ASTRONOMY 294Z: The History of the Universe
Professor Barbara Ryden

MIDTERM EXAM: SOLUTIONS

Short-Answer Problems

1) Arrange the following scientists in order of when they lived, earliest to latest: Isaac Newton, Aristarchus, Nicolaus Copernicus.

Aristarchus first, then Copernicus, then Newton.

2) You step outside on a clear night in Ohio. Over the course of the night, do stars appear to circle clockwise or counterclockwise around Polaris?

Counterclockwise.

3) Name one of the reasons why the heliocentric model of Copernicus met with initial resistance.

Choose one: it was heretical, the rapid motions implied boggled people's minds, Copernicus was a boring writer, and (perhaps most decisively) stellar parallax was not observed.

4) Which scientist was the first to eliminate the celestial sphere *from the heliocentric model: Copernicus, Digges, Kepler, or Newton?*

Thomas Digges

5) Suppose that mischievous space aliens move the Earth so that it's on a larger orbit around the Sun. On its new orbit, would the Earth's orbital period be longer or shorter than it is now?

Longer.

6) If the universe were contracting rather than expanding, would we see galaxies redshifted or blueshifted?

Distant galaxies would be coming toward us, so we'd see them blueshifted.

7) At rest, hydrogen absorbs light with a wavelength $\lambda_0 = 656.3$ *nanometers. You observe a star with a hydrogen absorption line at wavelength* $\lambda = 656.5$ *nanometers. Is the star moving toward you or away from you?* The wavelength is increased by the Doppler effect; therefore the star is moving away from you.

8) If a star has a parallax angle of 0.1 arcsecond, what is its distance, in parsecs?

10 parsecs. (Distance in parsecs equals one over the parallax angle in arcseconds.)

9) If a star is at a distance of 1 parsec, what is its parallax angle, in arcseconds?

1 arcsecond. (This is how the distance of 1 parsec is defined, in fact.)

10) Two stars have the same luminosity, but different distances. Which star will have the larger flux: the nearer star or the farther star?

The nearer star will have the larger flux (and thus appear brighter to you).

11) A galaxy is at a distance of 100 Mpc from us. From Hubble's Law, what is its radial velocity?

$v = H_0 d$, so $v = 70\,\mathrm{km/sec/Mpc} \times 100\,\mathrm{Mpc} = 7000\,\mathrm{km/sec}$.

12) Which of the following temperatures is closest to the temperature of the air in this room: 3 Kelvin, 30 Kelvin, 300 Kelvin, or 3000 Kelvin?

300 Kelvin (that's 27° Celsius, or 80° Fahrenheit).

13) A photon has an energy of 5 electron-volts. Is it a photon of infrared light, of visible light, or of ultraviolet light?

Ultraviolet light. (One point on this question for knowing that the photon is not visible; an additional point for knowing that it's ultraviolet rather than infrared.)

14) Did primordial nucleosynthesis take place before or after the universe became transparent?

Before ($t \approx 7\,\mathrm{min}$ versus $t \approx 350{,}000\,\mathrm{years}$)

15) Suppose that the density of the universe turns out to be slightly less than the critical density. Do you then expect the universe to end with a Big Chill (external expansion) or with a Big Crunch (eventual recollapse)?

Big Chill; lower density means that the braking power of gravity is insufficient to stop the expansion.

21) From the observed Doppler shift of the Andromeda Galaxy, we know that the Andromeda Galaxy is moving toward our galaxy (the Milky Way Galaxy), with a speed $v = 120\,\text{km/sec}$.
a) What is the speed v of the Andromeda Galaxy in units of parsecs per year?

$$v = 120\frac{\text{km}}{\text{sec}}\times\left(\frac{1\,\text{pc}}{3.1\times 10^{13}\,\text{km}}\right)\times\left(\frac{3.2\times 10^{7}\,\text{sec}}{1\,\text{year}}\right) = 1.24\times 10^{-4}\,\text{pc/year}\,. \quad (1)$$

b) The Andromeda Galaxy and the Milky Way Galaxy are now separated by a distance $d = 700{,}000\,\text{parsecs}$. If the Andromeda Galaxy continues to move straight toward the Milky Way Galaxy at its current speed v, how many years will it be until the Andromeda Galaxy and the Milky Way Galaxy collide? Since $d = vt$, where t is the travel time, we may write

$$t = \frac{d}{v} = \frac{7\times 10^{5}\,\text{pc}}{1.24\times 10^{-4}\,\text{pc/year}} = 5.7\times 10^{9}\,\text{years}\,. \quad (2)$$

The head-on encounter between two galaxies will be interesting to watch, but don't hold your breath; it won't happen for another 5.7 billion years.

22) An astronaut travels to Mars. Looking through a telescope toward the Earth, he sees that the Earth is in its new phase. Draw the relative positions of Mars, Earth, and Sun required for the astronaut to see a new Earth. When the astronaut on Mars sees a new Earth, what is the phase of Mars as seen by an observer on the Earth? The relative positions of Mars, the Earth, and

the Sun required for a Martian observer to see a new Earth are shown above. Under these circumstances, an Earthly observer will see a **full** Mars.

23) Suppose that the density of the universe today is exactly equal to the critical density, $\rho_{\text{crit}} = 9\times 10^{-27}\,\text{kg/m}^3$. If the density were contributed *entirely by planets identical in mass to the Earth, how many planets (on average) would there have to be per cubic parsec of the universe?* The critical density, in units of kilograms per cubic parsec, is

$$\rho_{\rm crit} = 9 \times 10^{-27} \frac{\rm kg}{\rm m^3} \times \left(\frac{3.1 \times 10^{16}\,{\rm m}}{1\,{\rm pc}} \right)^3 = 2.68 \times 10^{23}\,{\rm kg/pc^3}\ . \qquad (3)$$

We immediately note, as soon as we turn to the list of "Potentially useful numbers", that the mass in one cubic parsec is *smaller than* the mass of the Earth. Thus, we know that our final answer will be *less than* one planet per cubic parsec (this acts as a useful check on our calculation). The exact number will be

$$\frac{\rho_{\rm crit}}{M_{\rm earth}} = \frac{2.68 \times 10^{23}\,{\rm kg/pc^3}}{6 \times 10^{24}\,{\rm kg}} = 0.045/\,{\rm pc^3}\ . \qquad (4)$$

Just one dinky little planet for every 22 cubic parsecs is adequate to flatten out the universe!

Essay Question

24) Suppose you have a friend, "Flat-Earth Fred", who believes that the universe is flat rather than spherical. (All those NASA photographs of a spherical Earth? "They're all fake," grumbles Fred. He wants evidence that he can see directly with his own eyes.)

First, describe what evidence you could provide, without having to leave Columbus, that the Earth is spherical. (Hint: On the night of February 20, 2008, there will be a lunar eclipse visible from Columbus, Ohio.)

Second, suppose that you have a private jet and can fly anywhere in the world where there's an airport. With this added mobility, what additional evidence could you provide to convince Fred that the Earth is spherical?

While remaining in Columbus, I can try to overwhelm Fred with the sheer volume of pictures of the spherical Earth as sent down by the numerous weather satellites and surveillance satellites orbiting the Earth. "Why would so many different agencies in so many different countries persist in trying to hoax you?" I would ask Fred. If Fred remains unconvinced, I can haul him outside during the lunar eclipse and point out that the shadow of the Earth is circular, and that the only shape that always throws a circular shadow is a sphere.

Once my personal jet is fully fueled, I can fly Fred and myself to a Caribbean island. As we sit on the beach sipping rum punch, I can point out to Fred that the ships we see sailing away from the island always vanish "hull down". That is, their hulls disappear first, hidden from our view by the curvature of the Earth, and only later do the masts and superstructure vanish. (If the Earth were flat, the ships would just dwindle in size to a point as they sailed away.) I can also point out that ships sailing in different directions disappear "hull down" in exactly the same way. This indicates that the curvature of the Earth is the same in all directions (it's "isotropic", in other words); this is just what we expect for a sphere. If Fred is still unconvinced, I can refuel the jet and fly us down to Tierra del Fuego (or any other place in the Southern Hemisphere). There, I can point out that in the Southern Hemisphere, we can see the Southern Cross, which is invisible from Columbus. Conversely, the Big Dipper, easily seen from Columbus, is never seen from far southern latitudes. The different constellations seen in the Northern and Southern Hemispheres show that the Earth is curved in the north-south direction, just as you would expect for a sphere. If Fred is still unconvinced, I can toss him into the Straits of Magellan, and let the currents carry him away, until he has circumnavigated the entire (spherical) Earth, just as the survivors of Magellan's expedition did in the 16th century.

"Bon voyage, Fred!"