29.E: The Big Bang (Exercises)

Articles

Kruesi, L. “Cosmology: 5 Things You Need to Know.” *Astronomy* (May 2007): 28. Five questions students often ask, and how modern cosmologists answer them.

Kruesi, L. “How Planck Has Redefined the Universe.” *Astronomy* (October 2013): 28. Good review of what this space mission has told us about the CMB and the universe.

Lineweaver, C. & Davis, T. “Misconceptions about the Big Bang.” *Scientific American* (March 2005): 36. Some basic ideas about modern cosmology clarified, using general relativity.

Nadis, S. “Sizing Up Inflation.” *Sky & Telescope* (November 2005): 32. Nice review of the origin and modern variants on the inflationary idea.

Nadis, S. “How We Could See Another Universe.” *Astronomy* (June 2009): 24. On modern ideas about multiverses and how such bubbles of space-time might collide.

Nadis, S. “Dark Energy’s New Face: How Exploding Stars Are Changing our View.” *Astronomy* (July 2012): 45. About our improving understanding of the complexities of type Ia supernovae.

Naze, Y. “The Priest, the Universe, and the Big Bang.” *Astronomy* (November 2007): 40. On the life and work of Georges Lemaître.

Panek, R. “Going Over to the Dark Side.” *Sky & Telescope* (February 2009): 22. A history of the observations and theories about dark energy.

Pendrick, D. “Is the Big Bang in Trouble?” *Astronomy* (April 2009): 48. This sensationally titled article is really more of a quick review of how modern ideas and observations are fleshing out the Big Bang hypothesis (and raising questions.)

Reddy, F. “How the Universe Will End.” *Astronomy* (September 2014): 38. Brief discussion of local and general future scenarios.

Riess, A. and Turner, M. “The Expanding Universe: From Slowdown to Speedup.” *Scientific American* (September 2008): 62.

Turner, M. “The Origin of the Universe.” *Scientific American* (September 2009): 36. An introduction to modern cosmology.

Websites

Cosmology Primer: https://preposterousuniverse.com/cosmologyprimer/. Caltech Astrophysicist Sean Carroll offers a non-technical site with brief overviews of many key topics in modern cosmology.

Everyday Cosmology: cosmology.carnegiescience.edu/. An educational website from the Carnegie Observatories with a timeline of cosmological discovery, background materials, and activities.

How Big Is the Universe?: www.pbs.org/wgbh/nova/space/h...-universe.html. A clear essay by a noted astronomer Brent Tully summarizes some key ideas in cosmology and introduces the notion of the acceleration of the universe.

Universe 101: WMAP Mission Introduction to the Universe: http://map.gsfc.nasa.gov/universe/. Concise NASA primer on cosmological ideas from the WMAP mission team.

Cosmic Times Project: http://cosmictimes.gsfc.nasa.gov/. James Lochner and Barbara Mattson have compiled a rich resource of twentieth-century cosmology history in the form of news reports on key events, from NASA’s Goddard Space Flight Center.

Videos

The Day We Found the Universe: www.cfa.harvard.edu/events/mo...archive09.html. Distinguished science writer Marcia Bartusiak discusses Hubble’s work and the discovery of the expansion of the cosmos—one of the Observatory Night lectures at the Harvard-Smithsonian Center for Astrophysics (53:46).

Images of the Infant Universe: https://www.youtube.com/watch?v=x0AqCwElyUk. Lloyd Knox’s public talk on the latest discoveries about the CMB and what they mean for cosmology (1:16:00).

Runaway Universe: https://www.youtube.com/watch?v=kNYVFrnmcOU. Roger Blandford (Stanford Linear Accelerator Center) public lecture on the discovery and meaning of cosmic acceleration and dark energy (1:08:08).

From the Big Bang to the Nobel Prize and on to the James Webb Space Telescope and the Discovery of Alien Life: svs.gsfc.nasa.gov/vis/a010000...370/index.html. John Mather, NASA Goddard (1:01:02). His Nobel Prize talk from Dec. 8, 2006 can be found at www.nobelprize.org/mediaplaye...p?id=74&view=1.

Dark Energy and the Fate of the Universe: https://webcast.stsci.edu/webcast/de...=1961&parent=1. Adam Reiss (STScI), at the Space Telescope Science Institute (1:00:00).

Collaborative Group Activities

1. This chapter deals with some pretty big questions and ideas. Some belief systems teach us that there are questions to which "we were not meant to know" the answers. Other people feel that if our minds and instruments are capable of exploring a question, then it becomes part of our birthright as thinking human beings. Have your group discuss your personal reactions to discussing questions like the beginning of time and space, and the ultimate fate of the universe. Does it make you nervous to hear about scientists discussing these issues? Or is it exciting to know that we can now gather scientific evidence about the origin and fate of the cosmos? (In discussing this, you may find that members of your group strongly disagree; try to be respectful of others' points of view.)
2. A popular model of the universe in the 1950s and 1960s was the so-called steady-state cosmology. In this model, the universe was not only the same everywhere and in all directions (homogeneous and isotropic), but also the same *at all times*. We know the universe is expanding and the galaxies are thinning out, and so this model hypothesized that new matter was continually coming into existence to fill in the space between galaxies as they moved farther apart. If so, the infinite universe did not have to have a sudden beginning, but could simply exist forever in a steady state. Have your group discuss your reaction to this model. Do you find it more appealing philosophically than the Big Bang model? Can you cite some evidence that indicates that the universe was not the same billions of years ago as it is now—that it is not in a steady state?
3. One of the lucky accidents that characterizes our universe is the fact that the time scale for the development of intelligent life on Earth and the lifetime of the Sun are comparable. Have your group discuss what would happen if the two time scales were very different. Suppose, for example, that the time for intelligent life to evolve was 10 times greater than the main-sequence lifetime of the Sun. Would our civilization have ever developed? Now suppose the time for intelligent life to evolve is ten times shorter than the main-sequence lifetime of the Sun. Would we be around? (This latter discussion requires considerable thought, including such ideas as what the early stages in the Sun's life were like and how much the early Earth was bombarded by asteroids and comets.)
4. The grand ideas discussed in this chapter have a powerful effect on the human imagination, not just for scientists, but also for artists, composers, dramatists, and writers. Here we list just a few of these responses to cosmology. Each member of your group can select one of these, learn more about it, and then report back, either to the group or to the whole class.
    - The California poet Robinson Jeffers was the brother of an astronomer who worked at the Lick Observatory. His poem "Margrave" is a meditation on cosmology and on the kidnap and murder of a child: www.poemhunter.com/best-poems...fers/margrave/.
    - In the science fiction story "The Gravity Mine" by Stephen Baxter, the energy of evaporating supermassive black holes is the last hope of living beings in the far future in an ever-expanding universe. The story has poetic description of the ultimate fate of matter and life and is available online at: http://www.infinityplus.co.uk/stories/gravitymine.htm.
    - The musical piece *YLEM* by Karlheinz Stockhausen takes its title from the ancient Greek term for primeval material revived by George Gamow. It tries to portray the oscillating universe in musical terms. Players actually expand through the concert hall, just as the universe does, and then return and expand again. See: http://www.karlheinzstockhausen.org/ylem_english.htm.
    - The musical piece *Supernova Sonata* http://www.astro.uvic.ca/~alexhp/new...va_sonata.html by Alex Parker and Melissa Graham is based on the characteristics of 241 type Ia supernova explosions, the ones that have helped astronomers discover the acceleration of the expanding universe.
    - Gregory Benford's short story "The Final Now" envisions the end of an accelerating open universe, and blends religious and scientific imagery in a very poetic way. Available free online at: http://www.tor.com/stories/2010/03/the-final-now.
5. When Einstein learned about Hubble's work showing that the universe of galaxies is expanding, he called his introduction of the cosmological constant into his general theory of relativity his "biggest blunder." Can your group think of other "big blunders" from the history of astronomy, where the thinking of astronomers was too conservative and the universe turned out to be more complicated or required more "outside-the-box" thinking?

Review Questions

1. What are the basic observations about the universe that any theory of cosmology must explain?
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?
3. What does the term Hubble time mean in cosmology, and what is the current best calculation for the Hubble time?
4. Which formed first: hydrogen nuclei or hydrogen atoms? Explain the sequence of events that led to each.
5. Describe at least two characteristics of the universe that are explained by the standard Big Bang model.
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?
7. Why do astronomers believe there must be dark matter that is not in the form of atoms with protons and neutrons?
8. What is dark energy and what evidence do astronomers have that it is an important component of the universe?
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?
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?
11. Describe the anthropic principle. What are some properties of the universe that make it "ready" to have life forms like you in it?
12. Describe the evidence that the expansion of the universe is accelerating.

Thought Questions

1. What is the most useful probe of the early evolution of the universe: a giant elliptical galaxy or an irregular galaxy such as the Large Magellanic Cloud? Why?
2. What are the advantages and disadvantages of using quasars to probe the early history of the universe?
3. Would acceleration of the universe occur if it were composed entirely of matter (that is, if there were no dark energy)?
4. 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?
5. 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?
6. 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.
7. 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."
8. 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 the previous exercise.
9. 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?
10. Construct a timeline for the universe and indicate when various significant events occurred, from the beginning of the expansion to the formation of the Sun to the appearance of humans on Earth.

Figuring for Yourself

1. Suppose the Hubble constant were not 22 but 33 km/s per million light-years. Then what would the critical density be?
2. Assume that the average galaxy contains $10^11\ M_{\text{Sun}}$ and that the average distance between galaxies is 10 million light-years. Calculate the average density of matter (mass per unit volume) in galaxies. What fraction is this of the critical density we calculated in the chapter?
3. The CMB contains roughly 400 million photons per m^3. The energy of each photon depends on its wavelength. Calculate the typical wavelength of a CMB photon. Hint: The CMB is blackbody radiation at a temperature of 2.73 K. According to Wien's law, the peak wave length in nanometers is given by $\lambda_{\text{max}} = \frac{3\times10^6}{T}$. Calculate the wavelength at which the CMB is a maximum and, to make the units consistent, convert this wavelength from nanometers to meters.
4. Following up on the Figuring for Yourself Exercise 5 calculate the energy of a typical photon. Assume for this approximate calculation that each photon has the wavelength calculated in the previous exercise. The energy of a photon is given by

$E = \frac{hc}{\lambda}$, where h is Planck's constant and is equal to $6.626 \times 10^{-34}\ \text{J} \times \text{s}$, c is the speed of light in m/s, and λ is the wavelength in m.

5. Continuing the thinking in Figuring for Yourself exercises 6 and 7, calculate the energy in a cubic meter of space, multiply the energy per photon calculated in the previous exercise by the number of photons per cubic meter given above.
6. Continuing the thinking in the last three exercises, convert this energy to an equivalent in mass, use Einstein's equation $E = mc^2$. Hint: Divide the energy per m^3 calculated in the previous exercise by the speed of light squared. Check your units; you should have an answer in kg/m^3. Now compare this answer with the critical density. Your answer should be several powers of 10 smaller than the critical density. In other words, you have found for yourself that the contribution of the CMB photons to the overall density of the universe is much, much smaller than the contribution made by stars and galaxies.
7. There is still some uncertainty in the Hubble constant. (a) Current estimates range from about 19.9 km/s per million light-years to 23 km/s per million light-years. Assume that the Hubble constant has been constant since the Big Bang. What is the possible range in the ages of the universe? Use the equation in the text, $T_0 = \frac{1}{H}$, and make sure you use consistent units. (b) Twenty years ago, estimates for the Hubble constant ranged from 50 to 100 km/s per Mps. What are the possible ages for the universe from those values? Can you rule out some of these possibilities on the basis of other evidence?
8. 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.
