Chapter 27: The Early Universe

Toward the Beginning of Time

Outline

27.1 Back to the Big Bang
27.2 The Evolution of the Universe
27.3 The Formation of Nuclei and Atoms
27.4 The Inflationary Universe
27.5 The Formation of Structure in the Universe

Summary

This is traditionally the most difficult chapter for students (as well as for the instructor). Although many of the concepts can be discussed, it is ultimately realized that an analytical understanding of the Grand Unified Theories require a fairly significant understanding of the Physics involved yet they can be comprehended intuitively if presented carefully enough.

The chapter walks through the various eras in which matter condensed out of the primordial energy soup. As post Big Bang temperatures decreased with the expansion, energetic particles were more and more able to interact with one another forming larger and larger entities. As discussed in this chapter, the process continues to this day giving us the large-scale observable structure that has been the topic of discussion for the previous chapters.

Major Concepts

- Radiation-dominated era
- Primordial nucleosynthesis
- Formation of atoms and decoupling
- Inflation
- Horizon and flatness problems
- Formation of large-scale structure

Teaching Suggestions and Demonstrations

Table 27-1 is an excellent place to start for everyone. The sequence of events in the major eras and epochs should be understandable to most students. Normally a table like this might be presented in a scaled time-line. But even by using a logarithmic scale, it is not easy to show events from 10^{-43} s to 10^{10} years. Continue to refer back to this table while discussing the chapter. Have this table put onto a transparency and have it projected during lecture. While discussing a specific epoch, seeing the table will remind students of the era, time, and temperature of that epoch and its position relative to the other epochs.

Sections 27.1 – 27.3

Students often are able to relate to observational material better than theory. Much of the content of this chapter attempts to explain specific observations discussed in previous chapters. Some new observations are also introduced. There are a surprising number of observations that guide our understanding of the early universe. Use the following list as a guide.

1. The Hubble Law,
2. 2.7 K microwave background radiation,
3. Isotropy of the microwave background radiation,
4. Fluctuations in the microwave background radiation,
5. The primordial helium abundance,
6. The primordial deuterium abundance,
7. The ratio of the average mass density to the critical density (Ω_0),
8. The large scale structure of the universe,
9. The times of formation of quasars and galaxies,
10. Particle physics (most of which is not familiar to students but is critical to the discussion),
11. The basic forces of nature.

In each section, try to relate the material directly to one or more of the above observations. The theories attempt to reproduce and interpret what is observed. Here are the sections and the observations (by number) which are related to them.

27.1	Radiation Era	2, 3, 4, 10
27.2	Primordial Nucleosynthesis	5, 6, 7, 10
27.3	Formation of Atoms	2, 5
27.4	Cosmic Inflation	1, 3, 7, 10, 11
27.5	Growth of Perturbations	4, 8, 9

Section 27.4

The epoch of **inflation** is a particularly interesting one. To explain how it solves the flatness problem use the analogy of the ant on the balloon shown in Figure 27.13. To explain how it solves the horizon problem, imagine a few students spread out in the classroom. Someone comes in the door and whispers a message to a student, who then passes it to the next, and so forth until it has reached the other side of the room. This process would take a certain amount of time. In the inflation model, the students would all be clumped together in the middle of the room, would receive the message, and then (somehow) spread very quickly (that is "inflate") to opposite sides of the room. Hence, two people on opposite sides of the room would both know the message, even if not enough time had passed for the message itself to travel from one side to the other.

Section 27.5

The ripples in the background radiation found by the *COBE* satellite are yet another piece of evidence in support of both the Big Bang and the theory of the early evolution of the universe. They are consistent with the current structure of voids and filaments. As you discuss this chapter, constantly relate the material to observations and remind students that the theories are trying to reproduce and interpret what is seen observationally.

Student Writing Questions

1. What are the consequences of inflation not being correct? How will we know whether or not it occurred? Are there other solutions to the horizon and flatness problems that don't require inflation?

2. How might the universe be different today if heavy element nucleosynthesis had occurred during the Big Bang? Would stars and galaxies be any different? How about life; would it have developed differently, faster, not at all?

3. In the last few chapters you have encountered some of the greatest discoveries relevant to understanding our universe: nucleosynthesis, relativity, the Hubble Law, the cosmic microwave background, fluctuations in the background, dark matter, inflation. There may be others you would include too. Which, in your opinion, is the greatest discovery of them all? Which discovery truly changed forever the way humans view the universe? Justify your decision with specific reasons. Do not limit your answer to just scientific relevancy.

4. You now have a perspective on the evolution of the entire universe, and you are here studying it. What do you believe have been the most critical events over the past 13 billion to 15 billion years that have made it possible for you to be studying astronomy at this time?

Answers to End of Chapter Exercises

Review and Discussion

1. A few thousand years after the Big Bang, the amounts of radiation and matter were equal. Before that time, the universe was dominated by radiation; since then, it has been dominated by matter. The temperature was about 60,000 K.

2. Dark energy was not important in the early universe. It becomes more important as the universe expands because its density remains constant whereas the density of matter and radiation decrease.

3. The Planck epoch requires a theory of quantum gravity, which does not exist today. There is also nothing known observationally about that period of time.

4. Matter was formed in the order of neutrons and protons, then electrons, and finally helium and deuterium. This occurred as the universe expanded and cooled. When it finally cooled to about 4500 K, electrons recombined with atomic nuclei, forming atoms. This produced the event known as decoupling and it occurred when the universe was about 200,000 years old.

5. By the end of the galactic epoch, matter was no longer distributed smoothly throughout the universe. Large-scale structure had formed. Quasars were already shining brightly and the first stars had started to form. This was about one billion years after the Big Bang.

6. When the universe was about 100 seconds old, conditions such as temperature and density were just right for the fusion of protons and neutrons to form helium. 25% of matter by mass was converted in helium at that time. Not until stars started nucleosynthesis did hydrogen fuse into helium again. But all matter in the universe contains at least this 25% helium; any more than this is due to stellar nucleosynthesis.

7. To form elements heavier than helium requires temperatures and pressures greater than those needed to form helium. But the universe was expanding; temperature and pressure were dropping. So, after helium was formed, heavier elements could not form because temperature and pressure were too low.

8. Virtually all the deuterium was used in the formation of helium; little remained from this time.

9. The amount of deuterium that remains today depends on the amount that remained after helium was formed. That amount was very sensitive to the conditions of the universe at that time, particularly the density. The greater the density, the less deuterium that should have been left over. The deuterium abundance suggests that $\Omega_0 \approx 0.1$.

10. Helium and deuterium abundances strongly suggest that normal matter makes up only a few percent of the critical density but the total matter density is about one third the critical density.

11. When the universe cooled to the point where electrons could recombine with nuclei, neutral atoms started to appear. Radiation no longer interacted strongly with matter and the universe became transparent. The universe was a few hundred thousand years old at the time.

12. When the universe became transparent, the radiation and matter became decoupled; they no longer interacted. That radiation is still visible today and is called the cosmic microwave background radiation.

13. The epoch of inflation occurred when the universe was 10^{-35} s old. The universe doubled in size every 10^{-34} s until it was 10^{50} times bigger than before. This all ended at about 10^{-32} s.

14. The horizon problem is solved by inflation by taking points that were close together and in communication with each other and quickly separating them. They are the same today because they were the same then.

15. The flatness problem is solved by inflation. Although space was curved, at the time of inflation the universe grew so large, the curvature is now no longer significant.

16. If inflation is correct, then the density of the universe must be the critical density.

17. Hot dark matter is composed of lightweight particles—much less massive than the electron. The neutrino is an example of hot dark matter. Cold dark matter is composed of massive particles formed during the GUT era.

18. Fluctuations in baryonic matter could not have formed large-scale structures in as short a time as is observed. Dark matter decoupled very early from normal matter and its fluctuations had time to grow. Gas was later attracted to these regions, producing the large-scale structure now observed. Hot dark matter can produce large-scale structures but not small-scale structures. Cold dark matter can produce both.

19. Although dark matter is consistent with a high degree of isotropy in the background radiation, it does produce slight variations due to gravitational interaction with the radiation. This was predicted by models and discovered by COBE.

20. The WMAP experiment made high resolution measurements of the temperature fluctuations in the microwave background.

Conceptual Self-Test

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

Problems

1. Decoupling occurred when the universe was 1100 times smaller. 18 Mpc / 1100 = 16 kpc.

2. First, some theory. Mass density is mass divided by volume; $\rho_m \propto m / R^3$. $E = mc^2$. Solving for m gives $m = E / c^2$ so $\rho_E \propto E / R^3$, where this is now the energy density. The energy of a photon is given by $E = hf$, where f is the frequency. So $E \propto 1/\lambda$. As the universe expands, wavelengths expand in proportion; the cosmological redshift. So, $\lambda \propto R$ and $E \propto 1/R$. Substituting for E in the density expression finally gives $\rho_E \propto 1 / R^4$. Note that we started with mass density, which has a $1 / R^3$ dependence. These two different relationships give rise to the two curves in Figure 27.1.

   The density scales as R^4. $1000^4 = 10^{12}$. The density then will be the density now times this factor; 5×10^{-31}kg/m^3 $\times$ 10^{12} = 5×10^{-19} kg/m^3.

   The temperature scales with the size of the universe. It was smaller when at a temperature of one billion K by a factor of $10^9 / 2.7 = 3.7\times10^8$. Proceed as in the previous part of this question. 5×10^{-31}kg/m^3 $\times$ $(3.7\times10^8)^4$ = 9.4×10^3 kg/m^3.

3. From Chapter 25, quasars first formed around redshift of 6, when the universe was 7 times smaller. The temperature is calculated in Chapter 26, Problem 12. T = 19 K.

   Since the density scales as R^3 and the scale has changed by 7, $7^3 = 343$. The critical density is 8×10^{-27}, the density will be 2.7×10^{-24} kg/m^3.

4. (a) At decoupling, the universe was 1100 times smaller. The matter density will be the critical density times the scale factor R^3. $9\times10^{-27} \times (1100)^3 = 1.2\times10^{-17}$. For radiation, it is the current radiation density times R^4. $5\times10^{-31} \times (1100)^4 = 7.3\times10^{-19}$. Matter dominates by a factor of 16. This is consistent with the cross-over event occurring when the universe was 4 times smaller.

   (b) Nucleosynthesis ended at a temperature of 300 million K, or when the universe was 100 million times smaller. Proceed as in the previous part to this question. $9\times10^{-27} \times (10^8)^3 = 0.001$. For radiation, it is the current radiation density times R^4. $5\times10^{-31} \times (10^8)^4 = 50$. Radiation dominates by a factor of 50,000.

5. Since two particles of equal mass are formed, $m = 1.82\times10^{-30}$ kg. $E = 1.82\times10^{-30} \times (3\times10^8)^2$, $E = 1.6\times10^{-13}$ J. $f = 1.6\times10^{-13} / 6.6\times10^{-34}, f = 2.5\times10^{20}$ Hz.
   Now find the wavelength corresponding to this frequency. $\lambda = 3\times10^8 / 2.5\times10^{20}$, $\lambda = 1.2\times10^{-12}$ m $= 1.2\times10^{-10}$ cm.
   Apply Wien's law, solve for T. $T = 0.29/1.2\times10^{-10}$, $T = 2.4\times10^9$ K. The text gives 6×10^9 K.

6. Working backward, find how T depends on the mass of the particle. $T \propto 1/\lambda \propto f \propto E \propto m$. So, for a particle that is 1800 times that of the electron, a temperature 1800 times higher is required for production. For proton-antiproton pair production, this temperature is 6×10^9 K $\times$ 1800 = 1×10^{13} K, just as is given in the text.

7. $\lambda = 0.29 / 10^9$ K, $\lambda = 2.9\times10^{-10}$ cm. According to Figure 3.9 this is in the hard X-ray and gamma ray region.

8. The temperature during this time went from 900 million K to 300 million K. According to problem 1, a factor of 3 decrease in temperature would mean a factor of 3 increase in size. Since the volume goes by R^3, the volume increased by a factor of 27. Mass density would have decreased by the same factor, 27, but energy density would have decreased by a factor of 81.

9. According to the text, decoupling occurred when the universe was about 1100 times smaller. 14000 Mpc divided by 1100 gives 12.7 Mpc.

10. From problem 3 we found that the temperature is proportional to the mass of the particle formed. For a particle that is X times that of the electron, a temperature X higher is required for production. For this new particle, this temperature is 6×10^9 K $\times X = 10^{28}$ K, $X = 1.7\times10^{18}$ the mass of an electron. The mass of an electron is 1.82×10^{-30} kg $\times 1.7\times10^{18} = 3\times10^{-12}$ kg. The same reasoning applies for a particle formed at 10^{32} K. X will be 1.7×10^{22} and the mass will be 3×10^{-8} kg.

11. The following equation must be solved: $2^x = 10^{50}$. The easiest solution is by using logarithms. XLog(2) = 50, X = 166. The universe doubled 166 times in order to expand by 10^{50} in size.

12. The critical density is 9×10^{-27} kg/m^5. Given the mass and the density, the radius will be:
    (a) $R^3 = (10^{12} \times 2\times10^{30}) / (4/3\pi \times 9\times10^{-27})$, $R = 3.8\times10^{22}$ m = 1200 kpc.

    (b) Decoupling occurred at 4500 K. Remembering that the scale of the universe and temperature are inversely proportional, the universe must have been 4500 / 2.7 = 1700 times smaller. R = 740 pc.

(c) If the temperature is taken to be 300 million K, and the end of the nuclear epoch, then the scale was reduced by 300 million / 2.7 = 100 million. R = 2600 A.U.

13. Take the distance to decoupling to be about 14,000 Mpc (redshift of 1100). Use $s = R\theta$, where the angle is expressed in radians. $s = 14{,}000 \times .33 / 57 = 81$ Mpc. But this size is as it appears now, not when the universe was 1100 times smaller. Their size then was about 74 kpc.

14. The end of the GUT epoch occurred at a temperature of 10^{27} K. The universe was 3×10^{26} times smaller. Taking the distance from Table 25.1 to be 14,400 Mpc, the photosphere would have a size of $14{,}400 / 3\times10^{26} = 4.3\times10^{-23}$ Mpc = 1.3 meter.

15. Use a distance of 14,000 Mpc for seeing the radiation at decoupling. The size will be calculated by $s = 14{,}000 \times 1° / 57.3 = 244$ Mpc. But at the time of decoupling, these objects would have been 1100 times small or 0.22 Mpc = 220 kpc.

    Using the "current" size of 244 Mpc, which is the diameter, to give a radius of 122 Mpc and the current critical density to find the mass. $M = 9\times10^{-27} \times 4/3\pi(122 \times 10^6 \times 3.1\times10^{16})^3 = 2.0\times10^{48}$ kg. Dividing by the mass of the Sun, 2×10^{30}, into the total gives 1.0×10^{18} solar masses.

Resource Information

Transparencies

T-257	Figure 27.1	Radiation-Matter Dominance	p. 718
T-258	Figure 27.2	Pair Production	p. 719
T-259	Table 27.1	Major Epochs in the History of the Universe	p. 721
T-260	Figure 27.4	Epochs in Cosmic History	p. 723
T-261	Figure 27.5	Helium Formation	p. 726
T-262	Figure 27.7	Radiation-Matter Decoupling	p. 728
T-263	Figure 27.9	Flatness Problem	p. 730
T-264	Figure 27.11	Cosmic Inflation	p. 731
T-265	Figure 27.12	Inflation and the Horizon Problem	p. 732
T-266	Figure 27.13	Inflation and the Flatness Problem	p. 733
T-267	Figure 27.14	Structure Formation	p. 735
T-268	Figure 27.17	A Flat Universe	p. 737

Materials

The video *Creation of the Universe* (PBS Home Video) is an excellent exploration of many topics in cosmology.

Suggested Readings

Filippenko, A.; Pasachoff, M. "A Universe from Nothing." *Mercury* (March/April 2002). p. 15. Excellent overview of string theory, GUTS and inflation.

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.

Nadis, S. "Cosmic Inflation Comes of Age." *Astronomy* (April 2002). p. 27. Excellent, up-to-date overview of the Inflation theory.

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

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.

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.

Yulsman, Tom. "Give peas a chance: Hawking–Turot pea instanton proposal." *Astronomy* (Sept 1999). p. 38. Discusses theories of the origin of the universe.

Notes and Ideas

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

Demonstration and activity materials:

Notes for next time: