1	/4	Name	
2	/8	PID	
3	/3		
4	/6		
5	/8		
Total	/29		

You may use one sheet of notes during this test. You may not have any books or other notes. Some of the information in the table below is not used on this test. Good luck.

Kepler's 3rd Law	$P^2 = R^3/M$ (in AU, year, & M_{sun})	Hubble's Law	$v = H D$
	$M = 233\ v^2\ R$ (in parsec, km/s, & M_{sun})	Wien's Law	$\lambda_{peak}\ T$ = constant
Redshift	$z = 1/a - 1$; $a = 1/(1+z)$	Hubble's Constant	70 km/s/Mpc
	$v = c\ z$; $v = c\ (\lambda_{rec}/\lambda_{emit} - 1)$	Speed of Light	300,000 km/s
Number density	$ND(a) = ND(now)\ a^{-3}$.	Parsec	3.09×10^{13} km
Mass density	Matter: $MD(a) = MD(now)\ a^{-3}$	AU	1.50×10^{8} km
	Radiation: $MD(a) = MD(now)\ a^{-4}$	Year	3.16×10^{7} s

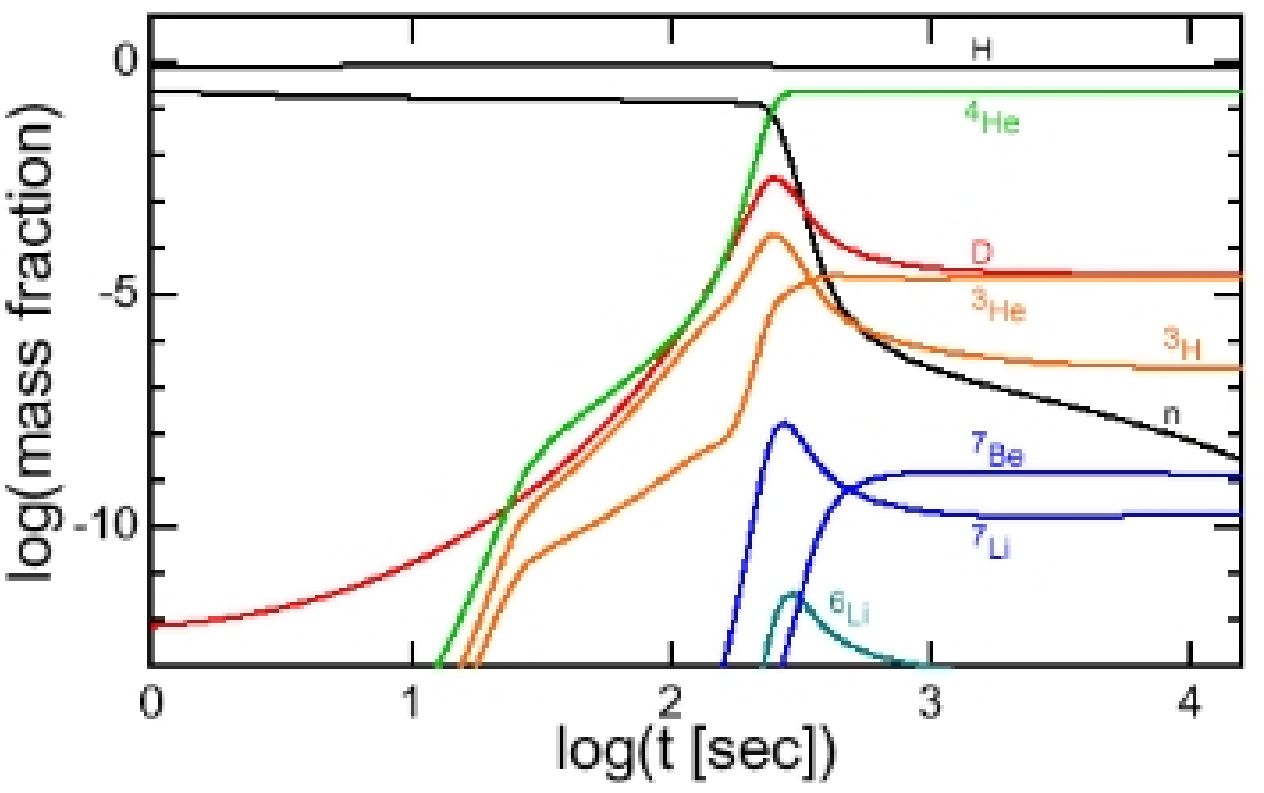

Figure 1 Fraction by mass of the elements vs. time after the beginning of the universe. Both axes are logarithmic: For log(t) = 2, the time $t=10^2=100$ s, and for log(abundance)=–10, the abundance is 10^{-10}. The graph is from Ned Wright's notes on cosmology.

1. In my hand are hydrogen and oxygen in the water, iron in the blood, calcium in bones, and carbon throughout. For each question, name one element that fits the description, or if there is no such element, write "none." There may be more than one correct element.
   a. (1 pt.) The nucleus in my hand was made in a supernova.
   b. (1 pt.) The nucleus in my hand was made on earth.
   c. (1 pt.) The nucleus in my hand was present when the universe was 1 second old.
   d. (1 pt.) The nucleus in my hand was made in the sun.
2. (1 pt. each) Who made each of these discoveries or measurements? (3 pts. each) Explain the evidence in one or two sentences.
   a. Discovery of radiation from the big bang.
   b. Proof that the planets do not orbit the earth.
3. (3 pts.) Simplicio reasons, "The discovery that the Andromeda Galaxy is moving toward us disproves Hubble's Law." Rewrite this statement to make it correct, and point out Simplicio's primary misconception.
4. The galaxy 0140+326 RD1 emitted some light before the sun was born, and the light reached us a few years ago to be recorded in the spectrum in Figure 2. In the laboratory, the wavelength of the Lyα spectral line is 1215Å.
   a. (2 pt.) Find the expansion parameter of the universe at the time when the light that Dey *et al.* saw left the galaxy. (If you cannot do part (a), you may choose a plausible value for the expansion parameter to do the remaining parts.)
   b. (2 pt.) Imagine a 1-liter bottle at the time the light left the galaxy. The bottle expands with the universe. What is its volume today?
   c. (2 pt.) Find the temperature of the radiation from the big bang at the time the light left the galaxy.

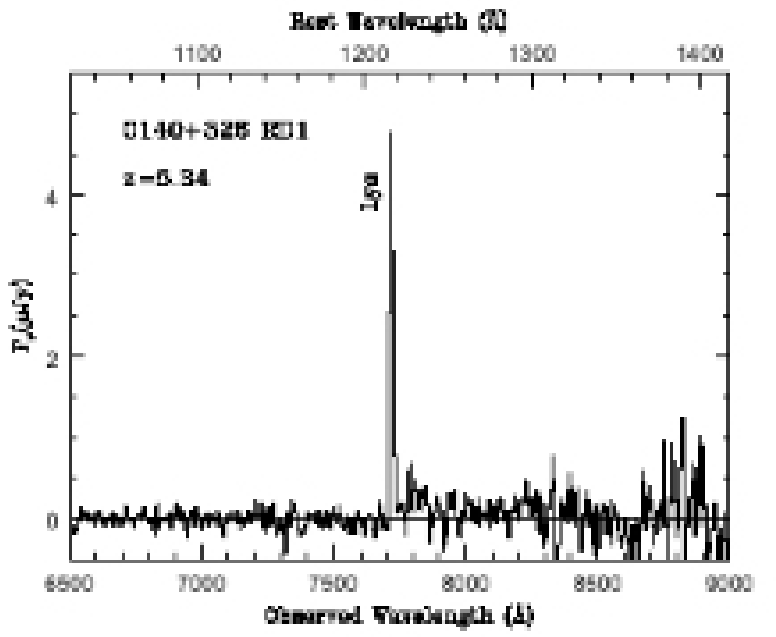

Figure 2 Spectrum of galaxy 0140+326 RD1 from Dey *et al.*, 1998.

5. Production of the light elements. Refer to Figure 1 on the cover sheet.
   a. (1 pt.) For which region of the plot is the temperature of the universe the hottest?
   b. (3 pts.) Simplicio reasons, "Around 200 s after the big bang, the ratio of neutrons to protons drops dramatically. The neutrons decayed and became protons." Rewrite this statement to make it correct, and point out Simplicio's primary misconception.
   c. Suppose we could adjust the reactions $n \leftrightarrow p + e^- + \nu + 2\text{MeV}$ to make the energy cost much smaller than 2 MeV. (2 pts.) How would the figure change? (Consider only the major constituents, H, He, and n. (2 pts.) How would the sun be different?

1.

a. The iron nucleus in my hand was made in a supernova. Calcium and carbon could have been expelled in a supernova.

b. No nucleus in my hand was made on earth.

c. The hydrogen nucleus in my hand was present when the universe was 1 second old.

d. No nucleus in my hand was made in the sun.

2.

a. Penzias & Wilson discovered radiation from the big bang. They found radiation that was isotropic, not polarized, and free of seasonal variation.

b. By observing the full phase of Venus, Galileo proved that the planets do not orbit the earth.

3. Although Andromeda is moving toward us, it does not disprove the big bang. If gravity is strong enough, as it must have been for Andromeda and the Milky Way, the expansion slows and reverses.

"The discovery of the galaxy moving toward us is evidence that the force of gravity can overcome [the motion imparted by] the big bang for galaxies close to each other. Simplicio didn't realize that Hubble's Law still holds true for our galaxy and Andromeda compared to distant galaxies but sometimes for galaxies near each other, the gravitational force can actually make them attract."—Kyle Krzemien

4.

a. $a = \lambda emit/\lambda obs = 1215/7700 = 1/6.34 = 0.158$. Alternatively, you may read the redshift from the figure and use $a=1/(1+z)$.

b. Volume = 1 L / a^3 = 1 6.34^3 = 254 L.

c. T = 2.7 K / a = 2.7 * 6.34 = 17 K.

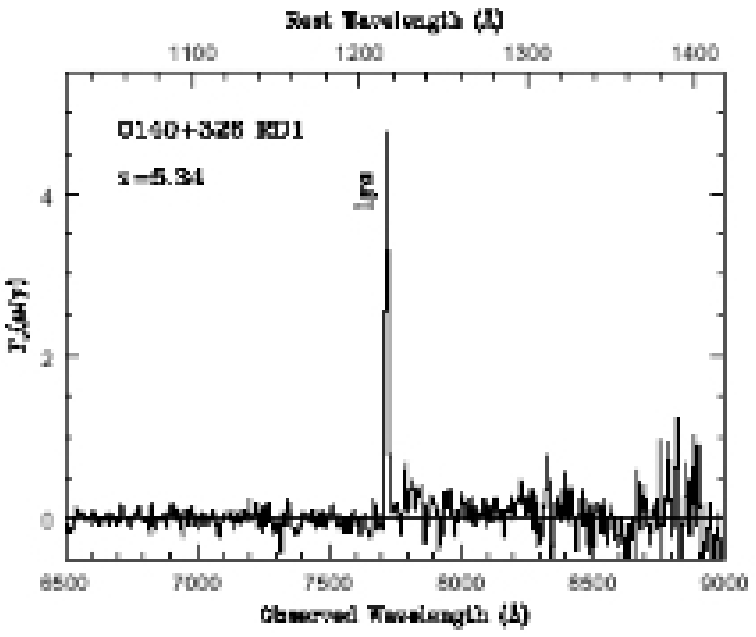

Figure 1 Spectrum of galaxy 0140+326 RD1 from Dey *et al.*, 1998.

5.

a. The temperature of the universe the hottest on the left side of the plot

b. Rewritten correctly: "Around 200 s after the big bang, the neutrons are incorporated primarily into helium, and the number of neutrons drops dramatically." Simplicio realizes that neutrons change into protons earlier, which causes the ratio n/p to drop. He does not realize that n/p stays about the same at 200 s when the neutrons are incorporated into nuclei.

c. If the energy cost to make neutrons is much smaller, then there would be more neutrons at 3 minutes. Consider the extreme case where the energy cost is nil. The number of neutrons and protons (hydrogen) are the same before 3 min. After 3 min, the neutrons drop as before, but all the protons join with neutrons to make ^{4}He: H disappears. The sun would have no hydrogen, and there would be no main sequence phase.