Name:______KEY_________

University of California, Santa Barbara
Department of Physics

Astronomy 2 | FINAL EXAM | Prof. Antonucci
Tuesday, June 10 | Spring 2008

I give my permission for my graded exam to be left in a public place: YES_X_ NO___

FACTS OF POSSIBLE INTEREST

Hubble Law: $v = H_0 d$

$G = 6.67 \times 10^{-11}$ Newton $m^2 kg^{-2}$ in MKS units

Seconds in a year $\sim 3 \times 10^7$

Newton's law of gravitation: F=$\frac{GMm}{r^2}$

1 light year $\approx 1 \times 10^{16} m$

Small angle formula: actual size $\approx$ distance $\times \frac{\text{angular size in arc sec}}{200{,}000}$

$c = 3 \times 10^5 \frac{km}{\sec} = 3 \times 10^{10} \frac{cm}{\sec} = 3 \times 10^8 \frac{m}{\sec}$

$1 par\sec = 3.26 ly = 3 \times 10^{16} m$

Eddington Limit for radiation pressure to be less than gravity:

$L < 1.3 \times 10^{31} \frac{Joules}{\sec} \left(\frac{M}{M_O} \right)$

Doppler Shift: $\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$

Inverse square law: $F = \frac{L}{4\pi d^2}$

Diffraction limited angular resolution: $\theta = \frac{\lambda}{D}$ (rad)

Parallax: $d = \frac{1}{p}$, d is the distance in parsecs, p is the parallax in arcseconds.

Surface are of sphere: $4\pi r^2$

Number of photons per baryon in present universe ~1billion

Calculations can be approximate; verbal answers should be quite brief (2 or 3 sentences) and to the point.
(5 Points per question or subsection throughout the test unless otherwise noted)

I. TWO GOOD SENTENCES OR LESS CAN ANSWER THE FOLLOWING QUESTIONS.

1. How does the resolving power of the Keck telescope in Hawaii, which is 10 meters in diameter, compare with that of the 2.4 meter Hubble telescope in space?
   a) First considering the Keck without the "adaptive optics" image sharpening optics.

The Keck can only details bigger than the seeing disk of about 1" without adaptive optics. Hubble gets $\theta = \frac{\lambda}{D} 206265 = \frac{500 \times 10^{-9} m}{2.4m} 206265 = 0.04''$

   b) Now consider the Keck telescope using this new adaptive optics technique. (Note for your information that this sounds better than it is, because there are limitations on using adaptive optics.)

If adaptive optics were perfect Keck would be 4 times better than Hubble:

$$\theta = \frac{\lambda}{D} 206265 = \frac{500 \times 10^{-9} m}{10m} 206265 = 0.01''$$

2. Why do massive stars have shorter lives than low-mass stars?

Massive stars have more pressure on their cores so they burn hotter. Fusion rates go up fast with temperature so these stars burn much faster.

3. If a star has a parallax of 0.20 arcseconds, what is its distance from us in parsecs?

$$d = \frac{1}{p} = \frac{1}{0.2} = 5pc$$

4. If a star moves directly toward us in the sky, does the Doppler Effect change its spectrum (i.e. the wavelength of the light emitted)? What if it moves purely perpendicular to our line of sight?

Motion toward us produces a measurable Doppler Effect; motion perpendicular to us produces no change in wavelengths due to the Doppler Effect.

5. If we look at the spectrum from ionized gas clouds, what can we infer if we see ONLY permitted emission lines?

Forbidden lines only occur in cool low density gas. If are completely absent we can assume that the gas cloud is relatively hot and dense.

6. a) What is the Angular Size Test in cosmology?

If we can measure the angular size of an object of known linear size we can determine if the small angle formula for flat space works, thus if our space is flat.

b) How has the angular size test, as applied to the Cosmic Microwave Background, been used to determine the overall shape of the universe, and what was the result?

The largest causally connected region on the CMB is estimated to be about 1" in the sky in a flat universe. The fact that we measure 1" for the dominant spot size on the CMB is strong evidence that we live in a flat universe.

7. Explain two ways in which creatures who live on a two dimensional surface can tell if their space is curved.

A 2D creature could measure the brightness of an object of known luminosity at a known distance. A 2D creature could measure the angular size of an object of known length at a known distance. A 2D creature could measure the diameter of a large circle and compare it to the diameter.

8. What is superluminal motion in blazars? What is the evidence for it? Does this violate Einstein's rule that nothing can go faster than the speed of light? Explain.

Superluminal motion is the apparent faster than light motion observed in plasma blobs that are fired toward us from active galactic nuclei. Such motion is observed in sequences of VLBI telescope images of AGN. The motion does not violate Einstein's special relativity because the faster than light motion is just an optical illusion caused by the motion toward us.

9. If distant quasars have super massive black holes (SMBH) that are eating up matter from a surrounding disk (i.e. an accretion disk), why should we find quiescent (starved! No accretion) SMBHs in some nearby galaxies?

Galaxies closer to us are closer to our age, so they're older than distant galaxies, and the matter in their accretion disks has had time to fall into the black hole.

10. The Earth receives 1400 Joules of sunlight on each square meter every second (you can assume the collector is perpendicular to the Sun's direction). We are 1.5×10^{11} meters away from the Sun. Calculate the total luminosity of the Sun.

$$1400\times 4\pi(1.5\times10^{11})^2 = 3.9\times10^{26}\,\frac{W}{\text{sec}}$$

11. To measure possible deviations from the straight-line Hubble Law observed in nearby space (cosmologically speaking), we need some "standard candle," that is, something whose luminosity we know in advance. To study the large scale properties of the universe, we need to observe something at high redshift. What objects are used as standard candles? Why do people think we know the luminosity in advance?

We use type Ia supernovae as standard candles. We think we know their luminosities because they all take place when a white dwarf reaches 1.4 solar masses.

12. We can see far fewer galaxies per square degree when we look in the Milky Way region of the Celestial Sphere. Why is that?

The dust in the galactic plane block much of the light traveling through it, so distant objects in the direction of the Milky way will be obscured.

13. Explain very briefly how the rotation curves of Spiral Galaxies indicate the presence of dark matter.

Objects farther from the center of the galaxy orbit faster than we would expect based on the amount of visible matter in the galaxy.

14. How does the Milky Way disk look from Earth at a wavelength of 0.5 microns? How about at 2 microns? And at 60 microns? (Hint: this involves starlight and absorption and emission by dust grains.)

At 0.5 micron, visible light, we see stars.
At 2 microns, near infrared we see stars in the pane and the bulge of the galaxy.
At 60 microns, infrared, we see dust in the plane of the galaxy.

15. What is a forbidden line?

A forbidden line is a line that corresponds to a transition that takes seconds, as opposed to nanoseconds for allowed transitions, to take happen.

16. What is meant by the Eddington Limit on luminosity of accreting objects?

The Eddington Luminosity is the maximum luminosity an accreting object can have before the outward force from radiation pressure is greater than the inward force from gravity on the in falling matter. It is the maximum sustainable luminosity for an accreting object.

17. What is meant by the Hubble Time? Calculate the value assuming $H_0 = 80 \frac{km/\sec}{Mpc}$ (though this isn't the best estimate today).

The Hubble Time is on estimate on the age of the universe. It is
$t_{H_0} = \frac{1}{H_0} = \frac{1}{80}\frac{Mpc}{km}\sec = \frac{1}{80} 3.09 \times 19 \sec = 12.5$ **billion years.**

18. What is meant by the Deuterium bottleneck?

After the universe dropped below the threshold temperature for electrons, the number of neutrons started dropping, but the universe was still too hot to allow Deuterium (one proton and one neutron) to remain intact. Deuterium production is the first step in Helium fusion, so the Helium and other light element abundances was set by how much time (a matter of a few minutes) went by after neutrons stopped forming and Deuterium could begin to form.

19. What is meant by decoupling of radiation from matter in the early universe? Why does decoupling occur at nearly the same time as recombination?

When most photons had energies above 1 Rydberg, photons were absorbed all the time and matter was ionized. When the temperature dropped and the photon energies dropped below 1 Rydberg, photons were no longer absorbed all the time, they decoupled from matter, and the matter (protons neutrons and electrons) recombined, was no longer ionized.

20. Suppose at the end of primordial nucleosynthesis that the baryons are composed of 90% protons and 10% neutrons. How much Helium is produced?

If there are 9 protons to every neutron, then for every two neutrons in Helium there are 18 protons, two of which go into Helium leaving 16 for Hydrogen. So we get

$$\frac{\#\,Helium}{\#\,Hydrogen} = \frac{1}{16}$$

Helium weighs 4 times as much as Hydrogen so the weight of Hydrogen is only 4 times that of Helium. All in all, 20% of the weight ends up in Helium.
Another way to look at this is that all the neutrons (10% of the baryons) end up in Helium, and for every neutron there is one proton, so 20% of the baryons are in Helium.

II. MULTIPLE CHOICE

21. You are using one of the two Keck telescopes in the summit of the Mauna Kea volcano in Hawaii. The telescope mirror diameter is 10m, so the radius is 5m. Observing a distant quasar for a period of 1 hour, you collect a million photons in the visible region of the spectrum at say 500 nanometers wavelength.

a) What is the visual flux of the quasar, in Jouls per square meter per second? Hint: first determine the rate of collection of photons per square meter per second.

1) $1.0\times10^{19}\,\frac{Joules}{\sec m^2}$
2) $1.4\times10^{-18}\,\frac{Joules}{\sec m^2}$ **Correct**
3) $3.0\times10^{-6}\,\frac{Joules}{\sec m^2}$
4) $1.5\times10^{-19}\,\frac{Joules}{\sec m^2}$

b) The quasar redshift is 0.2. What is the distance? (Hint: use the Doppler formula and Hubble's Law. Assume a Hubble constant of $60\frac{km/\sec}{Mpc}$.)

1) $2.5\times10^{-5}\,Mpc$
2) $2.5\times10^{-2}\,Mpc$
3) $1.0\times10^{3}\,Mpc$ **Correct**
4) $1.0\times10^{-3}\,Mpc$

c) What is the luminosity of the quasar?

1) $4.0\times10^{20}\,\frac{Joules}{\sec}\,or Watts$

2) $1.6\times10^{34}\,\frac{Joules}{\sec}\,or Watts$ **Correct**

3) $2.0\times10^{33}\,\frac{Joules}{\sec}\,or Watts$

4) $6.8\times10^{34}\,\frac{Joules}{\sec}\,or Watts$

d) The twin radio-emitting lobes have an angular separation of 100 arcseconds. What is the separation distance in light years?

1) $1.5\times10^{6}\,ly$ **Correct**

2) $1.5\times10^{8}\,ly$

3) $3.5\times10^{10}\,ly$

4) $3.5\times10^{12}\,ly$

22. The energy content of the radio lobes in the radio galaxy Cygnus A is at least 10^{54} Joules. How much matter would have to be converted into energy to make the lobes. (Express you answers in multiples of the Suns mass, M_O.)

1) $5.5\times10^{4}\,M_O$

2) $1.1\times10^{6}\,M_O$

3) $5.5\times10^{5}\,M_O$

4) $5.5\times10^{6}\,M_O$ **Correct**

23. What do you think the mass of the central supermassive black hole might be? (Hint: consider the efficiency of the extraction of energy in black hole accretion.)

1) At least $5.5\times10^{7}\,M_O$ **Correct**

2) At least $5.5\times10^{8}\,M_O$

3) At least $2.5\times10^{9}\,M_O$

4) At least $2.5\times10^{11}\,M_O$

24. Which (one) of the following is FALSE?
    1) A dense ionized gas produces permitted and forbidden emission lines of comparable strength. **False**
    2) Radio Galaxies show "Type 2" spectra in general: they only have narrow emission lines, both permitted and forbidden.
    3) If the subtype of quasars called blazers are at the distances given by Hubble's law, then the proper motions measured with very long baseline interferometry (VLBI) come out to be much greater than c!
    4) We know that quasars are very small, maybe a few AU despite often being brighter than a thousand galaxies.
    5) Quasars have "Type 1" spectra, showing broad permitted bases on the permitted emission lines.

25. Which (one) of the following is TRUE?
    1) Seyfert galaxies differ from most other galaxies in that they show strong emission lines in their galaxies. **True**
    2) Active galactic nuclei in Spiral galaxies are generally associated with radio lobes ~ a million light years across.
    3) Even radio telescope ARRAYS have poorer angular resolution than optical telescopes.
    4) The size of an object is given by the small angle formula, size = angular size in arcseconds times distance.
    5) A telescope with a mirror twice the diameter of another similar telescope collects photons at twice the rate.

26. The efficiency of black hole accretion disk is thought to be
    1) About 1%, similar to that of nuclear fusion.
    2) About 10%, but it's quite uncertain. **Correct**
    3) 11.7%.
    4) 100%, the same as matter-antimatter annihilation.

27. The temperature of the universe when the Cosmic Microwave Background photons were produced was about
    1) 3K.
    2) 300K.
    3) 3000K. **Correct**
    4) 3 million degrees.
    5) 3 billion degrees.

28. About how old was the universe when the CMB photons were produces?
    1) 3 seconds.
    2) 3 minutes.
    3) 3.8 minutes.
    4) 380,000 years. **Correct**
    5) They are still being produced today.

29. What is the approximate redshift of the CMB?
    1) Z=0
    2) Z=1
    3) Z=5
    4) Z=10
    5) Z=1000 **Correct**

<u>III. TRUE OR FALSE? (2 Points Each)</u>

30. Einstein's Special Theory of Relativity explains the gravitational force very well.

F

31. The oldest stars are made of pure Hydrogen and Helium; no spectral lines at all are seen from the heavier elements.

F

32. The surface brightness of the Sun, that is the flux per square degree on the Celestial Sphere, is the same whether you observe in from Earth of Pluto.

T

33. Microlensing observations of the stars in the Large Magellanic cloud (a smaller companion to our own galaxy) show that most of our galaxy's dark halo is in the form of brown dwarfs.

F

34. Radio galaxies are almost always Ellipticals.

T

35. Type Ia supernovae have luminosities that vary depending on the size of the star.

F

36. Iron is the heaviest element produced abundantly in stars because it has the least mass per nuclear particle.

T

37. The stars very close to the supermassive black hole at the exact center of the Milky Way obey all of Kepler's Laws.

T

38. Surveys of high redshift supernovae show that the expansion rate of the universe has increased over time.

T

39. Primordial nucleosynthesis of Helium began even before the universe was cool enough to allow Deuterium to form.

F

40. a) Our neighbor galaxy Andromeda is 600 kpc distant. Stars 1" from the center are orbiting at 110 $\frac{km}{sec}$, indicating the presence of an unseen massive dark object, a Supermassive Black Hole! What is the mass of this black hole? You need to know that an object in a circular orbit is always accelerating at a rate given by $\frac{v^2}{r}$, where v is the velocity and R is the orbital radius. (Express your answer in multiples of the Suns mass.)

$$\frac{V^2}{r} = a = \frac{GM}{r^2} \Rightarrow M = \frac{rV^2}{G} = 1.6\times10^{37}\,kg = \boxed{1.6\ 32\times10^6 M_\odot}$$

$$V = 110000\,\frac{m}{s} \qquad r = \frac{1''\times 600000\,pc\times 3\times10^{16}\,pc/m}{206265} = 8.7\times10^{16}\,m$$

41. a) How much energy is produced when the sun converts 1 kg of mass into energy?

$$E = mc^2 = 1\times(3\times10^8)^2 = \boxed{9\times10^{16}\,J}$$

b) How much energy is produced when the Sun converts 1 kg of hydrogen into helium?

$$E = 0.007 M_H c^2 = 0.007\times 9\times10^{16}\,J = \boxed{6.3\times10^{14}\,J}$$

c) The atomic bombs the U.S. dropped on Japan produced around "20 Kilo-Tons" of TNT equivalent, or 2×10^{15}J of explosive energy. How much matter was converted to energy inside the bomb? Give your answer in kilograms.

$$m = \frac{E}{c^2} = \frac{2\times10^{15}}{9\times10^{16}} = \boxed{0.022\,kg}$$

42. Using the Doppler Effect to determine the expansion speed of the Crab Nebula supernova remnant, we get an answer of 1400 (km/sec). This is the expansion velocity in the radial direction (i.e., the direction toward Earth). Repeated photographs show expansion with an angular speed of 2.2 x 10^{-14} radians (one radian $\approx$57 degrees) per second in the direction perpendicular to the line of sight. How far away is the Crab Nebula? (Hint: Assume that the expansion speed is the same in both directions.)

$$\theta = \frac{D}{d} \Rightarrow d = \frac{D}{\theta} = \frac{1400\ km}{2.2\times10^{-14}} = 6.36\times10^{16}\ km$$

43. Neutrinos are produced copiously in the first second of the Big Bang, and each has a little mass. It seemed a very attractive idea that they could comprised the dark matter! This is an example of the WIMP hypothesis that the dark matter is made of weakly interacting massive subatomic particles.

a) Explain the "phase space" argument that has disproved the idea that "electron type" neutrinos constitute the dark matter in galaxies.

No two neutrinos can exist in the same place if they have the same energy. Plotting the two in "phase space" we find that not enough neutrinos fit to account for all the dark matter.

b) If MACHOs account for some of the dark matter in the Milky Way, can you guess their approximate speeds? How fast would WIMPs be going in the Milky Way halo?

They would be traveling less than the escape velocity for the galaxy

44. Suppose a 10 $M_\odot$ black hole is accreting matter and radiating at the Eddington Limit. Approximate the radiating area as that of a circle with area pi R^2, where R = 10Rs. (Note that R(event horizon) is known as Rs, for the Schwarzchild radius.) Recall that there are two sides to a disk. Assume for simplicity that the whole disk has the same temperature. What temperature would be expected for such a disk?

$$A = 2\pi R^2 = 2\pi(10\times30\ km)^2 = 5.6\times10^{11}$$

$$L = 1.3\times10^{31}\times10 = 1.3\times10^{32}$$

$$F = \frac{L}{A} = \sigma T^4 \Rightarrow T = \sqrt[4]{\frac{1.3\times10^{32}}{5.6\times10^{11}\times5.6\times10^{-8}}} = 7.7\times10^{6}\ K$$

45. The most common spot size on the Cosmic Microwave Background maps is about one degree. This must be (roughly speaking) the size of the causally connected regions when the CMB was released. Explain.

Gravity could only have pulled matter into a region of higher density as far as the force could be felt. The size of that region is the causally connected region at 380000 y.

46. Explain the concept of the Power Spectrum. Explain what information we can derive from the largest peak in the power spectrum function.

The power spectrum tells us how many bumps there are of a given size. The peak, at a bump size of 1°, confirms that the universe is flat.

47. What is the definition of thermal equilibrium? How about Threshold Temperature? Show your calculation of the Threshold Temperature for the electron.

Thermal equilibrium is when everything is the same temperature. Threshold temperature is when photons aren't energetic enough to make electron positron pairs. $E = m_e c^2 = kT_{th} \Rightarrow T_{th} = \frac{m_e c^2}{k}$

48. What it meant by the "Matter-Antimatter Asymmetry"? What is the approximate value of this asymmetry, that is, when the universe was above the threshold temperature for the electrons and positrons, by what fraction did the number of electrons exceed the number of positrons? When the temperature was above the threshold value for proton and antiprotons, by what factor did the number of protons exceed the number of antiprotons?

It's interesting that the two answers are exactly the same!

What is the ratio of the number of protons today (which derive from the excess of protons over antiprotons) to the number of CMB photons in the local universe?

More matter than antimatter

early universe $\frac{1000\,000\,001}{1000\,000\,000}$

now $\frac{1}{1\,000\,000\,000}$ because photons never annihilated.