OpenStax Astronomy, Ch.29: WS Solutions (Apr-2021)

Solutions

1. What are the basic observations about the universe that any theory of cosmology must explain?

> Any cosmological theory must explain the expansion of the universe and the various stages the expansion has gone through (inflation, radiation-dominated, matter-dominated, and the present dark energy-dominated). Another key element of any good model is the cosmological principle: that on the large scale, the universe in any given time is the same everywhere (homogeneous and isotropic). More specific observations that require a cosmological explanation include why there is the background radiation (CMB) filling space all around us and why there is more helium in the universe than stars could have made since the beginning.

2. Describe some possible futures for the universe that scientists have come up with. What property of the universe determines which of these possibilities is the correct one?

> The possible futures for the universe will be determined by the fate of its expansion. In two models for the universe, the rate of expansion slows down. In one of these, expansion comes to a stop and reverses, with the universe ending in a “big crunch”—the implosion of matter, energy, space, and time. For this model, the mass-energy density ρ is greater than the critical density (which is presently $\rho_{\text{crit}} = 9.6 \times 10^{-27}$ kg/m^3). In the second model, the universe continues to expand forever, but ever more slowly, coming to a stop only after infinite time. For this model, the mass-energy density is exactly equal to the critical density. In a third model, the universe expands forever at a constant rate (given by a Hubble constant that does not vary with time). This would occur in an empty universe. In a fourth model, the universe accelerates at a faster and faster rate forever. For this model, the mass-energy density is less than the critical energy density for a given amount of dark energy. Current mass-energy density measurements indicate that the universe will expand forever.

3. What does the term Hubble time mean in cosmology, and what is the current best calculation for the Hubble time?

> The Hubble time is the age of the universe, estimated from calculating the Hubble constant and then taking its reciprocal (1/H). The current estimate for the Hubble time is about 14 to 15 billion years.

4. Which formed first: hydrogen nuclei or hydrogen atoms? Explain the sequence of events that led to each.

> A standard hydrogen nucleus consists of just a proton. Protons were formed by quark *condensation* at around 10^{-6} seconds after the Big Bang. Nucleosynthesis of other isotopes of hydrogen, such as deuterium (one proton and one neutron) and tritium (one proton and two neutrons), could happen when the universe was cool enough for more complex nuclei to form, at around three to four minutes. Hydrogen atoms (which also include an electron) did not form until the universe was about 380,000 years old, when its temperature dropped below about 3000 K. This was when the random motion of electrons became slow enough for them to be electromagnetically captured by protons to form hydrogen atoms.

5. Describe at least two characteristics of the universe that are explained by the standard Big Bang model.

Characteristics of the universe explained by the standard Big Bang model include its expansion, observation of a cosmic microwave background, and the relative abundances of the very light elements (such as the existence of more helium than stars could have made since the Big Bang).

6. Describe two properties of the universe that are not explained by the standard Big Bang model (without inflation). How does inflation explain these two properties?

> The standard Big Bang model without inflation does not explain why the mass-energy density of the universe would be equal to the critical density, nor does it explain the amazing uniformity of the universe. However, both of these features can be explained when an inflationary stage is added to the standard Big Bang model. A Big Bang model with a rapid, early expansion stage (inflation) is identical to the standard Big Bang model after 10^{-30} s, but it is significantly different prior. In an inflationary model, within the first 10^{-30} s, the universe expanded by a factor of about 10^{50} times that predicted by standard Big Bang. Such an expansion over a very short time drives any initial mass-energy density to the critical density and also produces the scale of uniformity we observe.

7. Why do astronomers believe there must be dark matter that is not in the form of atoms with protons and neutrons?

> Galaxies could not have formed as early as they did without dark matter gravitationally attracting ordinary matter and inducing galactic formation. The existence of dark matter is also necessary to explain the long-term stability of both spiral galaxies and galactic clusters. In both cases, we see material in their outer regions moving around their centers too fast for the gravity we deduce from ordinary matter to hold. There must be some other form of material there with gravity. Yet searches for electromagnetic radiation from this additional matter have been fruitless, leading scientists to believe that this “dark matter” does not consist of ordinary particles, such as protons and neutrons.

8. What is dark energy and what evidence do astronomers have that it is an important component of the universe?

> The notion of dark energy was suggested to help explain measurements, using Type Ia supernovae as distance indicators, that the expansion of the universe is speeding up. Such acceleration requires a source of energy. Scientists don’t yet fully understand what dark energy is. It may be a new form of energy for which there is not yet a theoretical explanation. Alternately, it may be the vacuum energy associated with “empty” space itself, as predicted by quantum mechanics.

9. Thinking about the ideas of space and time in Einstein’s general theory of relativity, how do we explain the fact that all galaxies outside our Local Group show a redshift?

> In the general relativistic view, the expansion of the universe is a “stretching” of space. As the scale of space increases, waves of light from a distant galaxy, moving through that space, will also be stretched. That is, their wavelengths increase, which is a redshift. The farther away a galaxy is, the more space it travels through, and the greater the increase in its wavelength by the time it arrives.

10. Astronomers have found that there is more helium in the universe than stars could have made in the 13.8 billion years that the universe has been in existence. How does the Big Bang scenario solve this problem?

> The Big Bang scenario begins with a universe that is very hot and full of energy. At the temperatures and densities that existed between 3 and 4 minutes after the beginning, conditions (temperature and density) in the entire universe were right for protons and deuterium nuclei to fuse into helium. In essence, the entire universe was acting the way centers of main-sequence stars do now. After 4 minutes, the universe had expanded so much that temperatures were not sufficient for the fusion of helium.

This explains the extra helium we see in the universe today and why there is neither less nor more of it.

11. Describe the anthropic principle. What are some properties of the universe that make it “ready” to have life forms like you in it?

> The “anthropic principle” is the idea that the physical laws that we observe must be what they are precisely because these are the only physical laws that allow for the existence of humans. Properties of the universe that make it “ready” to have life forms like us include: (a) a 1-part-in-10^5 mass-energy fluctuation in the early universe that allowed formation of galaxies like ours (which include regions for solar systems with sufficiently low intensity of X-rays and gamma rays), (b) a balance between the forces of expansion and contraction for the universe (so it didn’t expand or collapse too fast), resulting from a mass-energy density very close (or equal) to critical density, (c) a very slight initial excess of matter that survived matter-antimatter annihilation, (d) nuclear fusion reactions at rates that produce long-lasting stars, (e) the strength of gravity not being much stronger (so that stars form with smaller masses and live too short a time), and (f) the structure of atomic nuclei providing sufficient production of carbon nuclei in stars via fusion of three helium nuclei.

12. Describe the evidence that the expansion of the universe is accelerating.

> The only direct evidence of acceleration comes from supernovae (as described in the chapter), although other evidence fits the standard model we have described in the book that includes dark energy. In order to determine whether the expansion is accelerating, it is necessary to measure the rate of expansion at different distances, which is equivalent to making measurements at different times in the history of the universe. We have only one “standard bulb” that allows us to measure large enough distances to perform this experiment—the supernovae produced when white dwarfs in binary systems acquire too much mass and explode. The observations show that distant supernovae are fainter than would be expected if the universe were expanding at a constant rate. This means that when we detect the light from supernovae, we are farther away from them than we would be if the expansion rate were constant. The only way that can happen is if the rate at which we are moving away from the supernovae has sped up since the time the light left them.

13. Suppose the universe expands forever. Describe what will become of the radiation from the primeval fireball. What will the future evolution of galaxies be like? Could life as we know it survive forever in such a universe? Why?

> The radiation from the fireball will be more and more redshifted as time goes on, becoming characteristic of a cooler and cooler blackbody. (Put another way, the CMB photons will each have lower and lower energy.) The rate at which this fireball radiation “cools off,” however, will become slower and slower. Galaxies will gradually incorporate all of their gas and dust into stars. Since some material is retained in a dense stellar remnant whenever a star dies, ultimately galaxies will consist of black holes, neutron stars, and white (and eventually black) dwarfs. As the latter two types of objects cool off, they will cease to radiate energy, and the galaxies will become cold and dark, containing mostly these three types of dense remnants of stars. The galaxies will also be farther and farther apart as time goes on, making them harder and harder to see from neighboring galaxies. Life requires fresh energy, such as the output of a star to thrive. When galaxies are so dark that all the stars have gone out, life as we know it will become impossible. But this fate is so far in the future that there is no reason to get upset about it in our time.

14. Some theorists expected that observations would show that the density of matter in the universe is just equal to the critical density. Do the current observations support this hypothesis?

Every observation made to date shows that the density of matter is much less than the critical density. The amount of matter is best estimated by measuring its gravitational influence, and this has been done for galaxies (rotation curves) and clusters of galaxies. Even if dark matter is included, the density of matter is only about 30% of the critical density.

15. There are a variety of ways of estimating the ages of various objects in the universe. Describe two of these ways, and indicate how well they agree with one another and with the age of the universe itself as estimated by its expansion.

> The age of the universe can be estimated from the expansion rate, as we discuss in the chapter. The simplest version of the age from the expansion is the Hubble time, which is 14–15 billion years. Limits can also be placed on the age by assuming that the universe must be older than the oldest known objects within it. The oldest objects are the globular clusters that form a kind of halo around our Galaxy and others. The best estimate of the ages of the oldest globulars is about 13 billion years, consistent with the best estimate of the expansion age. Using the spectrum of uranium-238 in old stars and comparing its decay with the decay of uranium-238 in our solar system, astronomers have found the age of old stars to be about 12.5 billion years, again consistent with the expansion age. The recent WMAP results indicate that the first stars formed about 200 million years after the expansion began, again giving a consistent picture. Ages in the solar system can be estimated by studying the radioactive decay of rocky material. The ages derived for the rocks from the Moon, for example, are about one-third the age of the universe. No method of measuring ages is giving us an age greater than the expansion age of the universe.

16. Since the time of Copernicus, each revolution in astronomy has moved humans farther from the center of the universe. Now it appears that we may not even be made of the most common form of matter. Trace the changes in scientific thought about the central nature of Earth, the Sun, and our Galaxy on a cosmic scale. Explain how the notion that most of the universe is made of dark matter continues this “Copernican tradition.”

> Ancient peoples thought Earth was the center of the universe. Copernicus suggested and Galileo presented evidence that the Sun (and not Earth) was the center of the system of planets. Over the next three centuries, evidence accumulated that the Sun was only one of many thousands of stars. In the early twentieth century, Shapley showed that the Sun does not lie in the center of our Galaxy or at any particularly special place within the system of stars that we call the Milky Way. Studies of stellar evolution suggest that the atoms of which Earth and humans are made are standard byproducts of nucleosynthesis in stars and supernovae. There was nothing special about the stuff from which we are made; the same elements are found throughout our Galaxy.
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> Since 1995, we have been discovering planets and planetary systems around other stars, including some that resemble Earth (in that they are rocky worlds and within the habitable zones of their stars.) Based on our sample of several thousand planets discovered so far, astronomers now estimate that there are likely to be billions of planets in the Milky Way, and that, therefore, there may be nothing special about either our Earth or solar system.
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> In the mid-1920s, Hubble showed that there are many other galaxies with sizes and luminosities comparable to the Milky Way. We now know that the Milky Way is but one of billions of galaxies, albeit a fairly large one as galaxies go. Our Galaxy does not appear to have any special place within the universe of galaxies; indeed, the relativistic models suggest that the universe may have no center or edge at all. The Local Group, of which the Milky Way is one member, is an undistinguished and relatively poor group of galaxies.
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> All of the above clearly seems to show that our location, motion, and composition are not especially noteworthy. Recent studies have shown that much of the gravitating

matter in the universe does not radiate light. We do not yet know what this dark matter is made of, but are gathering that most of it is probably not made of the protons, neutrons, and electrons that are the basis of life on Earth. Thus, humans are most likely not even made of the most common form of matter in the universe.

Most recently, scientists were very surprised to discover that the universe is accelerating. Some form of dark energy is responsible for this acceleration, and again, we have not yet detected this dark energy here on Earth. Evidence is accumulating that this energy may dominate the mass-energy density of the universe. Everything that is familiar to us—all forms of matter and energy that we are made of, experience, and use in our everyday lives—constitutes only about 4% of all the types of matter and energy that make up the universe as a whole. This is even worse than the proverbial tip of the iceberg—about 7% of an iceberg typically floats above the surface of the water. We can see, touch, smell, and taste an even smaller portion of what makes up the universe.

17. The anthropic principle suggests that in some sense we are observing a special kind of universe; if the universe were different, we could never have come to exist. Comment on how this fits with the Copernican tradition described in Exercise 19.

If the anthropic principle is correct, then we do live in a special universe in the sense that many physical constants have the values they do because if they had any other values, life like ours could not have developed. It is conceivable that there are many other universes in which various physical constants have different values and, in most of these, life as we know it could not develop. However, within our universe, it is still true that we do not occupy a special place, and life may have developed in many different places. The discovery within the last decade of hundreds of “exoplanets” (planets outside our solar system orbiting other stars) adds to the likelihood of this.

18. Penzias and Wilson’s discovery of the Cosmic Microwave Background (CMB) is a nice example of scientific *serendipity*—something that is found by chance but turns out to have a positive outcome. What were they looking for and what did they discover?

Penzias and Wilson were measuring the radio emission from a variety of astronomical sources, such as supernova remnants. They found an annoying background noise (static) that seemed to come from everywhere at once, which they assumed meant that it came from inside their equipment. But after checking, they concluded that the radio static came from all directions in the universe, and after consulting astronomers more familiar with cosmology, they realized that they had discovered the background radiation left over from early in the universe, when radiation first “decoupled” from matter and began streaming freely. In a sense, they had found the “glow” of the initial fireball of the Big Bang.

19. It is possible to derive the age of the universe given the value of the Hubble constant and the distance to a galaxy, again with the assumption that the value of the Hubble constant has not changed since the Big Bang. Consider a galaxy at a distance of 400 million light-years receding from us at a velocity, v. If the Hubble constant is 20 km/s per million light-years, what is its velocity? How long ago was that galaxy right next door to our own Galaxy if it has always been receding at its present rate? Express your answer in years. Since the universe began when all galaxies were very close together, this number is a rough estimate for the age of the universe.

Since $V = H \times d$, the velocity of a galaxy at a distance of 400×10^6 light-years = 8000 km/s for H = 20 km/s per million light-years. The time required to travel 4×10^8 light-years at 8000 km/s is given by

$$T = \frac{\left(4 \times 10^{8} \text{ light-years}\right)\left(9.46 \times 10^{12} \text{ km/light-year}\right)}{(8 \times 10^{3} \text{ km/s})} = 4.7 \times 10^{17} = 15 \text{ billion y.}$$