Solutions

ASTRONOMY 5
Final Exam
Spring 2001
(Edited for questions relevant to Astronomy 5 2007 Final)

Follow the directions in each section. Write all answers on this examination paper. Feel free to ask for clarification of any question. You may utilize the textbook, lecture notes, your notes, homework solutions, and any handouts that we have passed out. However, the exam must be written in your own words. Direct quotes from the texts or lecture notes will not be given credit.

Write neatly please. Keep answers short and to the point. Credit is given for the quality of ideas, not the number of words on the page.

The first two sections are graded in difficulty from easy to hard. If you are having trouble with the ends of these sections, skip them and go on to the rest of the exam.

Point totals are given in each section. The total number of points is 118.

TRUE-FALSE: Do all. One point each. 25 total points.

1. We know the Universe is not contracting because the light from galaxies is not blueshifted. T

2. Primordial nucleosynthesis occurred before 1 second after the Big Bang. F
   happens ~3 minutes after the Big Bang

3. Recent measurements suggest that the expansion of the Universe may be accelerating. This is surprising because normal gravity is attractive. T

4. The HR diagram of a star cluster can be used to estimate its age. T

5. A particle freezeout occurs when photons lack enough energy to create certain particle-antiparticle pairs. T

6. A structural freezeout occurs when structures break apart as the Universe expands and cools. F
   structural freezeout occurs when the Universe cools enough for structures to form that would be broken apart at higher temp.

7. Black holes are discovered at the centers of galaxies by observing very high velocities for stars orbiting close to the center. → T

8. A GUT (grand unified theory) refers to theories that unify gravity, the electromagnetic, and weak forces. F
   GUT unifies strong, weak, and EM, not gravity!

9. Clocks in strong gravitational fields appear to run slowly when viewed from outside the gravitational field. T

10. Quarks that existed freely just after the GUT era later combined to form protons and neutrons when the Universe was cooler. T

Which of the following are true and which are false concerning inflation?

11. Inflation created the matter and energy that now comprise the Universe. T
12. Inflation generated the small density fluctuations that later formed galaxies and clusters of galaxies. T
13. Inflation synthesized helium and the light elements from hydrogen. F (see #2)
14. Inflation was the first event in the early Universe to be modeled with with the laws of physics, giving confidence to cosmologists that the laws of physics were valid even at very early times. F
Primordial nucleosynthesis was the first event that...
15. Older stellar populations look bluer because massive red stars evolve quickly away. Older population look redder b/c massive blue stars evolve quickly away. F
16. The Andromeda galaxy is falling towards the Milky Way because the two galaxies both belong to a positive density fluctuation that is just now collapsing. T

17. When we say that the electroweak and strong forces "freeze out" at 10^{-35} sec, we mean that following this time, neither force was important in the Universe again. Force "freeze out" means that they became separate forces. F
19. Cosmologists are considering theories involving other universes because evidence for them has turned up in irregularities in the cosmic microwave background radiation. No such irregularity would be observable! F
20. Current measurements of the matter density of the Universe support the prediction of the theory of inflation that the Universe should be flat. F
measurements of the matter density plus the dark energy density support this prediction.
21. A rough estimate of the age of the Universe can be gotten from the velocities of galaxies, assuming that their speeds of separation have remained roughly constant over time. age of Universe $= \frac{1}{H_0}$ T

22. The preponderance of matter over antimatter in our Universe is deeply puzzling because matter and antimatter are mirror images of one another in laboratory experiments. T

23. Olber's Paradox is resolved by the fact that the Universe is finite in size. F
... by the fact that the Universe is finite in age.

24. Hubble's law is valid even if a universe expands at very different rates in different places. F
Hubble's law is only valid if the universe expands at the same rate everywhere.

25. A galaxy's location along the Hubble sequence reflects the importance of major mergers in its formation history. T

MULTIPLE-CHOICE: Do all. Two points each. 50 total points.

26. Atomic spectral lines are produced because: c
   a) Atoms collide with other atoms.
   b) There are only a finite number of elements in the periodic table.
   c) Electrons in upper energy levels of atoms fall to lower energy levels, producing photons.
   d) There are an integral number of neutrons and protons in an atomic nucleus.
   e) Matter and anit-matter annihilate, producing photons.

27. According to general relativity, why does the Earth orbit the Sun? a
   a) The mass of the Sun curves spacetime, and this in turn curves The path in space taken by the Earth.
   b) The mysterious force that we call gravity holds the Earth in orbit.
   c) The Earth and Sun are connected by a "ropelike" set of invisible subatomic particles.
   d) Matter particles in the Earth and Sun are continually exchanging gravitons, which are the "force-carrier" particles of the gravitational force.

28. Which statement correctly describes the process that emitted the cosmic microwave background radiation? c
   a) It was emitted by an early generation of stars at a redshift of about 1000.
   b) It was emitted by hot dust at a temperature of 3000 K.
   c) It was emitted by early ionized gas as it became neutral.
   d) It was emitted by electrons jumping from one level to another in atoms.
   e) It was emitted by early neutral gas at a temperature of 3000 K.

29. Suppose you draw a circle and measure its circumference C and its radius r. You find that C is *less* than $2\lambda r$. What kind of geometry are you dealing with? b

   ↳ should be $2\pi r$!
   a) Flat geometry.
   b) Spherical geometry.
   c) Saddle-shaped geometry.
   d) Euclidean geometry.
   e) This situation can never occur.

30. What characteristic most determines how stars differ in luminosity? b

a) Their composition.
b) Their mass.
c) The time they are formed.
d) Where they are formed.
e) Their color when they are formed.

31. The formula for Hubble's law is: b

$$v = H_0 r.$$

Remember, "radial velocity" means velocity along the line of sight. This is the only velocity we can measure with a redshift.

Which of the following statements about Hubble's law is true?

a) The symbol v is the total velocity of a galaxy, and the symbol r is its distance from us.
b) The symbol v is the radial velocity of a galaxy, and the symbol r is its distance from us.
c) The symbol v is the radial velocity of a galaxy, and the symbol r is its radius.
d) The symbol v is the rotation velocity of a galaxy, and the symbol r is its radius.
e) The symbol v is the velocity of a galaxy sideways to the line of sight, and the symbol r is its distance.

32. Which statement is true about the lifetimes of stars? a

a) Little stars live longer because they don't burn energy very rapidly.
b) Little stars live shorter because they have less fuel.
c) Massive stars have more fuel, but they also burn it more rapidly, so they end up having the same lifetimes as little stars.
d) Stars begin life at the top of the main sequence and evolve down it as they run out of fuel, become dimmer, and cool.
e) Stars begin life as giants and contract to the main sequence just before they die.

33. By measuring the redshift of a galaxy we could NOT learn: d

a) Roughly how far away it is.
b) Roughly how long it took for the light to get from it to us.
c) How big the Universe was when the light left the galaxy compared to how big it is now.
d) How fast the galaxy is moving perpendicular to the line of sight.
e) How fast the galaxy is moving along the line of sight.

see note for # 31.

34. The disk of our Galaxy does NOT contain: c

a) Gas that is still forming young stars.
b) Material that fell into the Galaxy after the last major merger.
c) Stars that had formed before the last major merger. → the merger disrupts the disk.
d) Objects that are moving in circular, co-planar orbits.
e) Other planetary systems.

35. Where are most heavy elements made? b

a) In the Big Bang, at the beginning of the Universe.
b) In stars.
c) In the interstellar medium.
d) During the birth of stars.
e) In quasars.

36. The energy released in quasars comes from: e

a) Matter-antimatter annihilation near a black hole.
b) Black hole evaporation.
c) Nuclear reactions in an accretion disk around a black hole.
d) Energy emerging through a wormhole.
e) Heat generated via friction in an accretion disk around a black hole.

37. What is the strongest evidence that 90% of the mass of the Galaxy is in the form of dark matter? a

a) The orbital speeds of stars far from the Galactic center are surprisingly high, suggesting that these stars are feeling gravitational effects from unseen matter.
b) Although dark matter emits no visible light, it can be seen with radio telescopes, and such observations confirm that the halo of our Galaxy is full of this material.
c) Theoretical models of galaxy formation suggest that a galaxy cannot form unless it has at least 10 times as much matter as we see in the Milky Way, suggesting that the halo must be full of dark matter.
d) Our view of distant galaxies shows them to be full of obscuring, dark patches,
and we assume that our Galaxy must be full of similar dark patches also.

38. Which of the following is NOT true about the Planck time? b

a) Going back in time, it is the epoch when the horizon mass fluctuates by an amount equal to its own value.
b) It triggered the onset of inflation. → onset of inflation was triggered by freezeout of the strong force
c) It is the point where the known laws of physics break down.
d) It is the epoch "before" which space and time are ill-defined.
e) Understanding the Universe before the Planck time requires a fully unified theory of the GUT force and gravity.

39. Our horizon is a surface that surrounds us on all sides. Which one of the following statements about it is NOT true? ___c___
   a) Our horizon encloses the part of the Universe that we can see.
   b) Our horizon will encompass more matter in the future.
   c) Our horizon surface is the same horizon surface seen by all observers in the Universe.
   d) Our horizon is about 14 billion light-years in radius.
   e) Our horizon has a lookback time equal to the age of the Universe.

40. Consider a distant galaxy one billion light years away. Its trajectory with respect to our Galaxy so far can best be described as: ___c___
   a) A circular orbit, with period equal to the age of the Universe.
   b) An elliptical orbit, with period equal to the age of the Universe.
   c) A straight line directed away from our Galaxy.
   d) A straight line oriented sideways to the line joining our two galaxies.
   e) A straight line directed towards our Galaxy.

42. What caused inflation? ___c___
   a) Nuclear reactions bound protons to neutrons, releasing large amounts of energy and causing the Universe literally to "blow up."
   b) Large amounts of energy were released through matter-antimatter annihilation, causing the Universe to "blow up."
   c) The strong force split away the electroweak force, triggering the appearance of a strange form of vacuum energy that did not dilute as the Universe expanded.
   d) Gravity, having split off before the inflationary era, was rather weak and could not restrain the expansion.
   e) b and c.

44. Baryonic matter can comprise at most 10% of the dark matter because: ___a___
   a) More baryons than that during primordial nucleosynthesis would produce amounts of light elements that disagree with their observed abundances today.
   b) All forms of baryonic matter should be detectable in our telescopes, yet they are not seen.
   c) If dark matter were baryonic, it would be detectable in laboratory experiments, yet it has not been seen.
   d) Baryons in halos around galaxies would annihilate with clouds of antimatter particles, releasing energetic gamma-rays, which are not seen.
   e) No known candidates for baryonic dark matter exist.

45. It is bright around you everywhere, yet you cannot see very far. a
You have traveled around a lot and it is clear that you are not in a star, yet it is nearly as bright as looking directly at the surface of the Sun. You cannot find a single neutral atom anywhere, and virtually all the nuclei are hydrogen and helium. Where are you?

a) You are in the Universe when it was about 300,000 years old.
b) You are in the Universe more than 10^{100} years in the future.
c) You are in an accretion disk around a supermassive black hole.
d) You are inside the event horizon of a quasar.
e) You are in the Universe when it was about 10 seconds old.

46. Galaxies formed because: e

a) Energy from early quasars compressed the gas in regions near them.
b) Certain regions of the early Universe had extra density.
c) Gravity acted to prevent the expansion of certain regions of the Universe.
d) Density fluctuations were created during inflation.
e) b, c, and d.
f) a, b, and d.

47. Why are dark matter particles distributed throughout galactic halos rather than in a disk like baryonic matter? c

a) They are light enough to have expanded out into the halo.
b) Shock waves from supernovae explosions have blown them out into the halo.
c) Dark matter does not feel the electromagnetic force and so cannot collide, heat, radiate, lose energy, and settle into a rotating disk like baryons.
d) Dark matter rotates more slowly than baryonic matter.

48. Stars in the bulges of galaxies are generally older than those in disks because: e

a) Disk stars formed from gas that fell in after bulges were created.
b) Bulge stars were formed before many heavy elements had been created.
c) Bulge stars are those that existed before the last major merger.
d) The rising amount of heavy elements in disks triggered stronger disk star formation recently.
e) a and c.
f) b and d.

49. Two key pieces of evidence suggest that the expansion of the Universe is actually accelerating. These are: C

a) The measurement of distances to certain galaxies and the observation that their radial velocities are increasing.
b) The angular size of "measles" in the cosmic microwave background radiation and the upper limit to the baryon density (λ_{bary}) set by nucleosynthesis.
c) The angular size of "measles" in the cosmic microwave background radiation and the apparent brightnesses of distant supernovae.
d) The absolute size of "measles" in the cosmic microwave background radiation and the absolute brightnesses of distant supernovae.

50. As time goes on, the microwave background radiation will: f

a) Come from gas that is farther and farther away.
b) Always come from the same distance because we are seeing the same temperature.
c) Always come from gas that emitted the light roughly 1 Myr after the Big Bang.
d) Have a higher and higher redshift.
e) Always have traveled for 14 billion years since it was emitted.
f) a, c, and d
g) b and e

SHORT DEFINITIONS: Do 5 out of 8. Four points each. 20 total points.

51. Baryonic matter

Not covered in the course.
Will not be on final.

52. Weak anthropic principle – an explanation of why the Universe is the way it is (i.e., why the constants of nature such as the speed of light or the mass of an electron have the values that they do.) The W.A.P. states that there are many (possibly an infinite number of) universes with different properties but that only a few of them ⟹

have properties that can support life. Selected at random, a Universe that can support life would be very improbable, but our universe is not selected at random because we are in it. Since we are alive, we must live in one of the universes that can support life, which explains why the constants of nature in our universe lie within the very narrow range of values that can foster life.

53. Isotropy problem

The cosmic microwave background (CMB) radiation is the same in all directions, to one part in 100,000. This means that the universe had to be the same temperature everywhere when the CMB was emitted, 400,000 years after the Big Bang. The "isotropy problem" is that there was not enought time in 400,000 years for the universe to equilibrate to the same temperature everywhere because light didn't have time to travel across the universe by then. Inflation solves the isotropy problem by saying that the entire universe inflated from a tiny region just after the Big Bang, and that tiny region <u>did</u> have time to come into temperature equilibrium before it inflated.

54. Schwarzschild radius

The Schwarzschild radius is the radius of the sphere that you would have to compress an object into in order for it to become a black hole. It is defined as the radius at which the escape velocity is the speed of light, so not even light can escape from inside the Schwarzschild radius of a black hole. Every object has a Schwarzschild radius. More massive objects have larger Schwarzschild radii. For a black hole, the Schwarzschild radius is the same as its event horizon.

55. Uncertainty principle – a fundamental tenet of quantum mechanics which says that you cannot know both the location and the velocity of a particle to infinite precision — the more precisely you know the location, the less precisely you know the velocity, and vice versa. This relation can be translated into a statement about the measurement of the energy of a system over some period of time. The U.P. says that to know the energy of a system to high precision, you must observe it for a long time. An important effect of the U.P. is that the vacuum is not really empty over short periods of time (i.e., the total energy or mass of the vacuum is not precisely zero over short periods of time) so particle-antiparticle pairs are constantly appearing and disappearing. These pairs are the "quantum fluctuations" which are split apart by Inflation before they can disappear. They produce the initial overdense regions of space that eventually grow into galaxies and galaxy clusters.

56. Hubble sequence

– a system of classifying galaxies based on their overall shape. The Hubble sequence runs from elliptical (E) galaxies to spiral (S) galaxies to irregular (Irr) galaxies, with sub-classifications Sa, Sb, Sc, Sd for the spirals based on the size of their bulges. E galaxies are entirely bulge galaxies without a disk, Sa galaxies have disks with large bulges, and Sb, Sc, and Sd galaxies have bulges decreasing in size. Galaxy disks tend to contain young star, gas, dust, and on-going star formation, while galaxy bulges have only old stars, no gas or dust, and no star formation. Irr galaxies have some properties of disk galaxies (gas, dust, star formation) but do not have bulges or well-ordered disks. The location of a galaxy on the Hubble sequence indicates how important major mergers have been in its past — galaxies which have undergone major mergers are toward the E end of the sequence, whereas those that have not experienced major mergers are toward the Sd-Irr end of the sequence.

57. Lambda (~~λ~~) → Should be Ω_Λ.

Lambda is the "dark energy" component of the Universe. Ω_Λ tells us what fraction of the critical density of the Universe is provided by dark energy. Current measurements give $\Omega_\Lambda = 0.7$, so the dark energy provides 70% of the energy (or mass — remember that $E=mc^2$ says that matter and energy are in some ways the same thing!) needed to make the curvature of the Universe flat. Matter (dark matter + ordinary matter) provides the other 30%, so the Universe does in fact have flat geometry. However, instead of behaving like matter which feels the attractive force of gravity and tends to pull stuff in the Universe closer together, dark energy seems to have a repulsive force that is pushing stuff in the Universe further apart and accelerating the expansion of space.

58. Gravitational instability picture – a theory for the growth of structure in the Universe. It says that quantum fluctuations produced during Inflation resulted in slightly overdense and underdense regions of space, which tended to become more extremely overdense or underdense due to gravity. Gravity makes small variations in density unstable and they tend to become emphasized as time goes on — dense regions collapse in on themselves and attract matter from surrounding less dense regions. The end result is that dense regions become highly concentrated and underdense regions tend to empty out as the matter in them is gravitationally attracted to the surrounding dense regions. The gravitational instability picture gives an explanation of how small density variations in the early Universe could grow into the galaxies, galaxy clusters, and voids that we see in the Universe today.

QUANTITATIVE QUESTIONS: Do all 4 of these. Point totals vary and are marked at the end of each problem. Put answer in the blank. If you show your work, you are more likely to be given partial credit even if the answer is wrong. 23 total points.

59. The formula for the Schwarzschild radius of a black hole is: ____________

$$R_{Schwarz} = 2GM/c^2.$$

The Earth has a mass of about 10^{28} g and a Schwarzschild radius of about 1 cm. A massive star might have a mass as large as 10^{35} g. What is the Schwarzschild radius of such a star, in cm? Hint: get the factor that is the mass ratio, decide whether the star's value is smaller or larger than the Earth's, and multiply the Earth's value appropriately. (5 points)

$$\frac{R_{star}}{R_{Earth}} = \frac{\cancel{2}\cancel{G}M_{star}/\cancel{c^2}}{\cancel{2}\cancel{G}M_{Earth}/\cancel{c^2}} \Rightarrow \frac{R_{star}}{R_{Earth}} = \frac{M_{star}}{M_{Earth}}$$

next page ⟹

$$\frac{R_{star}}{R_{Earth}} = \frac{10^{35}\ g}{10^{28}\ g} = 10^7$$

$$R_{star} = 10^7 \times R_{Earth} = 10^7 \times 1\ cm$$

$$\boxed{R_{star} = 10^7\ cm} = 10^5\ m = 10^2\ km = \underline{100\ km!}$$

60. The formula for Wien's law is: 1 mm

$$\lambda_p = 0.29\ cm / T,$$

where λ_p is the peak wavelength of a thermal spectrum and T is in degrees Kelvin. What is the peak wavelength of the cosmic microwave background today, to the nearest mm? Hint: what is the temperature of the CMB radiation today? (5 points)

T_{CMB} today = 3 K

$$\lambda_p = \frac{0.29\ cm\ K}{T_{CMB}}$$

$$\lambda_p = \frac{0.29\ cm\ \cancel{K}}{3\ \cancel{K}}$$

$$\lambda_p = \frac{0.29\ cm}{3}$$

$$\lambda_p = 0.1\ cm$$

$$\boxed{\lambda_p = 1\ mm}$$

61. The formula for the Hubble law is: ______

$$v = H_0\, r,$$

where the value of H_0 is 70 km/s/Mpc or 21 km/s/million light years. A distant galaxy has a radial velocity of 4200 km/s. How long does it take light to travel from it to us? Hint: Think about which value of the Hubble constant is better to use. (7 points)

Since we want to know the light travel time, we want to use units of light years.

$$H_0 = 21\ km/s/\text{million light years} = \frac{21\ km/s}{10^6\ \text{light years}}$$

$$v = H_0 r$$

$$\frac{v}{H_0} = \frac{\cancel{H_0} r}{\cancel{H_0}}$$

$$\frac{v}{H_0} = r$$

$$r = \frac{4200\ \cancel{km/s}}{21\ \cancel{km/s}/\text{million ly}} = 200\ \text{million ly}$$

So light takes **200 million years** to travel to us.