distinguish it from the Doppler redshift that is caused by an object's motion through space. A most remarkable aspect of cosmic background radiation is that it is almost perfectly isotropic, which reflects its ancient origin.

CURRENT EVIDENCE SUGGESTS THAT THE RATE OF EXPANSION OF THE UNIVERSE IS INCREASING

The present rate of expansion of the Universe is given by Hubble's constant. To measure the change in expansion rate we must be able to look into the past or into the future. We will settle for looking into the past by focusing our observations on objects that are very far away. There are two reasons we are interested in this question. First, it affects our estimate of the age of the universe. If the expansion rate is decreasing, the Universe is probably younger than calculated from the Hubble constant. On the other hand, if the expansion rate is increasing, then the Universe actually would be older than calculated by the Hubble constant. The second and more profound reason we are interested in the rate of expansion is that it has an effect on the future of the Universe. A change in expansion rate is the best indicator of whether the Universe will keep expanding or the expansion will stop or even reverse so that a contraction process will ensue.

Cosmologists tell us that the ultimate fate of the Universe is a matter of its average density. The estimated critical density required to just halt expansion of the Universe is 5×10^{-10} g/cm^3 which is equivalent to about three hydrogen atoms per cubic meter. The estimated density of the universe is still considerably below this. However, it keeps rising as new stellar objects continue to be discovered. These new objects

BOX 1D The Apparent Magnitude of a Star Is a Function of Its Absolute Magnitude and Its Distance

By convention the *absolute magnitude* of a star is the magnitude it would have if it were located a distance of exactly 10 parsecs (pc) from Earth. Absolute magnitude is a very useful quantity, because it gives a measure of the intrinsic brightness of a star. *Apparent magnitude* is a measure of the light energy arriving at Earth. Apparent magnitude tells us how bright a star appears in the sky. The farther away a source of light, the dimmer it appears.

Astronomers have derived an equation that relates a star's apparent magnitude (m), its absolute magnitude (M), and its distance (d, measured in parsecs) from Earth:

$$m - M = 5 \log d - 5.$$

From this equation it should be apparent that if the quantities of two of the variables m, M, and d are known, the third one may be calculated. This equation has been most useful for estimating the distance of far away supernovas.

include dark objects such as burned out stars that no longer emit visible radiation and black holes that are very dense objects detected only by their gravitational effects.

While efforts to obtain a more accurate measure of the density of the universe continue, more direct evidence indicates that the expansion rate of the universe is increasing. The evidence comes from close scrutiny of a class of stars that explode violently. Such an event is referred to as a *supernova.* All supernovas begin with a sudden rise of about a millionfold in brightness. For this reason supernovas can be observed over enormous distances. It is believed that most supernovas have the same intrinsic brightness at their peaks regardless of their distance from Earth. This means that the intrinsic brightness of a supernova can be approximated by the constant that can be determined by measuring the brightness of close-by supernovas where the distance can be accurately estimated. By having fixed on a value for M, the apparent brightness m of a very distant supernova may be used to obtain a value for the distance (Box 1D). Comparison of this with the measured recessional velocity for several dozen distant supernovas gives values that indicate the rate of expansion of the universe is increasing.

SUMMARY

In this chapter we have considered the evidence supporting the hypothesis that the Universe began with a Big Bang that resulted in a rapidly and continuously expanding system.

1. From the shift in the spectra of light reaching us from distant galaxies, it has been determined that the distance between Earth and all galaxies is increasing. The more distant the galaxy, the greater the velocity of separation.
2. From the distance of different galaxies and the speed with which they are moving relative to one another, it has been estimated that all matter and energy originated from a single location in the Big Bang about 20 billion years ago.
3. The isotropic background radiation that is observable in all directions is believed to reflect radiation that was produced immediately after the Big Bang.
4. The Universe may keep expanding or the expansion may give way to arrest or even contraction. Current indications from measured recessional velocities of very distant supernovas favor the notion of indefinite expansion.

Problems

1. On average galaxies at a distance of 100 million light years are moving away from us with a velocity of 1500 km/s. Can this information be used to estimate the age of the Universe? (Answer: 20 billion years.) Show how you get this answer and indicate what assumptions you used.
2. One way to explain the Doppler shift is by claiming that Earth is at the center of the Universe. Why is this very unlikely?
3. How many seconds are in a light year?

4. What is the difference between a cosmological redshift and a Doppler redshift?
5. If you were an observer on a quasar, would you expect to find a direct proportionality between the recessional velocities of galaxies and their distance from you?
6. What recessional velocity is suggested by a redshift z of 3? How far away would you expect a galaxy to be that gave rise to this redshift?
7. In Fig. 2 calculate the recessional velocity for Hydra.

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