Chapter 10: The Expanding Universe

Einstein's Model of the Universe and Friedmann's Modification

After Einstein developed his theory of space, time and gravity, General Relativity, he applied it to cosmology. As described in Chapter 9, the theory connects matter with the geometry of 4-dimensional space-time. Einstein proposed a steady state model for the overall universe in which space is static, *i.e.*, unchanging in time. This would avoid having to incorporate a beginning or end to the universe into the model. Einstein's General Relativity added a novel feature to the universe: curved 4-dimensional space-time. This means that the shortest distance between two points — a geodesic, which is the path that light follows — is not necessarily a straight line.

But the model encountered the same difficulty as did Newton's model: the universe should be subject to gravitational collapse (see Ch. 6). **In order to avoid such a collapse,** Einstein needed to include in his equations a term called the **Cosmological constant,** which is given the symbol Λ (the upper-case Greek letter Lambda). The Cosmological constant — a form of what is termed "**dark energy**" — is **equivalent to a repulsive force throughout space, so that it counteracts the attractive force of gravity.**

However, in 1922 Russian physicist Alexander Friedmann showed that Einstein's model universe was unstable to gravitational collapse even if the Cosmological constant were non-zero. Friedmann proposed that this problem could be resolved if the universe were to expand rather than remain static. While Einstein did not like Friedmann's proposal, observations soon suggested that it was correct.

The Hubble Law

After establishing that the Milky Way is simply one among a huge number of other galaxies (see Chapter 6), Edwin Hubble proceeded to measure the distances to many galaxies. He was interested in following up a curious discovery made in 1912 by Vesto Slipher at Lowell Observatory in Arizona regarding the spectra of what then were called "spiral nebulae." The spectrum of a typical galaxy is the combined absorption-line spectra of all its stars, with the greatest contribution coming from stars similar to the Sun. Slipher found that the absorption lines in the spectra of nearly all galaxies are redshifted. This indicates that they are moving away from the Sun at speeds of hundreds or even thousands of km/s.

Hubble found that the amount of the redshift is greater for more distant galaxies, as illustrated in Figure 10-1. Hubble plotted on a graph the velocities — as determined from the Doppler shifts and equation 7-4 — vs. the distances of the galaxies he had observed. The data followed a straight line, indicating that the velocity of a galaxy is proportional to its distance. This is shown in Fig. 10-2, in which more refined measurements of distance are used. (Hubble underestimated the distances because of gross errors in his calibration of luminosities of Cepheid variable stars in nearby galaxies — see Chapter 6 — so he derived an incorrect slope for the line.)

The straight-line fit to the graphed data is described mathematically by a simple equation called the **Hubble Law**:

$$v = H_0 d \qquad (10\text{-}1)$$

v = velocity (in km/s), H_0 = Hubble's constant = 70 km/s/Mpc, d = distance [in Megaparsecs, (Mpc)].

Here v is the velocity at which the galaxy moves away from us and $\boldsymbol{H_0}$ is called **Hubble's constant**. Its value as currently measured is about H_o = 70 km/s/Mpc. This means that a galaxy that is 100 Mpc from the Milky Way is moving away from us at a speed of about 7,000 km/s. (*Note:* eq. 10-1 is not valid for galaxies in the Local Group of galaxies that includes the Milky Way, since the part of their motions that is caused by the gravitational interactions of the members is faster than the velocity that results from the Hubble Law.)

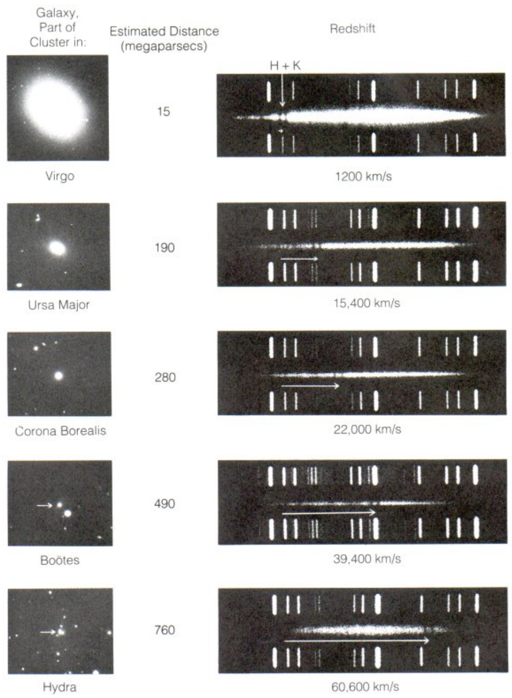

Figure 10-1. *Left panels:* Images of some galaxies with elliptical shapes. These galaxies all have roughly the same actual size and luminosity, so those that appear smaller and fainter are more distant. *Right panels:* Visible spectra of the same galaxies, in black-and-white. Longer wavelengths are to the right. There is a prominent double absorption line from once-ionized calcium (Ca^+) found in Sun-like stars that produce most of the light in such galaxies. The white horizontal arrows show how much this pair of lines is shifted from their rest wavelengths. (The short vertical bars are laboratory-generated emission lines used to calibrate the wavelength scale.) The shift is greater for the more distant galaxies. [Source: Mt. Palomar Observatory]

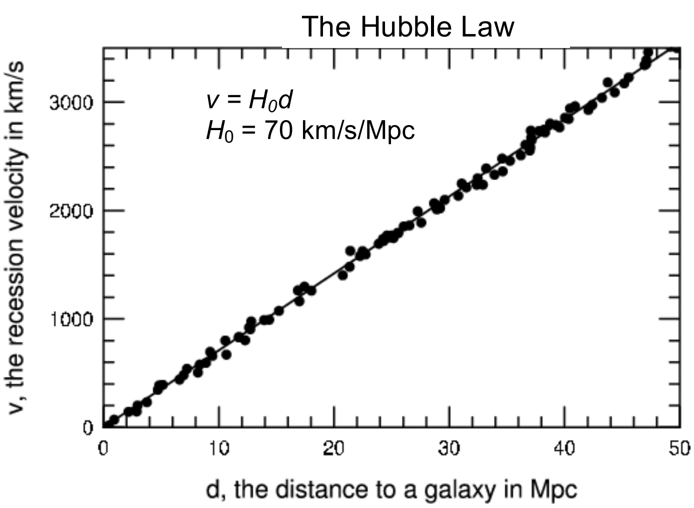

Figure 10-2. Velocity vs. distance graph for galaxies. A straight line fits the data quite well. The slope of the line is called "Hubble's constant," H_0.

If the distance to an object is greater than a few hundreds of megaparsecs, the velocities approach the speed of light, so Relativity comes into play. Because of this, astronomers use a quantity called the **redshift**, with the symbol z, instead of velocity when they apply the Hubble Law. The redshift is defined by the equation

$$(1+z) = (\lambda_{obs}/\lambda_0) = f_0/f_{obs} \qquad (10\text{-}2)$$

so that

$$z = (\lambda_{obs}/\lambda_0) - 1 = (f_0/f_{obs}) - 1. \qquad (10\text{-}3)$$

z = redshift (no units – just a number), λ_{obs} = observed wavelength (in nm), λ_0 = rest wavelength (in nm), f_0 = rest frequency (in Hz), f_{obs} = observed frequency (in Hz).

When the redshift is less than about $z = 0.2$, the velocity v is very close to cz, where c is the speed of light. That is why we can use velocity instead of z in Figure 10-2, since the galaxies involved are relatively local and the redshifts are small.

We can cast the Hubble Law, equation 10-1, into a form that gives the distance as a function of redshift:

$$d = \frac{v}{H_0} \approx \frac{cz}{H_0} \quad \text{(valid for } z \text{ less than about 0.2)} \qquad (10\text{-}4)$$

d = distance (in Mpc), v = velocity (in km/s), H_0 = Hubble's constant = 70 km/s/Mpc, c = speed of light = 3.0×10^5 km/s, z = redshift (no units).

The Hubble Law is extremely useful to astronomers who study the most remote objects that they can detect with their telescopes. The redshift vs. distance relation allows them to calculate the distances to galaxies too far away for telescopes to resolve individual stars, and to quasars, the extremely luminous centers of some galaxies. They do this by measuring the observed wavelength of the lines in their spectra, which is a relatively straightforward undertaking. They then use equation (10-3) to determine the redshift z and then equation (10-4) to calculate the distance.

The Expanding Universe

What does the Hubble Law say about the universe? The implication is quite profound: the universe is expanding! Figure 10-3 demonstrates how an expanding universe can cause the galaxies to move away from each other at velocities that are proportional to their distances.

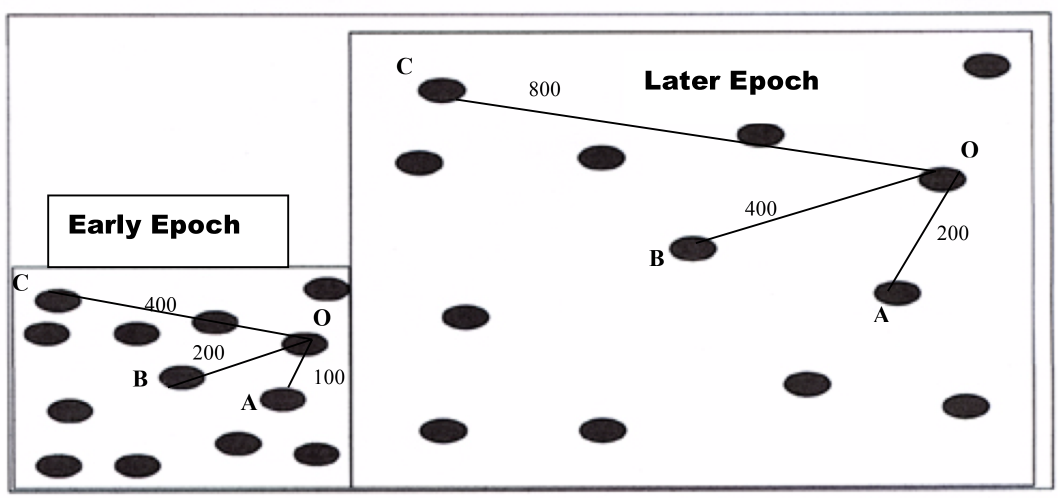

Figure 10-3. The effect of expansion of space on distances and velocities. The left panel shows the locations of galaxies — represented by ellipses — at some time ("epoch") in the past when the universe was half its current size. The right panel does the same at the current time. The observer is in galaxy O. Galaxy C moved from a distance of 400 to 800 Mpc from O while galaxy B moved from 200 to 400 Mpc and galaxy A moved from 100 to 200 Mpc. Since they all did this in the same amount of time, the speed at which galaxy C moves away from galaxy O is 4 times the speed of galaxy A, while the speed of galaxy B is 2 times that of galaxy A. Their distances also follow a 4:2:1 ratio. So, the velocities away from O are in direct proportion to their distances, as in the Hubble Law (eq. 10-1). Notice that, no matter which galaxy the observer is on, the same effect would be seen, *i.e.*, all the other galaxies would be moving away.

If every galaxy outside our Local Group is moving away from us, and if, as stated by the **Cosmological Principle** (see Chapter 6), the universe appears roughly the same from every position, then observers in other galaxies would find the Hubble Law to be valid from their locations. This would be true if space is expanding, as Friedmann proposed when he revised Einstein's model of the universe.

What do we mean when we say that the universe is expanding? In order to explain the Hubble Law, all of space must be expanding, *i.e.*, the distance between any two points increases because space itself becomes larger with time. So, after the universe has doubled in size compared with some earlier time, all the distances between various locations in the universe will also have doubled (see Figure 10-3).

As you might expect, the discovery that the universe is spreading out had a profound effect on our ideas about the cosmos. If the universe is expanding, it must have been much more compact in the distant past. This implies that the universe had a beginning. Recall that this was one of the possible solutions to the Dark Sky Paradox (see Ch. 6): if the universe has not existed forever, then there may not have been enough time for starlight to fill all of space and make the night sky bright.

Box 10-1. The origin and nature of time

An expanding universe implies a beginning. Does this require that time had a beginning as well?

Aristotle considered it paradoxical to think that time could have a beginning in time. In simple terms, how could one think of a beginning to time when the word "beginning" implies that time already existed? He therefore favored the notion that the universe has existed forever. If Aristotle had known about the expanding universe, he might have concluded that time must exist in a "meta-universe" (e.g., the realm of God or a "multiverse") out of which the universe was created.

Augustine of Hippo proposed that the universe was created with time, not in time, and considered God to be a timeless being. If Augustine's suggestion is valid, does it imply that time is a property only of this expanding universe? Would it have any meaning in a static universe?

In a clever proposal by James Hartle and Stephen Hawking, time has only existed during the past 14 billion years of a universe that is actually eternal. According to this idea, time might have been a space-like dimension before the universe changed. That is, before the expansion began, time did not have its current meaning. This works mathematically if one starts from the present time and calculates backward in time to the point that time began. But how can time change from a space-like to a time-like dimension when even the word "change" implies that time already existed? Hartle and Hawking appeal to the uncertainty of Quantum Mechanics to do this. However, it seems that there is still a logical problem for change to occur when time does not yet exist. It might make some sense, however, if the entire universe — not only all its space, but its past, present, and future as well — exists as a "package." (This is the view taken by Kurt Vonnegut in his novel *Slaughterhouse-Five*, in which the main character can slide back and forth in time but cannot change any of the events in his life.) The closest analogy might be that of a book: the complete book exists, but the reader can only make sense out of it if he or she reads it from the beginning to the end. If this is the case, perhaps time passes in the forward direction because it is the only logical way to experience the universe; this was proposed by the philosopher Immanuel Kant.

The Age of the Universe

If the universe is not infinitely old, how long ago did it begin? If you fell asleep in the front seat of a bus whose departure had been delayed, then woke up to find yourself on the highway, how could you estimate the time when the bus finally left the station? You could look over the driver's shoulder at the speedometer to see how fast the bus is moving, then look outside in the backward direction until you see a sign posting the number of miles from the city you left. If you divide the distance by the speed, you will calculate the approximate time that has elapsed since the bus departed. Of course, this wouldn't take into account possible changes in speed before reaching the highway, but if the bus station wasn't too far from the highway and the distance from the city is large, your estimate should be fairly close to the actual value. We can do the same with the Hubble Law: we know from the Hubble constant that two galaxies separated by a distance of 1 Mpc are moving 70 km/s away from each other. The age of the universe then just requires some unit conversions and arithmetic:

$$\begin{aligned}\text{Age of universe} &\approx 1/H_0 \approx 1/(70\text{ km/s/Mpc}) \approx [1\text{ Mpc}/70\text{ km}]\text{ s}\\ &\approx [(1\times10^6\text{ pc/Mpc})(3.1\times10^{16}\text{ m/pc})] / [(70\text{ km})(1000\text{ m/km})]\text{ s}\\ &\approx (4.4\times10^{17}\text{ s})(1\text{ yr}/3.16\times10^7\text{ s/yr}) \approx 14\text{ billion yr.}\end{aligned}$$

The data therefore indicate that **the universe began roughly 14 billion years ago**. This is the approximate age of the universe. It is actually quite accurate – to within about 2% – even when we take into account that the universe has probably not been expanding at a uniform rate since the beginning.

A Cyclic Model of the Universe

One way to avoid a beginning and the problem of time is for the universe to undergo endless cycles of creation and destruction, as in ancient Hindu cosmology. This avoids an ultimate creation event — and the logical problems that it raises — while allowing time to have the properties that we experience in our current universe. The universe could expand at first but at a rate that decreases because of gravity, then stop expanding and collapse back to its initial, ultra-dense state to start another cycle. In order for this to happen, there would need to be a high enough density of matter for gravity to slow and then reverse the expansion. We will check whether observations agree with this in Chapter 11.

Box 10-2. The origin of the universe

At the present time, any attempt to explain the ultimate origin of the universe relies on either theology or a very speculative extrapolation of our scientific knowledge of the universe. Here we briefly discuss some of the proposals for explaining how the universe originated.

The theological approach credits the existence of the universe to a great intelligence that we call "God." (One school of thought equates the universe with God or a part of God, who has existed forever.) But a confounding question is how God came to exist. The usual answer, that God's existence should be accepted as a given fact, could be applied to the universe as well.

One possibility in the scientific speculation category is that our universe is actually part of a greater multiverse. Such a multiverse could contain many universes — perhaps an infinite number — with a varying range of physical properties such as the number of dimensions, physical laws, and content. In one such model, whose leading proponent is Andrei Linde, the multiverse is a "mother" universe that is continually spawning new "child" universes, one of which is ours. In this scenario, our universe was not created purposely by a conscious creator. Instead, it is a random event in the mother universe, perhaps similar to a quantum fluctuation that can create particles out of a vacuum, but on a much grander scale. The other universes would be distinct from – or beyond communication with – ours and could not observe each other.

Exactly how much mass-energy needs to be created to make the universe? All of the mass-energy in particles is positive. On the other side, the gravitational attraction of masses for each other is a negative potential energy (see Ch. 4). Current estimates of the total mass-energy of the universe, including all the known positive and negative components, are consistent with a net mass-energy of zero! This means that such a universe could form from essentially nothing through a process similar to a quantum fluctuation.

But is this model really any different from the idea that God created the universe, except that an impersonal, unthinking multiverse following the rules of Quantum Mechanics has replaced an intelligent God? That is, is this not an atheistic theology rather than a scientific model? It is, indeed, if there are no observational tests that can be devised to test the model, at least potentially. For this reason, the proponents of such models are intent on developing such observational tests, which would focus on the observable properties of a universe that is created in the proposed manner. If they succeed, then the models will graduate from speculation to scientific hypotheses.

Summary

Edwin Hubble measured the distances to a number of galaxies with absorption lines in their spectra that were redshifted. He discovered that the magnitude of the redshift, which indicates the velocity at which a galaxy moves away from us, is proportional to its distance. This relation, now called the Hubble Law, can be explained if space — meaning the entire universe — is expanding. We can use the Hubble Law to determine distances to cosmic phenomena, *e.g.*, quasars, too far away for us to detect individual luminous objects that can be used as standard candles. The technique requires only that we measure the redshift from the spectrum and then apply equation 10-4.

The discovery of gravity by Newton started the era of modern cosmology, the study of the universe as a whole. An infinite universe that remains constant in time, on average, seemed a sensible model. But simple analysis shows that in such a universe the night sky should be as bright as the Sun in every direction. If we replace the assumption that the universe has always been the same with the idea that it had a beginning, we solve the dark sky paradox. The expansion of the universe discovered by Hubble implies that there was indeed such a beginning. The next chapter describes the current theory of the universe, the Big Bang model. This model describes a universe with a violent beginning that eventually led to the formation of stars, planets, and people.

Glossary

The universe: An abstract concept meaning the natural world in which we exist. Originally, it meant everything that exists, but it is possible that there are other universes and collections of universes.

Cosmology: Study of the universe as a whole.

Steady-state model: Theory in which the universe (on average) does not change with time.

Space-time: The framework of the 4-dimensional macroscopic universe, consisting of three dimensions in space and one in time.

Dark night sky paradox (often referred to as "Olber's paradox"): Problem with models in which the universe is infinite in space and has always existed: The night sky should be bright from distant starlight.

Cosmological Principle (sometimes called the "Copernican" Cosmological Principle): Assumption that the universe has the same appearance, on average, as observed from any place inside it.

Galaxy: A distinct system of many stars and clusters of stars.

Milky Way: Our own galaxy, seen from the Earth as a creamy band of light that extends from horizon to horizon (see Fig. 6-3).

Local Group of galaxies: A loose cluster of at least 30 galaxies including our own Milky Way and the Andromeda galaxy.

Parsec (abbreviation: pc; 1 kpc = 1000 pc; 1 Mpc = 1 million pc): Distance unit used for stars and galaxies. 1 parsec is the distance of a star with a parallax of 1 arcsecond. [1 parsec = 3.26 light-years = 3.1×10^{16} m, 1 kpc = 3.1×10^{19} m, 1 Mpc = 3.1×10^{22} m]

Megaparsec (abbreviation: Mpc): 1 million parsecs

Light-Year (abbreviation: lt-yr): The distance traveled by light in one year. There are 3.26 light years in 1 parsec.

Brightness (symbol: B, units: watts/m^2 or W/m^2): The energy in observed light from an object per unit area and per unit time within a certain range of wavelengths. Astronomers prefer the term “flux” or “flux density” when referring to this quantity.

Luminosity (symbol: L, units: watts or W): The total amount of energy radiated by an object in the form of electromagnetic waves.

Cosmological constant (symbol: Λ): A term in Einstein’s equations describing the space-time of the universe. It corresponds to a “dark energy” that counteracts gravity and promotes expansion.

Doppler shift: Change in wavelength of emission or absorption lines when the source of the lines is moving toward or away from the observer. The magnitude of the shift is proportional to the velocity relative to the observer as long as the velocity is less than about $0.2c$, where c is the speed of light. The mathematical formula for the Doppler shift is given in equation 9-4 (or the approximation given in eq. 5-2 for velocities less than about $0.2c$).

Redshift (symbol: z): A measurement of the increase in wavelength caused by the expansion of the universe. Quantifies the Doppler shift when the motion is away from the observer. See eq. (10-3).

Hubble Law: The relation (see Fig. 10-2 and eqs. 10-1 and 10-4) between velocity or redshift and distance of galaxies beyond the Local Group. Can be used to determine distances to remote objects. Led to the conclusion that the space of the universe is expanding.

Hubble’s constant (symbol: H_0): Slope of the Hubble Law. Its value at the current epoch of the universe is about 70 km/s/Mpc.

Epoch: A particular time in the history of the universe.

Multiverse: A hypothetical level of existence that contains many universes.

Mother universe: A hypothetical multiverse that continually generates new “child” universes.

Questions for Discussion

A. What would you conclude if you were brought to a location blindfolded, then you took the cover off your eyes, looked up in the sky, and saw thousands of birds flying radially away from the point where you were standing? You would probably think that they were all gathered at that spot just before you got there, perhaps because there was food on the ground, and that your presence scared them into flight. The faster birds would be farther away, with distance proportional to the speed at which they flew away from you. This sounds like the Hubble Law. Could a gigantic explosion centered on the Milky Way, hurtling many galaxies outward at different speeds, explain the Hubble Law? Why is such a model not attractive?

B. How can a universe have no boundary in space? What does it expand into?

C. Can science ever address the question of why the universe exists? Is this necessarily a valid question to ask?

D. Do you find a universe with a beginning easier or more difficult to comprehend than one that has always existed?

E. Is an ever-existing multiverse more attractive from a philosophical standpoint than the idea that a conscious being — God — created the universe? What are the problems with each concept?

F. Can there be nothing, *i.e.*, nonexistence? Can you express such a concept without using a form of the verb "is" that implies existence?

G. Do you think that we will never be able to determine the validity of all our theories about the origin and underlying nature of the universe because we are inside it?

H. Enter the world of science fiction. Suppose that you were an outstanding computer programmer and wrote a program that creates a multi-dimensional grid containing digital entities capable of sensing their surroundings, understanding what their senses imply, making decisions, moving through the grid, acting to change their environment, communicating with each other, etc. What relation would their world have to the world you live in, out of which they were created? Could you interact with their world so that they could not prove that you did so? What theology and speculations about existence and the origin of the universe might they have? Would any of these speculations and beliefs be good descriptions of the actual situation?

I. Consider the "multiverse" idea or the model in which the universe is infinite in space and has existed forever. In either case, it must be true that whatever can happen does happen from place to place and from time to time. If so, then there would be many beings essentially identical to you in all the possible variations of the circumstances and events of your life. What does this imply? Compare this concept with Everett's many worlds hypothesis designed to deal with the apparent logical inconsistencies of quantum theory (see Box 7-2 of Ch. 7).

Examples of How to Solve Problems Related to Cosmic Distances and the Hubble Law

1. A galaxy is located 50 Mpc from the Sun.

a. Calculate the velocity (in km/s) at which the galaxy recedes from us.

Answer: We use eq. (10-1) with H_0 = 70 km/s/Mpc: $v = H_0 d$ = (70 km/s/Mpc)(50 Mpc) = 3500 km/s.

We should really check to make sure that this is less than about 0.2 times the speed of light, since otherwise we need to worry about Special Relativity and eq. (10-1) would be inaccurate:
v/c = (3500 km/s)/(300,000 km/s) = 0.012. Since this is much less than 0.2, the answer is accurate.

b. Calculate how many years the light has traveled from the galaxy to reach us.

Answer: This is the same as converting Mpc to millions of light-years; all that is required to do this is to multiply the distance in Mpc by 3.26 (since 1 pc = 3.26 lt-yr). The answer will then be in millions of years, since it takes light 1 million years to travel 1 million lt-yr. So, we have

d = 50 Mpc (3.26 Mlt-yr/Mpc) = 160 million lt-yr. So, the light has traveled 160 million years to reach us.

2. The spectrum of a galaxy contains the Hα emission line of hydrogen, which has a rest wavelength of 656.3 nm. The observed wavelength is 676.0 nm.

a. What is the redshift of the galaxy?

Answer: We use eq. 10-3: $z = \lambda_{obs}/\lambda_0 - 1$ = (676.0 nm/656.1 nm) – 1 = 1.03 – 1 = 0.03

b. What is the velocity at which the galaxy recedes from us in km/s?

Answer: We use the approximation (see discussion between eqs. 10-3 & 10-4)
$v = cz$ = (300,000 km/s)(0.03) = 9000 km/s

c. What is the distance to the galaxy in Mpc?

Answer: We use the Hubble law, eq. 10-4: $d = cz/H_0$ = (9000 km/s)/(70 km/s/Mpc) = 130 Mpc

3. Galaxy A and galaxy B are estimated to have identical luminosities. Galaxy A is 100 times brighter than Galaxy B. From observations of Cepheid variables, we know that the distance to galaxy A is 2.0 Mpc. What is the distance to galaxy B?

Answer: We need to use eq. 6-2 for the distance. Since we do not know the luminosity, we need to form an algebraic ratio from that equation:

$$\frac{d_B}{d_A} = \frac{\sqrt{\frac{L_B}{4\pi B_B}}}{\sqrt{\frac{L_A}{4\pi B_A}}} = \sqrt{\frac{L_B}{4\pi B_B}} \times \sqrt{\frac{4\pi B_A}{L_A}} = \sqrt{\frac{4\pi B_A L_B}{4\pi B_B L_A}} = \sqrt{\frac{B_A}{B_B}}.$$

The simplification is possible because $L_A = L_B$ and the 4π's cancel. We can now solve for d_B:

$$d_B = d_A\sqrt{\frac{B_A}{B_B}} = (2.0\text{ Mpc})\sqrt{100} = \underline{20\text{ Mpc}}.$$

Homework Problems

Note: For problems in which you need to use Hubble's constant, adopt a value H_0 = 70 km/s/Mpc. Assume that the light from the stars and galaxies in question is not absorbed or scattered on its way to us.

1. A large elliptical galaxy at the center of a cluster of galaxies is located at a distance of 420 Mpc from us.

a. Calculate the velocity (in km/s) at which the galaxy recedes from us if its motion is completely due to the expansion of the universe as expressed by the Hubble Law.

b. Calculate how many years the light has traveled from the galaxy to reach us.

2. A very luminous type of star is observed in galaxy X, and another one is observed in galaxy Y. The distance to galaxy X has already been determined to be 5 Mpc. The star in galaxy X is 900 times brighter than the star in galaxy Y.

a. Calculate the distance to galaxy Y. [*Note:* Ch. 6 discusses how to do this and gives some worked-out examples.]

b. Calculate the velocity at which galaxy Y is expected to move away from us if its motion is completely due to the expansion of the universe as expressed by the Hubble Law.

3. The Balmer beta line of hydrogen, Hβ, has a rest wavelength of 486.1 nm. Astronomers observe an Hβ emission line from the center of a galaxy at a wavelength of 515.3 nm.

a. What is the redshift z of the galaxy?

b. What is the velocity at which the galaxy is moving away from us in km/s?

c. What is the distance to the galaxy?

4. The Balmer alpha line of hydrogen, Hα, has a rest wavelength of 656.3 nm. Astronomers observe an Hα emission line at a wavelength of 702.2 nm from the center of a galaxy.

a. What is the redshift z of the galaxy?

b. What is the velocity at which the galaxy is moving away from us in km/s?

c. What is the distance to the galaxy?

Homework Questions Requiring Logic

Explain how you arrive at your response to each question.

5. Two galaxies have spectra with the same redshift, $z = 0.05$. However, one of the galaxies is 100 times fainter than the other.

a. What is the simplest explanation of the difference in brightness?

b. What is another, less simple, possible explanation?

c. Propose one test for each of the two hypotheses.

6. Two galaxies lie next to each other on the sky. One has a redshift corresponding to a velocity of 350 km/s while the other has a velocity of 700 km/s. Propose two possible explanations of this. State which one you think is more likely and explain why. Is there a way to test these possible explanations?

7. If the Hubble Law diagram (Fig. 10-2) followed a straight line out to 50 Mpc but was flat beyond that, what would we conclude about the expansion of the universe? Keep in mind that the light that we now see from a galaxy left that galaxy at a time earlier than the present by an amount equal to its distance in light years.

Homework Questions Requiring Extra Thought

8. Edwin Hubble estimated the value of the Hubble constant to be about 7 times higher than our current measurement. A major part of his error was his assumption that the Cepheid variables he used to determine distances to galaxies are the same as those he observed in our Galaxy. We now know that there are two types. The type whose period-luminosity relation Hubble used are 3.6 times less luminous than those that he observed in the other galaxies. What was his error in the determination of distances to other galaxies because of this? You should answer this by determining the ratio of his calculated distance to the true distance. (See the discussion on distances using Cepheid variables in Ch. 6.)

9. Galaxy X has a redshift $z_X=0.05$. Galaxy Y lies in the same direction and has a redshift $z_Y=0.02$.
a. What is the redshift of galaxy X as observed from galaxy Y?
b. What is the redshift of galaxy Y as observed from galaxy X?

Astronomical Puzzle (Class Exercise)

10. Quasars are extraordinarily luminous objects that can be observed out to great distances. The standard explanation is that they are the centers of galaxies, each containing a supermassive black hole (see ch. 12) onto which gas falls at a fast rate. The distances to quasars are determined from the Hubble Law based on the high redshifts of emission lines in their spectra. Some astronomers have reported that quasars tend to cluster around galaxies having much smaller redshifts, which is very odd if the distances are much greater than those of the galaxies that are close to them on the sky. What are possible explanations of these observations?

Points to consider:
i. Are there any other possible processes that could cause a redshift? If so, try to devise a test of the hypothesis by considering what observational properties would result if it were true.
ii. Is there any reason for unassociated objects to appear close to each other on the sky?
iii. Is use of the Hubble Law appropriate when distances are greater than those of the galaxies used to determine Hubble's constant?