UNIT 2 EXPANDING UNIVERSE

Contents

2.0 OBJECTIVES

- To study the expanding universe.
- To see how expanding universe has given rise to the contemporary cosmological theories.
- To a brief idea of the nature, history and end of the universe.

2.1 INTRODUCTION

In this unit, we explore the phenomenon of expanding universe and see how it has given rise to the scientist cosmology of today. The unit is written depending heavily on the scholarly and reader-friendly article of an American Physicist, Gary Felder (2000).

2.2 THE PHENOMENON OF EXPANDING UNIVERSE

One of the features of the Big Bang cosmological model is an expanding universe. That is, starting from a very hot and very dense singularity, the components that evolved into what is now our universe first experienced a cataclysmic event. What followed was a continuous expansion, cooling, and thinning out of these components. The idea that the Universe is expanding has far-reaching ramifications in the field of physics than simply being another amazing astronomical phenomena. For one, it allows for a unification between those who have spent their lives studying the very small (particle physicists) and those who have dedicated theirs with the very large (astrophysicists). For a long time, particle physicists toiled in the middle of a particle zoo. The discoveries of quarks, leptons, as well as the strong, electromagnetic, weak, and gravitational forces filled their labs with mixed feelings (Villanueva 2009).

On one hand, they were constantly excited with the wealth of discoveries of these numerous tiny particles and their interactions, while on the other, they were conscious of the fact that the diversity of these forces deviated from the idea that nature was biased towards simplicity. They realized these forces should eventually unite for simplicity to prevail. From their calculations, this was only possible in the presence of very high energies. But since these energies were not present anywhere in the Universe, then the possibility was useless. This puzzle was solved when scientists studying cosmology realized that the Universe was expanding and as a result, was cooling and becoming less dense (Villanueva 2009 and Hawking 2002).

Scientists analyzed that if this were true, then it could be possible that the Universe was once very hot and very dense. In these conditions, the energies would have been extremely high.

There are proofs that the Universe experienced a cataclysmic event (Big Bang) and, subsequently, that it is expanding even now. One of the proofs is the detection of the cosmic microwave background radiation exhibiting a thermal black body spectrum of about 3 K. Another is the collection of red shift observations for galaxies, i.e., the further from us the galaxies are, the greater their measured red-shifts. That means, the outermost galaxies are speeding away much faster than the innermost ones. These two alone support the Big Bang theory (Villanueva 2009).

2.3 HISTORICAL BEGINNINGS

In 1929 an astronomer named Edwin Hubble announced a remarkable observation that changed our view of the world more than almost any other single discovery made this century. In every direction he looked, every galaxy in the sky was moving away from us. The nearby ones were moving relatively slowly, but the farther away a galaxy was the faster it was heading out. What can account for our great unpopularity? Is our galaxy somehow different from all others?

It turns out that there is another, arguably simpler explanation that is well supported by many other observations. It is that the entire universe itself is expanding! This expansion indicates not only that we should see every other galaxy moving away from us, but that observers in another galaxy should see exactly the same thing. In a uniform expanding universe, every observer sees herself at the center of the expansion, with everything else moving outwards from her (Felder 2000).

This statement forms the basis of our current theories of the structure and history of the universe. The study of the overall structure of the universe is called cosmology. The theory that has come to dominate cosmology since Hubble's observations goes by several names, but is most commonly known as the *big bang model.* This rest of this unit describes the big bang model. Next section describes what it means to say the universe is expanding, and subsequent sections address some questions that commonly arise in connection with the model.

Then the following Section discuss whether the universe is infinite or finite. While we don't yet know the answer to this question, Einstein's general theory of relativity predicts that finite universes contain a larger density of matter than infinite ones, so by measuring the density in the universe we should hopefully be able to make the determination. We end section by describing what it would mean for the universe to be infinite or finite (Felder 2000 and Brown 2007).

In the next Section we talk about the origin and history of the universe. As the universe expands and galaxies move apart from each other the average density is decreasing (Brown 2007). If we extrapolate the expansion backwards we conclude that there was a time roughly 10-15 billion years ago when the density was nearly infinite. In this section we briefly outline the history of the universe from that time to the present. In the final Section we continue the story, describing what relativity theory predicts will happen to the universe in the future. The two possibilities are that the universe will continue to expand forever or that it will eventually slow down and begin contracting. The theory tells us that which one will happen depends on whether or not the average density of the universe exceeds a certain value, the same value that determines whether the universe is infinite or finite. Relativity predicts that an infinite universe will continue to expand forever, whereas a finite universe will expand for a finite time and then contract (Russell 2009 and Felder 2000).

Check Your Progress I

Note: Use the space provided for your answers.

1) What are some of the proofs for Big Bang?

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2) What is the big bang model?

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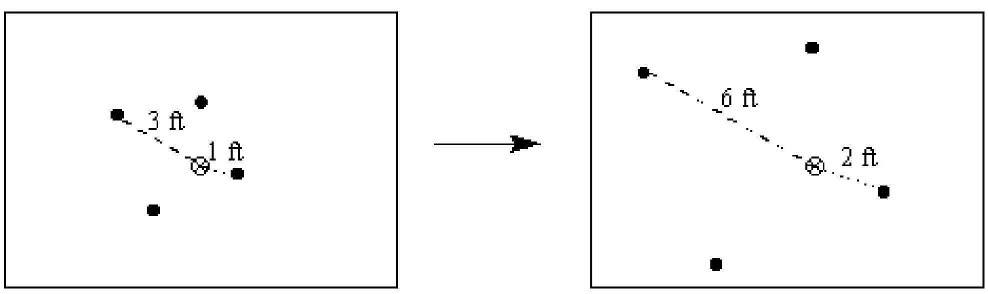
2.4 THE EXPANDING UNIVERSE: AN OVERVIEW

Simple analogies can clarify what it means for the universe to expand, but they can also be misleading. We can use one analogy, attempting to point out its shortcomings as we proceed. Think of the universe as a rubber sheet being stretched out. (If you are comfortable with visualization in three dimensions you can imagine a raisin cake expanding instead, but for the purpose of illustration we will stick with the two dimensional case.) Now imagine that there are drawing pins stuck into the rubber at various points representing galaxies. (In the raisin cake analogy these would be the raisins.) As the rubber (the universe) is stretched (expands), the drawing pins (galaxies) all get farther apart. Note that we haven't said anything yet about how big the rubber sheet is. For all we know it might be infinite. (This point will be addressed in a later section.) What we mean when we talk about expansion is that the rubber is being stretched out, causing the distances between the drawing pins to increase (Felder 2000 and Brown 2007).

To see what this expansion should look like to us, imagine an observer sitting on one of the drawing pins. This observer imagines himself to be at rest and measures all movement relative to his drawing pin (galaxy). Since the distance between any two drawing pins is increasing, it will appear to him that all the other ones are moving away from him. How fast will another drawing pin appear to move? That depends in part on how fast the rubber sheet is being stretched out, *i.e.*, how fast the universe is expanding. In addition, however, the apparent speed of the other drawing pins is also dependent on their positions relative to the observer. The nearby drawing pins will appear to be moving away very slowly, whereas the distant ones will appear to be moving away much faster. To see why this is so, suppose the rubber sheet doubles in size in one second.



The drawing pin that began one foot away from you is two feet away, meaning it appears to have moved by a foot. Its apparent velocity is therefore 1 foot per second. In the same time the drawing pin that started out three feet away also ends up twice as far away (six feet), but this means that it appears to have moved away at three times the speed of the first drawing pin (three feet per second). In terms of the expanding universe, this means that not only will every galaxy appear to be moving away from us, but the speed with which it does so will be directly proportional to its distance from us. A galaxy that is four million light years away will have twice the apparent velocity of one that is two million light years away (Felder 2000).

This pattern is precisely what Hubble observed. Not only did he see that all distant galaxies are moving away from us and that the more distant ones are moving away more rapidly, but he found that the rate at which they were receding from us was proportional to their distance from us (Felder 2000). In other words, his observations exactly matched what we just predicted for an expanding universe. This proportionality is known as Hubble's Law.

A problem arises when we consider an expanding universe. Suppose everything in the universe were to double in size. The distances between galaxies would double, the size of the Earth would double, the size of all our meter sticks would double, and so on. It would seem to an observer (who will also have doubled in size) as if nothing had happened at all. So what do we mean by saying the universe expands?

In fact, not everything grows as the universe expands. In the example of the rubber sheet, the distance between drawing pins keeps increasing but the drawing pins themselves remain the same size. Similarly, while distant galaxies are pulled away from each other by the expansion, smaller objects like meter sticks, people, and the galaxies themselves are held together by forces that prevent them from expanding. So we expect that billions of years from now galaxies will still be roughly the same size they are today, but the distances between them will on average be much larger.

2.5 INFINITE OR FINITE?

People have wondered for millennia whether the universe is limited in size or goes on forever. Fortunately we now have modern science to step in and supply us with the answer, which is that we don't know. We believe that the universe is governed by Einstein's theory of general relativity, which among other things addresses such matters as the overall structure of the universe. In the early 1920s Alexander Friedmann showed that using one assumption the equations of general relativity can be solved to show that a finite universe must have a larger density of matter and energy inside it than an infinite universe would have (Felder 2000). There is a certain *critical density* that determines the overall structure of the universe. If the density of the universe is lower than this value, the universe must be infinite, whereas a greater density would indicate a finite universe. These two cases are referred to as an *open* and *closed* universe respectively. The critical density is about 10^{-29} g/cm^3, which is equivalent to about five hydrogen atoms per cubic meter (Felder 2000). This may not seem like a lot; by comparison the density of water is roughly 1 g/cm^3 or about 500 billion billion billion hydrogen atoms per cubic meter. However, we live in a very dense part of the universe. Most of the universe is made up of intergalactic space, for which a density as low as the critical density is plausible.

Aside from the theory of relativity itself, Friedmann's only other assumption in deriving his results was that on average the density of the universe was the same everywhere. This doesn't mean that every place in the universe is exactly the same. We already mentioned that the Earth is much more dense than space. However, if we measure the average density in our galaxy it will be about the same as the average density in any other galaxy, and the number of galaxies per unit volume should be roughly the same in different parts of the universe. This assumption matches all our observations to date. Individual galaxies differ from one another in some of their specific properties, but on average their properties don't appear to change from one region of the sky to another. Nonetheless, the idea that the universe is roughly the same everywhere—a property known as *homogeneity*—is still an assumption. We can probably only see a tiny fraction of the universe and we have no guarantee that the parts we cannot see look like the parts we can. Lacking any evidence to the contrary, however, we will assume that the property of homogeneity holds true.

So we should be able to answer the question of the universe being infinite or finite by measuring the density of everything around us and seeing whether it is above or below the critical value. This is true in principle, and measuring the average density of the universe is a very active field of research right now. The problem is that the measured density turns out to be pretty close to the critical density. Right now the evidence seems to favor an infinite universe, but it is not yet conclusive.

To recap, one of the assumptions of the standard big bang model is that the universe is more or less homogeneous—the same everywhere. As far as we can see, which is billions of light years in every direction, this assumption appears to be correct. Under this assumption general relativity says that whether the universe is infinite or finite depends on its density. Measurements of that density reveal that it is close to the critical value. Right now the data seem to point more towards an open (infinite) universe, but new data coming in the next 10-20 years should resolve the question much more definitively (Felder 2000).

Given our uncertainty about this question, we will briefly comment on what it would mean if the universe is infinite or finite and how those two possibilities relate to the idea of the universe expanding. An infinite universe is in some ways easier to imagine than a finite one. Since the universe is supposed to be everything that exists, it seems intuitive that it should go on forever. Of course an infinite universe is impossible to picture, but we can get at what it means by saying that no matter how far you go there will always be more space and galaxies. It is hard, however, to reconcile this picture with the idea that the universe is expanding. If it's already infinite, how can it expand?

To see how, remember that by expansion we mean that the distance between galaxies is increasing. Suppose right now there is a galaxy every million light years or so. After a long enough time this infinite grid of galaxies will stretch out so that there is a galaxy every two million light years. The total size of the universe hasn't changed—it's still infinite—but the volume of space containing any particular group of galaxies has grown because the separation between the galaxies is now larger.

What about a finite universe? This phrase sounds like a contradiction because if the universe ends somewhere then we would naturally want to know what was beyond it, and since the universe includes everything, whatever is beyond that edge should still be called part of the universe. The resolution of this paradox is that even if the universe is finite, it still doesn't have an edge. If we head off in one direction and resolve to keep going until we find the end of the universe, we eventually find ourself right back where we started. A finite universe is *periodic*, meaning that if you go far enough in any direction you come back to where you started (Felder 2000).

Trying to picture a closed (finite) universe is in some ways even harder than trying to picture an open (infinite) universe because it is easy to mislead yourself. For example, people often compare a two-dimensional closed universe to the surface of a balloon. This analogy is helpful because such a surface has the property of being periodic in all directions, and it is easy to picture the expansion of such a universe by imagining the balloon being blown up. In fact, this analogy is like the rubber sheet analogy we used before, except now the sheet has been wrapped up to form a sphere. The problem is that this picture immediately leads to the question of what is inside the balloon.

This question comes from taking the analogy too literally. Nothing in general relativity says that a two-dimensional closed universe would have to exist as a sphere inside a three-dimensional space; the theory only says that such a universe would have certain properties (*e.g.* periodicity) in common with such a sphere. For this reason, as shown by Gary Felder (2000), it is useful to keep the balloon in mind as a convenient analogy but it is ultimately best to think of the closed universe as a three-dimensional space with the strange property that things which go off to the right eventually come back again from the left.

What does expansion mean in a closed universe? Since this universe has a finite size, it makes sense to talk about that size increasing. Again suppose that there is now a galaxy every million light years. Suppose also that if we were to head off in a straight line we would travel 100 billion light years before coming back to where I started, passing about 100,000 galaxies on the way. If we take the same journey billions of years later, the number of galaxies won't have changed but the distances between them will have doubled, so the total distance for the round trip will now be 200 billion light years.

Check Your Progress II

Note: Use the space provided for your answers.

1) What is the importance of Hubble's Law?

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2) Is the universe finite?

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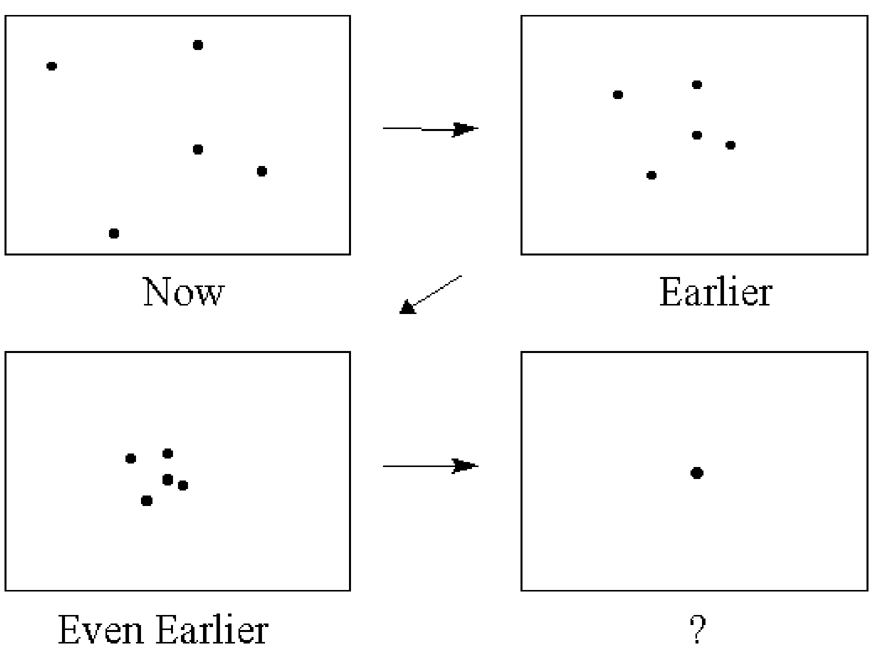
2.6 THE BIG BANG AND THE HISTORY OF THE UNIVERSE

At the beginning of this century, physicists generally had a strong bias toward the idea that the universe was essentially unchanging. Local phenomena would of course change from minute to minute, and stars and galaxies might be born and die, but taken as a whole the universe was assumed to be more or less the same now as it had been billions or trillions of years ago, with no beginning or end (Felder 2000). Einstein, disturbed that his theory of general relativity seemed to be inconsistent with a static universe, tried to modify the equations of the theory. When Hubble's observations showed that the universe was indeed expanding, Einstein retracted this modification and called it the biggest blunder of his life. Given that the universe is growing, the question of whether the expansion started at some point in the past inevitably arises. Our current theories say the expansion *did* have a beginning. This section discusses why we believe this and what it means to even say so. It also contains a brief outline of the history of the universe from that beginning to the present day.

The Big Bang

To see what it means to say the universe had a beginning, consider a group of galaxies chosen at random throughout the universe. The illustration below shows five galaxies as they appear now and as they would have appeared at several times in the distant past. At some point in the past (about 6-10 billion years ago), all of these galaxies would have been half as far apart as they are now. At an earlier time they would have been half as far apart as that, and so on. If you extrapolate this process backwards you eventually come to a time in the past when the galaxies would have been right on top of one another. Put another way, the density of matter (or energy) in the universe was higher at earlier times, and extrapolating this process backwards we come eventually to a time when that density would have been infinite. This moment of infinite density is called the *big bang*.



Having defined the moment of the big bang in this way—the time when all distances between objects were zero— we cannot talk about that time. A point of infinite density, known in physics as a "singularity," makes no sense. Moreover, our current theories do not predict that such a moment occurred in the past. Our best physical theories, including general relativity and quantum mechanics, stop working when we try to describe matter that is almost infinitely dense. That word "almost" is important. The theories don't simply break down at the instant of the big bang singularity; rather, they break down a short time afterwards when the density has a certain value called the *Planck density* (Felder 2000).

The Planck density, which is the highest density we can hope to describe with our current physics, is over 10^{93} g/cm^3, which corresponds to roughly 100 billion galaxies squeezed into a space the size of an atomic nucleus. For virtually any application we can imagine this limitation of our theories is completely irrelevant, but it means we can't describe the universe immediately after the big bang. We can only say that our current model of the universe begins when the density was somewhere below the Planck density and we can say virtually nothing about what the universe was like before that. We therefore take as our initial condition a universe at or just below the Planck density, and any questions about the instant of the big bang itself are eliminated from consideration.

Is this a cop-out? It certainly is. Physicists have not given up on understanding what happened before this time, but we admit that right now we have no theory to describe it. Many people are working to develop such a theory, but until that happens we are left having to start our description of the universe when the density was large but still finite. Once we impose this limitation on ourselves, our picture of the universe works equally well for an infinite or a finite universe. If the universe is finite then it may very well have been extremely small at the moment when the density was at the Planck level. If the universe is infinite then it was also infinite at that early time. The density was enormous and the distances between particles vanishingly small, but that dense mass of particles went on forever.

The History of the Universe

Describing the history of the universe is obviously a fairly large task, so we can only with mentioning a few highlights. For a very good description of much of the early history the book *The First Three Minutes* by Steven Weinberg is excellent. At the moment when the density of matter equalled the Planck constant, the universe consisted of a hot soup of elementary particles. When we say this medium was hot that means that the particles, on average, had very high energies. All of the fundamental particles such as quarks, electrons, and photons were present. At present these particles are mostly combined into larger units such as atoms, molecules, penguins, and so on, but at the extremely high temperatures of the early universe they remained separate. If several particles were to have combined into a more complicated structure such as an atom they would have been instantly ripped apart in collisions with the high energy particles flying around everywhere. As the universe expanded, the density and temperature of this mixture decreased. After a small fraction of a second the quarks combined into protons and neutrons in a process called *baryogenesis.* A few minutes later the protons and neutrons combined into atomic nuclei in a process referred to as *nucleosynthesis.* Hundreds of thousands of years later these protons and neutrons combined with electrons to form atoms.

In the period of recombination the universe was still almost perfectly homogeneous, meaning that the density was the same everywhere. While the density still is the same everywhere when averaged over huge regions of space, it certainly varies locally. The density of the Earth is vastly larger than the density of interstellar space, which is in turn much greater than the density of intergalactic space. In contrast, the difference in density between the most and least dense regions at the time of recombination was about one part in 100,000. Between then and now the converging of matter into galaxies, stars, etc. took place (Felder 2000).

The mechanism by which this converging occurred is fairly simple, although its details continue to be studied and debated. At the time of recombination the universe consisted of a nearly uniform hot gas with regions very slightly denser than the average and others very slightly less dense. If the density had been *exactly* the same everywhere then it would have always stayed that way. However, a region slightly denser than the surrounding gas would have a stronger gravitational attraction, and mass would tend to flow into it. This process would make this region even denser, causing it to attract matter even more strongly. In this way the almost uniformly dense universe gradually became less and less uniform, resulting in the dense grouping of matter we see around us now. On a fairly large scale these groupings make up galaxies, and matter that grouped on a smaller scale makes up the stars inside those galaxies. A very small portion formed into smaller objects orbiting around those stars and a small portion of that matter formed into people reading physics papers on the Internet.

2.7 THE END OF THE UNIVERSE

Hubble's observation that the universe is expanding suggested more generally that the universe is changing with time. As in most subjects, we know more about the past than we do about the future, but if we assume that our current physical theories are correct then we can predict a great deal about the future of our universe. Is the universe going to exist forever or will it someday come to an end as it began? Put another way, will the expansion of the universe continue forever? If the universe keeps on expanding it will presumably continue to exist for an infinitely long time. On the other hand, if the expansion ever stops, then the universe will contract until it once again reaches the Planck density (and after that we have no idea what it will do). In what follows we will explain what determines which of these scenarios is going to occur and say more about what each of them means (Felder 2000).

We know from general relativity that expansion of the universe is slowed down by the mutual gravity of all the matter inside it. Whether or not the expansion will continue forever depends on whether or not there is enough matter in the universe to reverse it. If the density of matter in the universe is less than a certain critical value, then the universe will never stop expanding. If, on the other hand, the density of matter is greater than the critical value, then the pull of gravity will eventually be strong enough to stop the expansion and the universe will begin contracting. In Section III we saw that whether or not the universe is finite or infinite depends on whether the density of matter is above or below a critical value. That value turns out to be exactly the same as the critical value that determines whether or not the expansion will reverse. In other words, general relativity says that an open (infinite) universe will expand forever and a closed (finite) universe will eventually re-collapse.

If the universe expands forever, the clusters of galaxies in it will move farther and farther apart. Eventually each galaxy cluster will be alone in a vast empty space. The stars will burn out their fuel and collapse, leaving nothing but cold rocks behind. Eventually these will disintegrate as well. This whole process will take an unimaginably long time but it will occur eventually, and the universe will thereafter consist of nothing but loosely spread out elementary particles. All of the energy in the universe will then be distributed in a more or less uniform way at some extremely low temperature, and as the universe continues to expand this temperature will fall and the universe will become ever more empty and cold. This scenario is sometimes referred to as the heat death of the universe.

On the other hand, if the universe has a high enough density, then the galaxies will eventually start moving back towards each other. Once they are close enough together all galaxies and stars will collapse, until at some point the universe will once again consist of nothing but densely packed, highly energetic particles. Eventually all matter will be compressed to the Planck density, the density at which our current theories fail. Lacking a theory for such densities, we cannot predict what will happen then. One possibility is that the universe will bounce back—indeed, perhaps it has been in a cycle of expanding and contracting forever. Then again perhaps the universe will simply annihilate itself and cease to exist. Determining which of these possibilities would occur will require the development of a theory of physics at extremely high densities (Felder 2000).

Check Your Progress III

Note: Use the space provided for your answers.

1) Why did Einstein object to some of the elements of quantum mechanics?

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2) What is baryogenesis and what is its significance?

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2.8 LET US SUM UP

In this unit we discussed the expanding universe and some of the cosmological consequences that are derived from it. This gives rise to a world that is so gigantic and magnificient.

2.9 KEY WORDS

Baryogenesis : In physical cosmology, baryogenesis is the generic term for hypothetical physical processes that produced an asymmetry between baryons and antibaryons in the very early universe, resulting in the substantial amounts of residual matter that make up the universe

Hubble's Law : A law stating that the redshifts in the spectra of distant galaxies (and hence their speeds of recession) are proportional to their distance.

2.10 FURTHER READINGS AND REFERENCES

Felder Gary (2000) “The Expanding Universe” The Math and Physics Help Home Page http://www4.ncsu.edu/unity/lockers/users/f/felder/public/kenny/papers/cosmo.html Retrieved on March 3, 2011.

Villanueva, John Carl (2009) “Expanding Universe” Universe Today, August 3, 2009 http://www.universetoday.com/36492/expanding-universe/. Retrievedon January, 2011.

Aczel, A.D. *God’s Equation: Einstein, Relativity, and the Expanding Universe*. New York: MJF BOOKS, 2003.

Barrow JD, Silk J. *The Left Hand of Creation: The Origin and Evolution of the Expanding Universe*. New York: Oxford University Press, 1993.

Eddington, A.S.*The Expanding Universe*. Cambridgeshire: Cambridge University Press, 1987.

Hawking, SW. *The Theory of Everything: The Origin and Fate of the Universe*. Beverly Hills, CA: New Millennium Press, 2002.

Schwerin A (1993) *The Expanding Universe : An Introduction to Philosophy*. San Francisco: EMText, 1993.

Brown, CS. *Big History: From the Big Bang to the Present*. New York: New Press, 2007.

Narlikar, J.V. *An Introduction to Relativity*. Cambridge: Cambridge University Press, 2010.

Nussbaumer H, Bieri L. *Discovering the Expanding Universe*. Cambridge: Cambridge University Press, 2009.

Russell, B. *Abc of Relativity*. New York: Routledge, 2009.

Schatzman, E.L. *Our Expanding Universe*. New York: McGraw-Hill, 1992.

Whittaker, H. *The Universe*. Mankato: Smart Apple Media, 2011.