Astronomy 9: History of Cosmology

Final Exam—Solutions

2000 May 16

I. MULTIPLE CHOICE

1. (**C**) Aristotle's conception of the universe was spatially finite and was not eternal.
2. (**E**) Based on current evidence, dark energy seems to be the most abundant constituent of the universe, followed by non-baryonic dark matter; luminous stars are way down below 1% of critical density.
3. (**D**) According to Bishop Usher, who summed the Biblical begats, the universe began in 4004 B.C.
4. (**A**) Recent microwave background observations suggest that the universe is characterized by a nearly flat geometry.
5. (**D**) The fundamental forces, in order of decreasing strength, are strong, electromagnetic, weak, and gravity.
6. (**E**) The highest energy which can be created in current particle accelerators corresponds to a time when the age of the universe was approximately 10^{-6} seconds.
7. (**B**) The expansion of the universe does not contradict Hoyle's Steady State theory.
8. (**D**) Albert Einstein won the Nobel prize for his work on the photoelectric effect.
9. (**E**) To an observer in space, light from Earth's surface would appear slightly red-shifted (not blue-shifted) due to gravity.
10. (**B**) Measurements of the Hubble constant are today more than five times smaller than Hubble's original estimate.
11. (**D**) The so-called "ultraviolet catastrophe" refers to a classical prediction that blackbodies should radiate an infinite amount of energy at high frequencies.
12. (**A**) The earliest of the listed measurements of the finite speed of light was performed by Roemer, using the moons of Jupiter.
13. (**B**) The Michelson-Morley interferometer did not provide evidence that the earth moves.
14. (**D**) Einstein's remark about the Moon not existing when no one was looking at it was directed against the Copenhagen interpretation of quantum mechanics.
15. (**D**) Einstein's model is static.
16. (**A**) A (positive) cosmological constant causes the expansion to accelerate.
17. (**A**) Models with a cosmological constant can have a "hovering" phase and so can be older than t_H.
18. (**A**) The Hubble time is the age of the universe you would get if you assumed the universe had always been expanding at its current rate.
19. (**E**) A negative H_0 means the universe is contracting.
20. (**A**) Our universe appears to be entering a phase where it is dominated by something like a cosmological constant.

II. TRUE OR FALSE

1. **False**. A closed universe with a Λ might not be doomed to collapse, and an open universe with a (negative) Λ might not expand forever.
2. **False**. Curved spacetime need not be embedded in some higher-dimensional space.
3. **True**. Due to the expansion of the universe, the distances to (unobservable) remote parts of the universe might be increasing faster than the speed of light.
4. **False**. Special relativity still applies *locally*, and so it may well be impossible to build a ship that travels across the galaxy at faster-than-light speeds.
5. **True**. Einstein's equivalence principle states that a uniform gravitational field is equivalent to a uniformly accelerating reference frame.

III. DEFINITIONS

1. **Inertia** is the tendency of objects to resist a *change* in their motion; in the absence of forces, things want to keep moving in a straight line at constant speed.
2. **Mach's Principle** is the idea that inertial (non-accelerating) reference frames can only be defined in relation to the overall mass distribution in the universe. It is not entirely consistent with general relativity and so probably does not fully apply to the universe.
3. **Perfect Cosmological Principle**: the universe looks basically the same for observers located anywhere in space *and time*. The basis for the Steady State theory, the PCP is contradicted by observational evidence.
4. A **Platonic solid** is one of the five perfect geometrical solids whose faces are all regular polygons and whose vertices all look the same. Kepler tried in vain to use a nested set of them to explain the distances of the planets from the sun.
5. The **cosmological constant** (Λ) is a dark energy which fills the vacuum of space. A positive Λ tends to accelerate the expansion of the universe (kind of like anti-gravity). Originally introduced by Einstein to allow an eternal, static (but later proved unstable) universe, it has reappeared in recent observational data.
6. A **blackbody** is a perfect absorber (hence the "black"), and it is also a perfect emitter. The spectrum of the cosmic microwave background is a good example of a blackbody spectrum, which is independent of the composition of the emitter and only depends on its temperature.
7. The **natural selection of universes** is a speculative idea we encountered in *Cosm.* Universes create "baby" universes, and only the ones which develop intelligent life learn how to multiply. If this is the case, most universes will harbor conditions favorable to life.
8. The **Copernican Principle** states that Earth's location in the cosmos is not special. First developed in connection with a heliocentric solar system, we now know that even the locations of our solar system and galaxy are not special.
9. The **Anthropic Principle** comes in many varieties ranging from near-tautology to striking metaphysical speculation, but the essential idea is that *life* in some way plays an important role in the universe; it is in a sense an anti-Copernican principle.
10. **Entropy** is generally a measure of the disorder of a system. Generally, the more information something has, or the more complex it is, the lower its entropy. The second law of thermodynamics states that entropy does not decrease in a closed system, and it implies that the universe is winding its way down towards a "heat death".
11. The **uncertainty principle** in quantum mechanics states that the harder you try to measure the position of something, the less you know about its momentum, and vice versa. Another version relates energy and time: the universe itself could be a "free lunch": if it has zero total energy, it can live arbitrarily long!
12. If you compress an object to higher and higher densities, the gravitational forces near its surface will become stronger and stronger. Eventually, nothing, not even light, can escape, and a **black hole** is formed.
13. A **Cepheid** is a special type of variable star whose period is related to its luminosity. It is therefore useful as a "standard candle" for measuring distances to other galaxies.
14. The **Hubble law** is the linear relationship, $v = Hd$, between the recession velocity of galaxies (due to the expanding universe) and their distance.
15. **Determinism** is the (Newtonian) idea that if you know precisely all the positions and velocities of all the particles in the universe, you can predict everything that will ever happen. Of course, with quantum mechanics, we find that there are always uncertainties, and we can only talk about probabilities.
16. The **Cosmological Principle** states that no location and no direction in the universe is special; the universe is homogeneous and isotropic (at least on large scales).
17. **Quintessence** was originally Aristotle's idea for a celestial "fifth element" in addition to the four terrestrial elements: air, earth, fire, and water. Today it has become a popular name for forms of *dark energy* in the universe (such as a cosmological constant), which might be causing the expansion of the universe to accelerate.

18. **Quasars** are very luminous distant objects at the centers of remote galaxies. They are probably huge black holes devouring lots of gas. The fact that there seem to have been more of them in the past poses problems for the Steady State theory.
19. **Tired Light** is an (unpopular) alternative theory to explain the redshifts of distant galaxies: rather than being stretched along with the expansion of space, light simply gets tired and loses energy on its journey, so space doesn't have to expand.
20. **Wave/particle duality** is a property of matter and radiation: light can behave either like a wave or a particle (photon), while particles of matter can sometimes behave like waves.

IV. SHORT ANSWER

1. It has long been known that in an eternal universe in which the stars have been around forever, the night sky should appear as bright as the surface of a star. There are two reasons why it doesn't. The first (and most important) reason is that the universe has not been around forever, and the light from very distant stars has not yet had time to reach us. The second is that the universe is expanding, so the light from distant galaxies has lost energy due to the expansion. Another point is that the sky actually *is* bright, but only if you look at it using microwaves. If you went back to a time when the universe was 1000 times smaller, this radiation was actually in the visible part of the spectrum. So the expansion of the universe is important, too. The problem of the dark night sky has been known as Olbers' paradox, though it was known much earlier (to Kepler).
2. We have to use the special-relativistic formula for the addition of velocities, since the two velocities are so close to the speed of light, $u = v = 0.99c$.
$$V = \frac{u+v}{1+uv/c^2} = \frac{0.99c}{1+0.99^2} = \frac{1.98c}{1.9801} \approx 0.99995c.$$
3. Using Cepheids to get the Hubble constant.
   (A) From the graph, the brightness of the Cepheid repeats every six days.
   (B) From the period–luminosity graph, a period of six days corresponds to $L \approx 10^{30}$ W.
   (C) Since $b = L/4\pi d^2$, we can solve for distance to get
   $$d = \sqrt{\frac{L}{4\pi b}} = \sqrt{\frac{10^{30}\,\mathrm{W}}{4\pi(10^{-19}\,\mathrm{W\,m^{-2}})}} = 9 \times 10^{23}\,\mathrm{m}$$
   or
   $$(9 \times 10^{23}\,\mathrm{m}) \times \left(\frac{1\,\mathrm{Mpc}}{3.0856 \times 10^{22}\,\mathrm{m}}\right) = 29\,\mathrm{Mpc}.$$
   (D) The observed wavelength is 661 nm, while the emitted wavelength was 656 nm:
   $$z = \frac{\Delta\lambda}{\lambda} = \frac{661-656}{656} \approx 0.0076.$$
   (E) Since z is very small compared to 1, the recession velocity must be small compared to c, and we can safely apply the simple linear relationship between redshift and velocity, $z \approx v/c$:
   $$v = cz = (0.0076)(3 \times 10^5\,\mathrm{km\,s^{-1}}) \approx 2300\,\mathrm{km\,s^{-1}}.$$
   (F) Hubble's law says that $v = H_0 d$, so we can combine the answers from (C) and (E):
   $$H_0 = \frac{v}{d} = \frac{2300\,\mathrm{km\,s^{-1}}}{29\,\mathrm{Mpc}} \approx 80\,\mathrm{km\,s^{-1}\;Mpc^{-1}}.$$
   Since our best estimates of H_0 are in the range 65–75 km s^{-1} Mpc^{-1}, this is not too bad.

V. ESSAY QUESTIONS

1. See discussion in Gleiser, p. 303.
2. Quote taken from Harrison, p. 240.
3. See Hawley & Holcomb, pp. 97–103, 264–78.
4. Who knows?