Astronomy 102, Midterm Exam #3

Thursday December 11, 2003

2.00 pm – 3.15 pm

Do not turn the pages of the exam until you are instructed to do so.

You are responsible for reading the following rules carefully before beginning.

Exam rules: You may use *only* a writing instrument and a calculator while taking this test. You may *not* consult any computers, books, notes – neither on paper nor stored in a calculator – nor each other. All of your work must be written on the attached pages, using the reverse sides if necessary. Important equations, numbers and conversion factors, used in the problems, are found in the last pages of the exam, in the form of the **Useful Equations sheet** and the **How Big Is That sheet**. The final answers must be indicated clearly. Exams are due at 3.15 pm.

The questions are each worth five (5) points. Partial credit is available for those questions involving essays, short answers, drawings or explicit calculations, and for multiple-choice questions indicated possibly to have more than one correct answer (e.g. "check all answers that apply").

Note: select only one answer for each question, except if the problem explicitly indicates to "check all that apply".

Name: ____________________________________

ID number: ________________________________

Recitation: _______________________________

1. A quasar is observed to have a spectral redshift corresponding to a speed of 8.6×10^8 cm/s. How far away is the quasar?

   ☐ 4.3×10^{13} ly.

   ☐ 4.3×10^8 ly.

   ☐ 4.3×10^3 ly.

   ☐ 4.3×10^6 ly.

   ☐ None of the above.

2. You measure a galaxy as being 4.9×10^8 ly away. What redshift (in terms of its velocity) will the galaxy's spectrum display?

   ☐ 9.8×10^8 cm/s.

   ☐ 9.8×10^6 cm/s.

   ☐ 9.8×10^{14} cm/s.

   ☐ 9.8×10^3 cm/s.

   ☐ None of the above.

3. This would be good ways to generate strong gravitational radiation (**check all that apply**):

   ☐ Sudden merger of two large black holes.

   ☐ Produce a large amount of exotic matter near a black hole’s horizon.

   ☐ Cause a black hole to rotate at a large, constant rate.

   ☐ Move a black hole through space at a constant speed close to that of light.

   ☐ None of above.

4. Suppose we were to find that our previous measurements of the Hubble constant are wrong, and that the true value is 2 times the old value. In this case, our estimate of the age of the Universe would change to a value

   ☐ 0.2 times the previously-accepted age.

   ☐ 0.5 times the previously-accepted age.

   ☐ 2 times the previously-accepted age.

   ☐ 5 times the previously-accepted age.

5. In one incarnation of Star Trek, a Federation-run space station guards one end of a wormhole that connects two opposite quadrants of the Milky Way Galaxy. Using the wormhole, one can travel a distance equal to 0.45 times the diameter of the Galaxy and back in 98 minutes according to a clock on the space station. By what factor shorter is the apparent time of traveling through the wormhole compared to traveling without it according to the space station?

   ☐ 1.4×10^{7}

   ☐ 4.1×10^{8}

   ☐ 8.2×10^{8}

   ☐ 4.9×10^{10}

6. Hubble's Law expresses the observed fact that:

   ☐ All distant galaxies are receding from us at speeds approaching the speed of light.

   ☐ All distant galaxies are approaching us at speeds proportional to their distance from us.

   ☐ All distant galaxies are approaching us at speeds approaching the speed of light.

   ☐ All distant galaxies are receding at speeds proportional to their distance from us.

   ☐ None of above.

7. Consider our discussion about vacuum fluctuations, Hawking radiation, and exotic matter, and indicate which of following statements are true (**check all that apply**):

   ☐ It is possible, though extremely unlikely, for black holes to emit television sets and leather-bound copies of the works of Proust, via Hawking radiation.

   ☐ Because virtual electrons and virtual positrons are made in equal numbers by vacuum fluctuations, black holes emit electrons and positrons equally.

   ☐ According to the uncertainty principle, a virtual particle-antiparticle pair can be generated out of nothing, for a brief time.

   ☐ It is possible for one member of a virtual pair to be swallowed by a black hole while the other member escapes.

   ☐ Hawking radiation by the black holes in active galaxy nuclei explains the large luminosities seen in these objects.

8. The following statements describe exotic matter (**check all that apply**):

   ☐ Exotic matter has a negative mass.

   ☐ A stable wormhole must contain exotic matter.

   ☐ Vacuum fluctuations in strongly warped space-time are exotic.

   ☐ All antimatter is exotic.

   ☐ Exotic matter and regular matter annihilate each other when placed in contact.

9. Which of the following are examples of exotic matter (**check all that apply**):

   ☐ Vacuum fluctuations far from any source of gravity.

   ☐ Vacuum fluctuations near the surface of a white dwarf.

   ☐ Vacuum fluctuations near the surface of a neutron star

   ☐ Vacuum fluctuations near the decoupling surface of the Big Bang.

   ☐ None of above.

10. Consider our discussion of the temperature and entropy of a black hole, and indicate which of following statements are true (**check all that apply**):

☐ The laws of thermodynamics do not permit black holes to have positive entropy.

☐ The temperature of the earth is equal to absolute zero.

☐ The entropy of the earth is greater than zero.

☐ A black hole must have large entropy, or it would represent a violation of the second law of thermodynamics.

☐ The temperature of a black hole is less than absolute zero.

11. A certain galaxy is seen to be receding from us at a speed 10% of the speed of light. Its distance from us is approximately

☐ 0.15 light years.

☐ 15 light years.

☐ 1500 light years.

☐ 15 million light years.

☐ 1500 million light years.

12. Consider the apparent and absolute horizons of black holes and indicate which of the following statements are true (**check all that apply**):

☐ A photon emitted from the core of a collapsing star at the moment the absolute horizon is formed would forever remain on the surface of the horizon.

☐ A photon emitted from within the absolute horizon of a collapsing star would be able to escape, if the star could stop collapsing.

☐ The absolute horizon grows from a point to a final size of the Schwarzschild Singularity.

☐ The absolute horizon is never larger than the apparent horizon.

☐ A star in the process of collapsing has two horizons, one inside the other.

13. Consider what we discussed about wormholes and time machines and indicate which of following statements are true (**check all that apply**):

☐ If wormhole time machines are indeed stable, paradoxical situations such as the matricide paradox are allowed to happen.

☐ A wormhole can be created by two black holes that overlap in hyperspace and are in the 'black hole' (collapsing) configuration.

☐ Wormhole time machines are particularly stable and long-lived forms of wormholes.

☐ A time machine can be created by moving one of a wormhole's 'openings' through space at relativistic speeds with respect to the other one.

☐ In physical space, a wormhole appears as a cylindrical tunnel connecting widely separated locations.

14. Wormhole time machines may not be possible because (**check all that apply**)

☐ Cosmic censorship: the singularities they require may always be surrounded by event horizons.

☐ Circulation and build-up of vacuum fluctuations at the mouths of the wormhole, which causes one or the other of the wormhole's component singularities to evaporate.

☐ The matricide paradox; a time machine would allow one to travel backward in time, kill one's mother, preventing one's own birth, and thereby prevent one from travelling back in time. This is paradoxical, and is forbidden by known laws of physics.

☐ Circulation and build-up of light within the wormhole, which leads very quickly to an extremely large energy, the gravity of which causes the wormhole to collapse.

☐ None of above.

15. Consider the effects of exotic matter on space-time in the vicinity of a black hole and indicate which of the following statements are true (**check all that apply**):

☐ Vacuum fluctuations near a black hole horizon can lead to the evaporation of the black hole.

☐ A black hole deflects light less if it has exotic matter around it than if it does not.

☐ Since mass can never be negative, and since mass is equivalent to energy, there is no such thing as matter with negative energy density.

☐ Suppose it were possible for a star to be made up completely of exotic matter. No planets could orbit this star.

☐ A wormhole can exist longer if exotic matter is added to it.

16. Consider Hubble's law and cosmological expansion of the Universe and detemine which of the following statements are (**check all that apply**):

☐ The expansion of the universe is isotropic: galaxies seem to recede according to Hubble's law, no matter which direction you look.

☐ There is one spot in the universe from which all galaxies appear to be receding, which is the center of the universe, from which the big bang started.

☐ There is no observational evidence for cosmological homogeneity.

☐ As the universe expands, material is continually created to occupy the additional volume.

☐ The cosmological expansion of the universe is an expansion of spacetime itself, which carries objects along with it. In a sense, then, the galaxies we observe to be receding are really at rest with respect to the space-time, which is dragging them along.

17. Consider the big bang and the current state of the Universe and detemine which of the following statements are true (**check all that apply**):

   - ☐ The Big Bang is a gravitational singularity, and according to cosmic censorship all such singularities are surrounded by an event horizon. Thus, if Cosmic Censorship is true, our own Universe could appear as a black hole in another, larger Universe.
   - ☐ The best estimates, from observations of galaxy motion and of small anisotropies in the cosmic background, indicate that the Universe is open.
   - ☐ The wavelengths of light at which the early universe is brightest have been Doppler shifted into the microwave range.
   - ☐ The Universe is apparently flat, and thus marginal: the observed expansion will slow down and stop.
   - ☐ The decoupling surface is the earliest part of the universe's life that we can observe, using light.

18. The lifetime of a black hole (the time it takes it to evaporate by emission of Hawking radiation) with a mass of 2 M_{sun} is

   - ☐ Extremely short, which is why very few of them are observed.
   - ☐ Slightly shorter than the present age of the Universe.
   - ☐ Longer than the present age of the Universe, but much shorter than the lifetimes of the longest-lived stars.
   - ☐ Longer than the present age of the Universe, but about the same as the lifetimes of 2 M_{sun} stars.
   - ☐ A great deal longer than the age of the Universe or the lifetimes of stars.

19. The age of the Universe is approximately

- ☐ 1.6×10^{8} years.
- ☐ 1.6×10^{9} years.
- ☐ 1.6×10^{10} years.
- ☐ Infinity (it has no known beginning).
- ☐ None of above.

20. The radius of the observable Universe is approximately

- ☐ 1.6×10^{8} light years.
- ☐ 1.6×10^{9} light years.
- ☐ 1.6×10^{10} light years.
- ☐ Infinity (it has no known limits).
- ☐ None of above.

21. Four distant galaxies are seen by their Doppler-shifted spectra to be receding from us at a speeds 1218 km s^{-1}, 2436 km s^{-1}, 3654 km s^{-1}, and 4872 km s^{-1}. The distances to these galaxies have a ratio of

- ☐ 1:0.93:0.6:0.3
- ☐ 1:1.5:2.0:2.5
- ☐ 1:2:3:4
- ☐ 1:4:9:16
- ☐ 1:10:100:1000

22. Inflationary models of the early Universe were motivated primarily by the following observational result(s) (**check all that apply**):

☐ The very long wavelengths at which the Cosmic Microwave Background is observed.

☐ The extreme smoothness of the Cosmic Microwave Background.

☐ The extremely large luminosity represented by the Cosmic Microwave Background.

☐ The high-velocity recession of stars and planets from the Cosmic Microwave Background.

☐ None of above.

23. A brick, illustrated below, encounters a strong gravity wave, traveling from left to right. Draw a sequence of sketches, indicating the changes in the brick's appearance as one cycle of the gravity wave passes.

24. From our viewpoint in the Milky Way, the Universe appears to be expanding at the same speed for a given distance away, no matter which direction we look; in other words, it appears as if we are at the center of the expansion. From another, distant galaxy, the Universe would appear to

☐ Expand from a center in the vicinity of the Milky Way Galaxy.
☐ Expand from a center located at that galaxy.
☐ Expand from a center halfway between that galaxy and the Milky Way.
☐ All of above.
☐ None of above.

25. The following is experimental support for the Big Bang:

☐ The detection of the Cosmic Microwave Background, by Penzias and Wilson.
☐ The finding by Ryle *et al.* that the number of galaxies per unit volume in the Universe was larger in the past than in the present.
☐ The discovery by Hubble that the Universe expands.
☐ All of the above
☐ None of above.

26. A distant galaxy is seen by its Doppler-shifted spectrum to be receding from us at a speed V, which is small compared to the speed of light. Another galaxy, twice as far away as the first, is seen. What is its recession speed?

☐ $V/2$.
☐ V.
☐ $2V$.
☐ $4V$.
☐ None of above.

27. In observations of a certain galaxy, a spectral line that normally has wavelength of 0.5 x 10^{-4} cm appears instead at wavelength 0.55 x 10^{-4} cm. How far away is the galaxy, in millions of light years? (Show your work if you wish to qualify for partial credit.)

28. The spectrum of the Large Magellanic Cloud, a galaxy visible from Earth's southern hemisphere, shows *blue*-shifted spectral lines. This means (**check all that apply**):
   - ☐ That this galaxy recedes from us, as it should since the Universe is expanding.
   - ☐ That this galaxy is extremely distant.
   - ☐ That the black hole at the center of the Milky Way is tremendously more massive than this galaxy, resulting in its light suffering a gravitational blueshift on its way to us.
   - ☐ That this galaxy is nearby and has substantial motion in response to its attraction to the Milky Way and other neighboring objects, in addition to its motion from the expansion of the Universe.
   - ☐ None of above.

29. Suppose opacity within decoupling surfaces weren't a problem; would it then be possible in principle for us to see the Big Bang singularity? (**Check all that apply**)

☐ Yes, because the non-infinite speed of light allows us to look into the past, all the way to the beginning of time, just by looking far enough away.

☐ No, because the singularity's event horizon gets in the way.

☐ Yes, because the large abundance in space of primordial wormhole time machines allows light emitted by the singularity 10^{10} years ago to reach us in the present time.

☐ No, because it would require detection of light or other particles that arrived from the future.

☐ None of above.

30. At what time after the Big Bang did electrons decouple?

☐ 10^{-35} s.

☐ 1 s.

☐ 200 s.

☐ 2×10^5 s.

☐ None of above.

31. Einstein originally proposed that the cosmological constant be added to the equations of the general theory of relativity, in order that (**check all that apply**):

☐ Isotropic and homogeneous solutions of these equations could be produced.

☐ Expanding or contracting solutions of these equations could be produced.

☐ Static solutions of the equations, involving no singularities, could be produced.

☐ The singularities evident in his first solutions of the equations could not be realized in nature.

☐ His mathematical error in the original form of general relativity would be corrected.

32. The Cosmic Microwave Background has long wavelengths because (**check all that apply**):

- ☐ It was emitted so far away from us, the Universe is expanding, and thus the light is extremely redshifted.
- ☐ It was emitted from near the event horizon surrounding the Big Bang singularity, and suffers an extreme gravitational redshift.
- ☐ It was emitted after the Universe had expanded and cooled to a temperature of 2.7 degrees above absolute zero, far too cold to emit visible light.
- ☐ It was emitted from behind the decoupling surface, and the Universe was so opaque then that only the longest-wavelength light gets through.
- ☐ None of above.

33. The Cosmic Microwave Background is virtually isotropic because

- ☐ It is emitted from the new matter that is constantly being produced out of nothingness to give the Universe its steady-state appearance; this new matter is uniformly distributed in space.
- ☐ It is emitted from spacetime points fairly close to the Big Bang singularity, and since all light paths terminate in the singularity we see the Background in whatever direction we look.
- ☐ Its wavelengths are actually larger than the Universe, and thus its energy is uniformly distributed throughout the Universe.
- ☐ All of above.
- ☐ None of above.

34. Why might a positivist argue that the study of black hole interiors and their singularities is not important? **Check all that apply.**

☐ It has been proven mathematically that the interiors of black holes are simple and completely understood; no further work is required.

☐ All of the entropy of the black hole is represented by the surface area of the horizon rather than its interior.

☐ The real world is not accessible to the senses, nor to extensions of our senses such as experimental instruments.

☐ Anything inside an event horizon is inaccessible to experiments from the outside; no experimental check can be made on the validity of theories of the interior.

☐ None of above.

35. Despite the argument above, why might a positivistic scientist be persuaded of the importance of studies of black hole interiors and singularities?

☐ Black holes can in principle combine to become wormholes, so that their interiors may in some sense *become* accessible to measurements.

☐ Cosmic censorship might not be universally true; naked singularities might therefore exist, accessible to measurements.

☐ The large-scale structure of the Universe resembles in many respects the interior of an event horizon, since the Universe itself originated in a singularity; the Universe is of course observable.

☐ All of above.

☐ None of above.

36. An era of extraordinarily rapid expansion early in the Universe's life, called the *inflationary* era, took place for the following reason:

- ☐ The huge amount of energy available in the form of heat, and the small number of elementary particles it was possible to make when the Universe was so hot, led to a runaway energy "cost" in the production of these particles.
- ☐ The evaporation of small black holes, produced early in the Big Bang, by Hawking radiation led to a burst of gamma rays, pushing the already-expanding contents of the Universe apart even faster.
- ☐ Vacuum fluctuations were exotic in the early Universe, and during the inflationary era the vacuum produced higher-mass vacuum fluctuations than it does now; the "antigravity" effects of these vacuum fluctuations accelerated the expansion of the non-exotic matter.
- ☐ All of above.
- ☐ None of above.

37. Assume we are living a matter-dominated Universe with a mass density that this much less than the critical density (A = 1). Based on the current value of the Hubble constant, what will the age of this Universe be?

- ☐ 1.5×10^{10} yr.
- ☐ 1.0×10^{10} yr.
- ☐ 1.3×10^{10} yr.
- ☐ 1.6×10^{10} yr.

38. Assume we are living a matter-dominated Universe with a mass density equal to the critical density (A = 2/3). Based on the current value of the Hubble constant, what will the age of this Universe be?

☐ 1.5 x 10^{10} yr.

☐ 1.0 x 10^{10} yr.

☐ 1.3 x 10^{10} yr.

☐ 1.6 x 10^{10} yr.

39. Describe the history of the Universe before the Big Bang occurred.

40. Is the Universe open, marginal or closed? In a few sentences, choose one of these answers and defend it by citing experimental and theoretical results we have discussed this semester.

Useful Equations

Length contraction, time dilation and velocity addition:

$$\Delta x_1 = \Delta x_2 \sqrt{1 - \frac{V^2}{c^2}}$$

$$\Delta t_1 = \frac{\Delta t_2}{\sqrt{1 - \frac{V^2}{c^2}}}$$

$$v_1 = \frac{v_2 + V}{1 + \frac{v_2 V}{c^2}}$$

Minkowski absolute interval:

$$\text{Absolute interval} = \sqrt{\Delta x_1^2 - c^2 \Delta t_1^2} = \sqrt{\Delta x_2^2 - c^2 \Delta t_2^2}$$
$$= \sqrt{\Delta x^2 - c^2 \Delta t^2}$$

Useful rearrangements of the Absolute Interval formula:

$$\Delta t_1 = \frac{1}{c} \sqrt{\Delta x_1^2 - \Delta x_2^2 + c^2 \Delta t_2^2}$$

$$\Delta x_1 = \sqrt{\Delta x_2^2 - c^2 \Delta t_2^2 + c^2 \Delta t_1^2}$$

Mass-energy equivalence:

$$E = mc^2$$

Mass of a moving object:

$$m = \frac{m_0}{\sqrt{1 - \frac{V^2}{c^2}}}$$

Doppler shift:

$$\lambda = \lambda_0\left(1 + \frac{V}{c}\right)$$

$$V = c\left(\frac{\lambda}{\lambda_0} - 1\right)$$

Schwarzschild circumference:

$$C_S = \frac{4\pi GM}{c^2}$$

Circumference of a spherical object of diameter *d*:

$$C = \pi d$$

Hubble's Law:

$$V = H_0 D$$

Age of a matter-dominated universe:

$$t = A\frac{1}{H_0}$$

How big is that?

Diameter of hydrogen atom	1.06×10^{-8} cm
Diameter of the Moon	3.5×10^{3} km
Diameter of the Earth	1.3×10^{4} km
Diameter of the Sun	1.4×10^{6} km
Diameter of the Milky Way galaxy	1.7×10^{5} ly

Distance to the Moon	3.8×10^{5} km
Distance to the Sun	1.5×10^{8} km
Distance to the next nearest star	4 ly
Distance to the center of the Milky Way	2.7×10^{4} ly
Distance to the nearest galaxy	1.7×10^{5} ly

Mass of hydrogen atom	1.67×10^{-24} gm
Mass of the Moon	7.4×10^{25} gm
Mass of the Earth	6.0×10^{27} gm
Mass of the Sun	2.0×10^{33} gm ($1\ M_{sun}$)
Mass of the Milky Way galaxy	$5 \times 10^{10}\ M_{\odot}$

Luminosity of the Sun	3.8×10^{33} erg/s ($1\ L_{sun}$)
Luminosity of the largest stars	$10^{5}\ L_{\odot}$
Luminosity of the Milky Way galaxy	$10^{10}\ L_{\odot}$
Luminosity of quasar 3C 273	$10^{12}\ L_{\odot}$

Earth's rotation period	8.64×10^{4} s (1 day)
Moon's revolution period	28 days
Earth's revolution period	365.25 days (1 year)
Sun's revolution period within Milky Way	2.4×10^{8} years

Age of the solar system	4.6×10^{9} years
Expected life span of the Sun	1.5×10^{10} years
Age of the Universe	1.6×10^{10} years

Earth's equator rotation speed	0.47 km/s
Earth's revolution speed	30 km/s
Sun's speed within the Milky Way	220 km/s
Milky Way's speed within the local Universe	500 km/s
Typical lengths:	
Normal star diameter	10^6 km
Distance between stars	a few ly
Normal galaxy diameter	10^5 ly
Distance between galaxies	10^6 ly
Typical masses:	
Smallest star	0.1 M_{sun}
Normal star	1 M_{sun}
Giant star	10 M_{sun}
Normal galaxy	10^{10} - 10^{11} M_{sun}
Galaxy cluster	10^{14} - 10^{15} M_{sun}
Typical luminosities:	
Normal star	1 L_{sun}
Giant star	10^3 - 10^5 L_{sun}
Normal galaxy	10^9 - 10^{10} L_{sun}
Quasar	10^{12} - 10^{13} L_{sun}
Typical time spans:	
Planetary revolution	1 year
Galaxy rotation	10^7 - 10^9 years
Life of giant stars	10^6 - 10^9 years
Life of normal star	10^{10} years
Typical speeds:	
Planetary orbits	10 km/s
Stellar motion in galaxy	100 km/s
Between nearby galaxies	100 km/s

Other important constants:

1 ly = 9.46×10^{12} km = 9.46×10^{17} cm

1 km = 10^5 cm

1 hour = 3600 seconds

$\pi = 3.14159265359$

Speed of light: $c = 2.99792458 \times 10^5$ km/s = $2.99792458 \times 10^{10}$ cm/s = 1 ly/year

1 Mly = 10^6 ly

1 erg = 1 gm cm^2/s^2

1 year = 3.16×10^7 seconds

Hubble's constant: H_0 = 20 km/(sec Mly)

Newton's gravitational constant:
$G = 6.67 \times 10^{-8}$ $cm^3/(gm\ s^2)$

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