Chapter 26: Cosmology

The Big Bang and the Fate of the Universe

Outline

26.1 The Universe on the Largest Scales
26.2 The Expanding Universe
26.3 The Fate of the Cosmos
26.4 The Geometry of Space
26.5 Will the Universe Expand Forever?
26.6 Dark Energy and Cosmology
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Summary

The origin, history, and fate of our universe are the topics of Chapter 26. The Big Bang theory and observational evidence in support of it are discussed. New data regarding a possible acceleration of the expansion of the universe are presented, and dark energy is introduced.

It is not uncommon for the General Education or Liberal Arts student to get overwhelmed by the material in this chapter. And it will get worse in the next chapter! How do you get them connected to this material? What is the most important aspect of this chapter that you would hope they really understand and remember? Probably the most important concept for them to learn is that the universe has an age. Not only does it have an age, we can measure how old it is. And it is truly amazing that we can do this and that it is not all that conceptually difficult. At first your students may be surprised that the universe even has an age; the notion that it is infinitely old or ageless is not uncommon. The universe is not 50 million years old, nor is it 810 billion years old, nor 6 trillion. A common misconception among students is that there is no way to determine the age of the Universe. This chapter will dispel that misconception by introducing the methods used for doing just that.

Major Concepts

- Cosmological principle
  - Homogeneity
  - Isotropy
  - No edge or center to the universe
- Expansion and the Big Bang
  - Hubble's law
  - Cosmological redshift
  - Olbers's paradox
  - The Big Bang
- The fate of the universe
  - Critical density
  - Models: unbound, marginally bound, bound
  - The age of the universe
  - Cosmic accceleration
- Geometry and curvature of space
- Cosmic background radiation

Teaching Suggestions and Demonstrations

Cosmology deals with the so-called "big questions"; the questions students asked themselves just before deciding to sign up for your class. The subject can be mind-boggling. Tell students that if they leave class with no questions and with a sense of complete understanding, they must not have been paying attention! Encourage discussion and questions, and remind students that all the puzzles are certainly not yet solved in this field. Cosmology requires students to imagine both incredibly short and incredibly long times, to think outside our world of three dimensions, and to consider the most fundamental questions, such as, "How did the universe begin and how will it end?"

Section 26.1

Since the beginning of the course, you have been showing your students how our early perceptions placed us at the center of the Universe. As our observations changed, we moved away from our lofty position until we landed in the outer reaches of a galaxy among billions. The **cosmological principle** takes this one step further. Students may at first balk at the assumptions of the cosmological principle. After all, we have been discussing all semester how matter is organized and clustered. Assure them that the homogeneity requirement applies to large scales only, not to our immediate neighborhood, galaxy, or cluster of galaxies. Show the galaxy survey in Figure 26.1. The idea that the universe has no edge follows directly from the cosmological principle. (Besides, how could it have an edge? Edges are boundaries and what could be on the other side that we would not include as part of our universe?) Then, the idea that there is no center follows directly from the idea that there is no edge. Challenge students to find the center of the room with no references to the edges. Better yet, show the balloon again and ask the students where the "center" of the *surface* is. (Remember, though, that the Universe, in this analogy, does not include the interior of the balloon.)

Section 26.2

Pose Olbers's paradox to see if any students can come up with a solution. Remind them of Hubble's law relating recessional velocity to distance, which was described in Chapter 24. To explain why this observation implies **cosmic expansion** (and to also explain why it does not imply that we are at the "center"—a common student misconception) use an analogy. For example, draw three cars in a row traveling down the highway. Imagine that the first one is going 80 mph, the second 60 mph, and the third 40 mph. Then ask students to imagine the view from any one of the vehicles. People in the last car see both of the others receding from them, with the first one receding at a greater rate. People in the middle car also see both vehicles receding, one in each direction. And, those in the front car see the other two cars moving away also, as they fall farther and farther behind. The space between the vehicles is expanding, and each observer sees the more distant car moving the fastest.

A very common analogy used in astronomy texts is usually called the **"raisin cake" model**. You mix up batter for a raisin cake and put it in the oven. The raisins are spread throughout the batter. As the cake bakes and expands, the raisins are carried apart from each other. If two raisins begin, say, 2 cm apart and spread to 6 cm apart by the end of a certain time, then two raisins that were originally 4 cm apart will spread to 12 cm in the same time. The recessional velocity in the second case was greater. The batter expanded, carrying the raisins with it. In a similar way, space expands, carrying the galaxies with it.

The raisin cake analogy is useful to help students visualize the Hubble Law in 3-D. The problem with it, though, is that the cake clearly has edges. An excellent analogy to use, which gets around this problem, is the **balloon analogy** as shown in Figure 26.5. ➲ DEMO Rather than tape objects to the balloon, you could simply draw small galaxies on the balloon and have the students describe what happens when the balloon is inflated. The best way to set this demonstration is to partially inflate the balloon (before class) and draw small galaxies on the surface using a permanent marker. By drawing small galaxies with the balloon partially inflated, you are less likely to see galaxies themselves expand while the balloon inflates. Once you have drawn your galaxies, let the air out of the balloon and you are ready for class. Another note: you will find it most constructive to use a spherical balloon.

There are so many concepts you can show with the balloon: isotropy, homogeneity, curvature of space, no edge to the universe, the Hubble Law, no center to the universe, play back the universe to the Big Bang, the expansion of space rather than motion of galaxies through space. A good Hubble Law can be derived using this demonstration and a cloth or paper measuring tape. Inflate the balloon and measure a few distances from a "home" galaxy. Inflate the balloon some more and re-measure the distances. Calculate a "velocity" by dividing the change in distance by some arbitrary amount of time. Plot these velocities against the new distances and a Hubble Law will be seen.

You can also use the balloon analogy to demonstrate the **cosmological redshift** and compare it to the Doppler redshift. As a photon travels to us through space, its wavelength is stretched as the space itself expands. Try the demonstration shown in Figure 26.6. Point out that the wavelength expands as the photon moves through the expanding universe. The wavelengths of the photons which travel further are given more time to expand, while those that originate from closer galaxies do not have time to expand as much. This is why the most distant objects are redshifted more than the objects that are closer.

Blow up the original balloon (with the galaxies) one more time; then slowly release the air and ask students to watch the galaxies as the expansion of the universe is played backwards. If you could remove all the air, then the galaxies would all land back in one spot. So, Hubble's law and the expansion of the universe imply that the universe all began in one spot. All of matter and space was one point that exploded in an event named the **Big Bang**, which marked the beginning of the universe. Students will almost certainly have heard of the Big Bang; thus, present the current observation of the expansion of the universe as the first piece of evidence in support of the Big Bang theory.

A limit to the **time that has elapsed since the Big Bang** can be estimated, as described in the text, from $1/H_0$. To show students why this is true, do some other examples. If you drive 120 miles at a velocity of 60 mph, how long ago did you start? To get 14 billion years from 1/(70 km/s/Mpc) you need to do some unit conversions. Take the time to do it; an estimation of the age of the universe is fundamentally important, and students should see where the value of 14 billion years comes from. Also discuss that this estimate depends critically on the value chosen for the Hubble constant *and* also on an assumption that this value has been constant over time. What if the expansion of space has slowed over time, for instance? Imagine your friend traveling 120 miles to see you. You have a view of the highway and notice she is going 40 mph as she approaches the exit. If you assume she went 40 mph the whole time, then you calculate that she took 3 hours to make the trip. If, however, she was going 60 mph earlier and slowed later, then the trip took less time.

There is certainly a lot of uncertainty about **when** the Big Bang occurred, but astronomers are in general agreement that it did occur and it marks the beginning of the universe. Very likely, at least one of your students will ask the question, "What happened *before* the Big Bang?" One answer is simply that there is no such thing as *before* the Big Bang – time started with it. A brilliant analogy for a similar type of question given by Stephen Hawking (paraphrased) is the following: Imagine standing exactly on the North Pole of Earth. Where is 2 miles north of your location?

The question "**where** was the Big Bang" can be even tougher than "when was the Big Bang" for students to grapple with. Pull out the balloon again, inflate it, and then deflate it. Ask students which sticker or coin represents the center of the expansion. The answer is that none of them represents the center. All space was at one point at the time of the Big Bang. The explosion did not fling matter through space, originating at one point; it flung space itself.

Section 26.3

Use lots of diagrams and analogies in discussing these sections, which can be very difficult for students to understand, but also very exciting as they involve research at the forefront of astronomy. Figure 26.8 and the analogy of the spacecraft leaving the planet helps students understand the difference between a bound and an unbound universe. Explain the concept of **critical density** carefully, because the density of the universe plays such an important role in its evolution and fate. Figure 26.9 looks fairly simple but will require explanation. Point out that we are stuck at our current spot in time; all three lines pass through that point because that represents the rate of expansion we now experience. What the universe was like in the past or will be like in the future is not known positively; different options are shown by the different curves.

To probe the concept of critical density more deeply, we can once again use some of the very simple physics used in previous chapters to actually calculate the value of the critical density, and it is surprisingly simple. The critical density occurs when the motions of the galaxies are essentially moving with exactly the right velocity to just escape the gravitational pull of the matter in the universe. We know that the escape velocity is

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

Now express the mass in terms of a density, using a spherical volume.

$$M = \frac{4}{3}\pi R^3 \rho$$

Substituting for *M* and squaring both sides gives

$$v_{esc}{}^2 = \frac{8}{3}\pi G R^2 \rho$$

But the velocity can be given by using the Hubble Law. Note that the distance *R* is just any arbitrary distance and the Hubble Law can be written as $v = \mathrm{H}_0 R$. This velocity is also the same as the escape velocity because that is how fast the galaxies are moving in this case.

$$\mathrm{H}_0{}^2 R^2 = \frac{8}{3}\pi G R^2 \rho$$

Finally, solving for the density we get

$$\rho = \frac{3}{8\pi G}\mathrm{H}_0{}^2$$

Putting in a value for H_0 of 70 km/s/Mpc, the density is 1×10^{-26} kg/m^3. Notice that the density depends strongly on the Hubble constant. If the Hubble constant is smaller than 70, then the critical density is significantly less, although not small enough to solve the dark matter problem. It is amazing that, from the simple concept of the escape velocity which was derived in an early chapter, we have succeeded in computing the critical density of the universe. A little physics can be a powerful tool.

Section 26.4

Bring the balloon back out as an example of positive **curvature**. Of course, its surface is two-dimensional, so it is only an analogy of what positively curved space-time would be like. Explain to students that as three-dimensional (3-D) creatures ourselves, it is very difficult for us to imagine curved 3-D space. So, we imagine a 2-D universe instead. Blow the balloon up and notice not only the expansion but also that this balloon-surface universe is bounded, has no center, and has no edge. The 2-D analogies for flat and negatively curved space are a plane and a saddle. (See *More Precisely 26-1*.)

Sections 26.5 and 26.6

An example of calculating the actual density of matter is interesting because there is one easy example available and the results may not be expected. The Local Group has a diameter of about 1 million pc. Its (spherical) volume calculates to be 1.5×10^{67} m^3. The Andromeda and Milky Way galaxies dominate with masses about 3×10^{11} solar masses. M33 has a bit less mass at 1×10^{11} solar masses and the other 18 galaxies combined are probably another 1×10^{11} solar masses. The total mass is 8×10^{11} solar masses or 1.5×10^{42} kg. Dividing mass by volume gives a density of 10^{-25} kg/m^3 for the Local Group. This is 10 times the critical density and it doesn't even include dark matter!

Have we over-estimated the mass? Not really, for the answer to equal the critical density would mean there could only be 1×10^{11} solar masses in this volume and we know the Milky Way is more massive than this. Possibly we have underestimated the volume. This is much more likely. The critical density requires calculating an <u>average</u> density for the universe. The Local Group is a small cluster or concentration of matter; this is probably not at all average for the universe. By increasing the radius of the Local Group by a factor of 2 (which would encompass little additional mass), the density would be the same as the critical density. This example demonstrates the difficulty astronomers encounter when trying to determine the actual density of matter in the universe.

Figure 26.12 is another very important one, as it represents observational evidence that the universe's expansion is **accelerating**. This fairly new idea surprised astronomers; it should sound surprising to students as well because it does not at all fit the gravity-dominated scenario we have assumed up to now. Gravity is apparently *not* slowing down the rate of expansion as predicted; something else must be involved. (What if you threw a ball up in the air, and instead of slowing down because of gravity, it sped up?) Introduce **dark energy** and the uncertainties that surround it. Go over the excellent discussion of the age of the universe and Figure 26.14 carefully.

Section 26.7

➲ **DEMO** The **cosmic background radiation** phenomenon can be easily demonstrated. Bring out one more time the balloon on which you had drawn the small wavelength radiation. It is the best way to demonstrate the cosmic background radiation. With the balloon inflated only a slight amount, point to the waves and tell the students that they are the very high energy (short wavelength) photons that were everywhere during the very early stages of the expansion. Ask them to watch what happens as the balloon is inflated. Also, once you have inflated the balloon, ask them whether the wavelengths, if detected today, would be higher or lower energy than when they originated in the early Universe. You can go through some straightforward mathematics to show that the wavelengths of the modern radiation (the cosmic background radiation) is longer by the same ratio as the size of the Universe today compared to the expected size when the energetic photons were flying around everywhere. The wavelength of the photons has expanded into the microwave region of the electromagnetic spectrum.

Student Writing Questions

1. What kind of universe do you want to live in: open, closed, or flat? Why? Scientists also have their preferences (we prefer to say preference rather than bias), and this can influence how they may interpret observations. It is a part of being human. The question "Why?" is important. Why should you or anyone prefer the universe to be one way or the other? Try to explain your personal feelings about this.

2. What if a significant part of the redshift measured for all extragalactic objects was actually non-Doppler. That is, instead of the redshift being interpreted as completely due to motion or even the Hubble flow, a significant part of it was due to some unexplained phenomenon. How would this affect the Hubble constant? Would dark matter be "necessary?" Would clusters of galaxies be unstable? What would be the effects on the cosmic density parameter? What else would be affected by this discovery?

3. About 500 years ago people struggled with the concept of a curved surface for Earth. (Even longer ago than this, but at this time, more people were affected. Sailors feared falling off the edge of Earth.) Relate the difficulty in understanding this concept with the current problem of understanding the concept of the curvature of space. How are they similar and how are they different? What role does human experience play in understanding these concepts?

Answers to End of Chapter Exercises

Review and Discussion

1. Pencil-beam surveys extending to a distance of 2000 Mpc suggest that the universe is uniform on a large scale. There do not appear to be any structures larger than about 200 Mpc.

2. The cosmological principle is made up of two assumptions fundamental to cosmology. They are homogeneity and isotropy. At a large enough scale, the universe is homogeneous; one part is pretty much like any other part. Isotropy means that it looks the same in all directions. The cosmological principle tells us there can be no edge to the universe and there is no center to it either.

3. According to the cosmological principle, the universe is homogeneous and isotropic. If it is also infinite in extent and unchanging in time, then the universe is uniformly populated with galaxies filled with stars. In that case, when you look at the night sky, your line of sight must eventually encounter a star; the sky should appear as bright as the surface of the Sun. This was first proposed by Olber and is known as Olber's paradox. Since this is not what is observed, however, something must be different than what was assumed. The universe is, in fact, not infinite and it is also expanding. The expansion redshifts the radiation to longer wavelengths, so distant stars would not be seen in the visible part of the spectrum.

4. Hubble's law is a relationship between velocity of recession of objects in the universe and their distance, $v = H_0 d$. Since we know that velocity is distance divided by time, the Hubble constant, H_0, is a measure of one divided by time, the time of the expansion of the universe to its present size. It turns out that this time gives a maximum age for the universe.

5. Although we appear to be at the center of the Hubble flow, it turns out that all other locations in the universe appear to be at the center too. This is due to the fact that the Hubble flow is not due to the motion of objects into the universe; rather, it is an expansion of the universe itself. Space, itself, is expanding.

6. Since the Hubble flow is an expansion of space itself, galaxies are not rushing outward into unoccupied parts of the universe. The universe is evenly filled with matter but space is expanding, which gives rise to an appearance of galaxies flying outward from us.

7. Where did the Big Bang occur? In a word, everywhere. It was an explosion of all of space and time, not an explosion in space.

8. A wave of electromagnetic radiation, as it moves through the universe, will experience the same expansion of the space experienced by the universe. As the wave travels farther and farther, it expands more and more. By the time it is observed, it appears redshifted in proportion to the distance it has traveled.

9. The density of matter in the universe determines whether it will expand forever or not. If the density of the universe is sufficiently high, the universe will eventually stop expanding and start collapsing. If the density of the universe is sufficiently low, the universe will continue to expand forever. Between these two extremes is the critical density; the universe will stop expanding after an infinite amount of time. The value of the critical density depends on the Hubble constant.

10. Everything continues to expand; eventually no galaxies are even visible from Earth. Stars will die out and the universe will experience a "cold death." Everything will freeze.

11. There is not enough luminous matter known in the universe to stop its expansion. In fact, there appears to be about 100 times too little of this matter to stop the expansion.

12. The amount of dark matter in the universe is still not well known. There may be enough to produce the critical density; maybe there is even more. There are other arguments that suggest the total density of matter (luminous and dark) must be at the critical density.

13. The observations of distant supernovae indicate motions that are slower than expected. This suggests that the universe is actually accelerating.

14. The cosmological constant is a factor used to "adjust" how the universe expands. Previously thought to be zero, it now is estimated to have a value that accounts for the acceleration of the universe that distant supernovae suggests is occurring. What it actually is or what causes it is not known.

15. Globular clusters are the oldest objects observed that can be accurately age dated. The universe must be older than these clusters, so their oldest ages are important to determine. Their age sets the minimum age for the universe.

16. Just after the Big Bang occurred, the universe was filled with X-ray and gamma-ray radiation. Since that period, it has traveled through the universe, its wavelength expanding

as the universe has expanded. It is now observed in the microwave part of the spectrum. It proves us with information about the very early universe; it is the light from the very oldest object visible in the universe—the universe itself!

17. The cosmic microwave background radiation is black body radiation. As its wavelength expands, the representative temperature must drop, according to Wien's law.

18. The cosmic microwave background is theoretically isotropic (the same in all directions). But observations show a subtle difference in two opposite directions that can be accounted for by our absolute motion through space.

19. Modern cosmology is based upon specific scientific principles, which are testable. It also makes predictions which are also testable. This approach may not, in the end, preserve our current cosmological theories, but it will lead to a more thorough understanding of the universe and a consistent theory of its formation and evolution.

20. Dark matter and dark energy, at this time, are simply names to things that appear to exist but for which there is no known explanation. Actually, explanations exist but astronomers are uncertain whether any are correct! Is it good science? Right now, astronomers seem to be given little choice in the matter because observations have contradictions to classical theories. Many new things have been discovered, about this there is no doubt. Whether dark matter or energy are the correct explanations will be determined through more good science and observation.

Conceptual Self-Test

1. F
2. F
3. F
4. T
5. F
6. F
7. F
8. T
9. T
10. T
11. A
12. D
13. B
14. B
15. B
16. D
17. C
18. C
19. D
20. D

Problems

1. 20 - (-20) = 5Log(d) - 5, $d = 10^9$ pc.

2. The distance is 1,000 Mpc. Interpolate between the values of 873 Mpc for a redshift of 0.200 and 1080 Mpc for 0.250. This will be only a rough estimate because this type of

interpolation requires a linear relalationship, which redshift and distance do not have. The result is 0.231.

3. The volume of space out to a distance of one billion parsecs is $\frac{4}{3}\pi\left(1\times10^{9}\ \text{pc}\right)^{3}=4\times10^{27}\ \text{pc}^{3}$. There are $(10^6\text{pc})^3 = 10^{18}\text{pc}^3$ in one cubic megaparsec. Dividing this into the previous volume gives 4×10^9. If the galactic density is 0.1 galaxy per cubic megaparsec, then this number would be multiplied by 0.1 to give 400 million galaxies in this volume.

4. 1 Mpc^3 is a volume equal to $(3.1\times10^{22}\ \text{m})^3 = 3.0\times10^{67}\ \text{m}^3$. The 5 billion stars will each have a volume of $6.0\times10^{57}\ \text{m}^3$. A solar radius is 7×10^8 m, a solar volume is $1.4\times10^{27}\ \text{m}^3$.
How many stars would fit into the volume around one star?
$6.0\times10^{57}\ \text{m}^3 / 1.4\times10^{27}\ \text{m}^3 = 4.2\times10^{30}$ stars.
The volume that would hold that many stars is simply 4.2×10^{30} stars $\times\ 6.0\times10^{57}\ \text{m}^3 = 2.5\times10^{88}\ \text{m}^3$.
The radius of this volume is 1.8×10^{29} m $= 5.9\times10^{12}$ pc $= 5.9\times10^{6}$ Mpc.

5. The diagonal of any one of the 10 by 10 Mpc squares is $\sqrt{200} = 10\sqrt{2}$. The right triangle to be solved has sides of 10 and $10\sqrt{2}$. The hypotenuse is the distance from one corner to the other corner.

$$\text{Distance} = \sqrt{10^2 + (10\sqrt{2})^2}$$

$$\text{Distance} = 17\ \text{Mpc}$$

The recessional velocity at this distance is $17 \times 70 = 1200$ km/s.

6. The maximum age of the universe is given by $1/H_0$. But units must be resolved because of the mixture of km and Mpc, seconds and years. $\text{Mpc} = 3.1\times10^{19}$ km and 1 yr $= 3.2\times10^{7}$ s.

$$\text{Age} = \frac{1}{H_0} = \frac{3.1\times10^{19}\ \text{km/Mpc}}{H_0\times3.2\times10^{7}\ \text{s/yr}} = \frac{9.7\times10^{11}\ \text{yr}}{H_0} = \frac{970}{H_0}\ \text{billion years}$$

For the three values of the Hubble constant given, the ages are 16, 14 and 12 billion years old, respectively.

7. (a) 1 $\text{A.U.}^3 = 3.35\times10^{33}\ \text{m}^3$. Multiplying this by the density gives 3.0×10^{7} kg.

(b) The mass of the Earth is 6×10^{24} kg. Dividing this by the density will give the volume, $6.7\times10^{50}\ \text{m}^3$. This is a cube with sides of 9×10^{16} m. This distance is 3 pc.

8. The velocity divided by the Hubble constant gives the distance to the Virgo cluster; 1200 / 70 = 17.1 Mpc. The volume within this distance is $4/3\pi(17{,}100{,}000\ \text{pc})^3 = 2.1\times10^{22}\text{pc}^3$. Converting this to cubic meters gives $6.2\times10^{71}\text{m}^3$. Multiplying by the critical density gives 4.9×10^{45}kg. Dividing by the Sun's mass gives 2.5×10^{15} solar masses.

The escape speed is calculated in the usual way.

$$v_{escape} = \sqrt{\frac{2 \times 6.7 \times 10^{-11} \times 4.9 \times 10^{45}}{5.3 \times 10^{23}}} = 1.1 \times 10^{6} \text{ m/s or } 1100 \text{ km/s}$$

9. (a) Use the expression derived in Problem 6 relating the age of the universe to the Hubble constant. With an age of 12 billion years for the oldest star clusters, this gives H_0 = 970 / 12 = 81 km/s/Mpc.

   (b) For a critical density only, the constant in the previous relationship changes, since as the text states, for H_0 = 70 km/s/Mpc. leads to an age of 10 billion years. Thus, the constant is 700 billion years. Dividing by 12 billion year age of the clusters gives 58 km/s/Mpc.

10. From Table 25.1, take the "radius" of the universe to be 8430 Mpc. 1 Mpc = 3.1×10^{22} m, so this distance is equal to 2.6×10^{26} m. Assuming a spherical volume to the universe, $4/3\pi r^3$ gives 7.5×10^{79} m^3.

    (a) For a critical density of 8×10^{-27} kg/m^3, the total mass will be 6×10^{53} kg.

    (b) One solar mass is 2×10^{30} kg. The above mass of the universe is therefore 3×10^{23} solar masses.

11. The density given is about 100 times smaller than the critical density. Because the density depends on the Hubble constant squared, and this density is 100 times smaller, then the Hubble constant must be 10 times smaller or 70 / 10 = 7.0 km/s/Mpc. This is well below the accepted range from observations.

12. From Wien's law, the wavelength at maximum = 0.29 / T. For T = 2.7 K this gives λ_{max} = 0.107 cm. The redshift is 6; $\Delta\lambda = \lambda_2 - \lambda_1 = 6\lambda_1$. So, $\lambda_2 = 0.107 = 7\lambda_1$. λ_1 = 0.0153 cm. Using Wien's law again, T = 0.29 / 0.0179. T = 19 K.

13. (a) From Wien's law, the wavelength at maximum = 0.29 / T. For T = 2.7 K this gives λ_{max} = 0.11 cm.

    (b) 10 μm = 0.001 cm. 0.001 cm / 0.107 cm = 0.0093

    (c) 100 nm = 10^{-5} cm. 10^{-5} cm / 0.107 = 9.3×10^{-5}

    (d) 1 nm = 10^{-7} cm. 10^{-7} cm / 0.107 = 9.3×10^{-7}

14. From Wien's law, the wavelength at maximum = 0.29 / T. For T = 2.7000 K this gives λ_{max} = 0.107407407 cm. For T = 2.7034 K this gives λ_{max} = 0.107272323 cm.
    $v = (\Delta\lambda / \lambda)c$ = (0.000135083 / 0.107407407)300,000 km/s = 377 km/s

15. As in Problem 12, use Wien's law for a temperature of 6000 K. This gives λ_{max} = 0.000048 cm. The ratio of $\Delta\lambda / \lambda_1$will be the same for all lengths. If d_2 is the current distance to the Virgo Cluster and d_1 was the distance back when T = 6000 K, then the following relationship should hold: $\lambda_2 / \lambda_1 = d_2 / d_1$ and 0.107 / 0.000048 = 18.5 / d_1, d_1 = 8300 pc.

Resource Information

Student CD Media

Movies/Animations
Cosmic Structure
Big Bang

Interactive Student Tutorials
None

Physlet Illustrations
Creation and Annihilation and Temperature

Transparencies

T-246	Figure 26.1	Galaxy Survey	p. 694
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T-248	Figure 26.4	Hubble Expansion	p. 697
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T-251	MP 26-1	Curved Space	p. 705
T-252	Figure 26.12	Accelerating Universe	p. 707
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		Microwave Background Spectrum	p. 712
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		Earth's Motion through the Cosmos	p. 712

Materials

A chart entitled "The History and Fate of the Universe" is available from The Contemporary Physics Education Project. It is also included as a supplement to the March 2003 issue of *The Physics Teacher*. Check http://UniverseAdventure.org for more details.

Be sure to bring a balloon to class for performing some classic cosmology demonstrations.

Suggested Readings

Adams, Fred C. and Laughlin, Greg. "Embracing the end." *Astronomy* (Oct 2000). p. 48. Describes the "Degenerate Era," the ultimate end of the universe when all that remains are the remnants of stars.

Adams, Fred C. and Laughlin, Gregory. "The future of the universe." *Sky & Telescope* (Aug 1998). p. 32. Provides an overview of the entire life of the universe.

Arkani Hamed,Nima; Dimopoulos, Savas; Dvali, Georgi. "The universe's unseen dimensions." *Scientific American* (Aug 2000). p. 62. Describes recent advances in string theory related to cosmology.

Boyle, A.; Grimes, K. "Ghostbusting the Universe." *Astronomy* (December 2003). p. 44. Discusses the role of neutrinos in dark matter. Also includes some discussion of quarks and leptons.

Bromm, V. "Cosmic Renaissance." *Mercury* (Spetember/October 2003). p. 25. Nice discussion of galactic evolution. Nice overview of cosmology.

Caldwell, Robert R.; Kamionkowski, Marc. "Echoes from the big bang." *Scientific American* (Jan 2001). p. 38. Describes small flucuations in the cosmic microwave background that would be formed by gravitational waves from the early universe.

Falk, Dan. "An interconnected universe? Exploring the topology of the cosmos." *Sky & Telescope* (July 1999). p. 44. Discusses the topology of the universe.

Finkbeiner, Ann K. "Cosmic yardsticks: supernovae and the fate of the universe." *Sky & Telescope* (Sept 1998). p. 38. Describes measurements of the Hubble constant using Type-Ia supernovae.

Gallmeier, Jonathan; Grilley, David; Olson, Donald W. "How old is the universe?" *Sky & Telescope* (Jan 1996). p. 92. Gives a computer program which calculates the age of the universe for different input values of the Hubble constant, the density parameter, and the cosmological constant.

Gefter, A. "Decoding the Mystery of Dark Energy." *Mercury* (September/October 2003). p. 34. Nice discussion of Dark Energy. Explores interesting ideas about what might be the outcome of the accelerating universe far into the future.

Glanz, James. "Accelerating the cosmos." *Astronomy* (Oct 1999). p. 44. Describes observations of distant supernovae, the cosmological constant, and the acceleration of the universe.

Glanz, James. "On becoming the material world." *Astronomy* (Feb 1998). p. 44. Discusses primordial nucleosynthesis.

Grimes, K., Boyle, A. "The Universe Takes Shape." *Astronomy* (October 2002). p. 34. Explores various geometries/topologies for the universe. Uses many concepts introduced in this chapter.

Kaku, Michio. "What happened before the Big Bang?" *Astronomy* (May 1996). p. 34. Discusses the idea of parallel universes.

Krauss, Lawrence M. "Cosmological antigravity." *Scientific American* (Jan 1999). p. 52. Discusses explanations for the observed expansion of the universe.

Krauss, Lawrence M. "The history and fate of the universe: a guide to accompany the contemporary physics education cosmology chart." *The Physics Teacher* (Mar 2003). p. 146. An excellent summary of current understanding of the history and future of the universe, with resources for teachers.

Landy, Stephen D. "Mapping the universe: large-scale structures." *Scientific American* (June 1999). p. 38. Describes the results of the Las Campanas Redshift Survey with an emphasis on cosmology and the structure of the universe.

Luminet, Jean Pierre; Starkman, Glenn D.; Weeks, Jeffrey R. "Is space finite?" *Scientific American* (Apr 1999). p. 90. Describes possible topologies of the universe.

Nadis, S. “Will Dark Energy Steal all the Stars?” *Astronomy* (March 2003). p. 42. Excellent overview of Dark Energy. Many enlightening diagrams and an excleent timeline.

Ostriker, Jeremiah P. and Steinhardt, Paul J. “The quintessential universe.” *Scientific American* (Jan 2001). p. 46. Describes our understanding of the structure of the universe.

Parker, Samantha; Roth, Joshua. “To see the world in a grain of sand: the Hubble Deep Field.” *Sky & Telescope* (May 1996). p. 48. Describes results obtained from the Hubble Deep Field.

Rees, Martin. "Just 6 numbers." *Astronomy* (July 2000). p. 54. Describes six numbers that determine the nature of the universe.

Rees, Martin. “Exploring our universe and others.” *Scientific American* (Dec 1999). p. 78. Looks at our state of understanding the universe and discusses direction for future research.

Roth, Joshua. “The race to map the microwave background.” *Sky & Telescope* (Sept 1999). p. 44. Discusses the nature of the cosmic microwave background.

Steele, Diana. “Unveiling the flat universe.” *Astronomy* (Aug 2000). p. 46. Describes BOOMERANG results which support the idea of a flat universe.

Tyson, Neil De Grasse. “On being dense.” *Natural History* (Jan 1996). p. 66. Gives examples of the densities of different components of the universe.

Weil, Thomas A. “Looking back cosmologically.” *Sky & Telescope* (Sept 1997). p. 59. Discusses the concept of the “lookback time” and provides a computer program to calculate the lookback time of an object as a function of the redshift of the object and the value of the Hubble constant.

Witten, E. “Universe on a String.” *Astronomy* (June 2002). p. 40. Discusses string theory and how it might account for dark matter and dark energy.

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: