Name: ______________________________

Exercise Twenty-Eight: Indoor

Radial Velocities and the Hubble Law

I. Radial Velocities from Spectral Line Measurements

The standard method for finding radial velocities in astronomy is to measure the wavelengths of spectral lines. Objects that are moving away from the observer will have their spectral lines Doppler-shifted toward longer wavelengths than would be measured if they had no radial velocity. This is called the red shift. If the object is moving toward the observer, the spectral lines will be shifted toward shorter wavelengths (a blue shift). For radial velocities much smaller than the speed of light, the formula used to find the radial velocity is

$$V_r/c = (\lambda - \lambda_0)/\lambda_0$$

where λ is the astronomically measured wavelength of a certain line of a specific element, λ_0 is the wavelength measured in the laboratory, V_r is the radial velocity, and c is the speed of light (3.00×10^5 km/sec). This formula is only valid for small radial velocities, however (for V_r/c less than about 0.1).

1. Calculate V_r/c for a star moving 30 km/sec away from us. Place your answer here:

   $V_r/c =$ __________

2. Is the formula valid for a velocity this great?

3. Would the formula be valid for a velocity 200 times this great?

A formula that is valid for any value of radial velocity is found from Einstein's theory of relativity to be

$$V_r/c = [(\lambda/\lambda_0)^2 - 1]/[(\lambda/\lambda_0)^2 + 1]$$

For five galaxies, the wavelengths of the H and K lines of ionized calcium (prominent in the spectra of all galaxies) are to be taken from Table 28.1.

4. For each of these galaxies, first calculate the red shift of the H line and derive a velocity from its red shift.

5. Then calculate the red shift from the K line, and derive a velocity.

6. Finally, average the two velocity measurements for each galaxy to find the radial velocities of these galaxies. Place your answers here:

Galaxy 1: V_r = __________ km/sec

Galaxy 2: V_r = __________ km/sec

Galaxy 3: V_r = __________ km/sec

Galaxy 4: V_r = __________ km/sec

Galaxy 5: V_r = __________ km/sec

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7. Although these are only hypothetical galaxies, notice that all of their radial velocities are positive (indicating motion *away from* the observer). This is true of most galaxies. How might you interpret this fact?

II. Distances of Galaxies

The distances to galaxies are difficult to determine. Lacking standard distance indicators such as trigonometric parallaxes (they are too far away to be measured), brightness of individual stars (they are too far away to be seen individually), or even standard diameters (they come in all sizes), faraway galaxies pose a problem in distance determination. Various methods have been attempted, such as using the diameters or brightnesses of globular clusters or giant HII regions. One promising method uses the rotationally broadened widths of 21-cm HI radio lines as an indicator of the total optical luminosity. For the farthest galaxies, the brightnesses of the galaxies themselves must be used. It has been found, for instance, that the 10th brightest galaxy in rich clusters of galaxies has pretty much the same brightness from cluster to cluster. In this lab, we will assume that the galaxies for which we have measured the red shifts in Section I are all about the same absolute magnitude, $M = -22.0$ (27 magnitudes brighter than the sun).

1. How many times the solar luminosity does each of our galaxies have? (Remember that 1 magnitude is a factor of 2.5 and every 5 magnitudes is a factor of 100). Place your answer here:

   $L =$ ____________ $L_\odot$

2. Knowing the absolute magnitude of our galaxies, we can use their apparent magnitudes, m, to derive their distances, using the relation

   $$m - M = 5 \log d - 5$$

   Figure 28.1 is a plot of this relationship between d and m for m up to 20th magnitude and for $M = -22.0$. Using this figure and m given in Table 28.1, find the distances of our galaxies, and place your answers here:

   Galaxy 1: $d =$ ____________ pc

   Galaxy 2: $d =$ ____________ pc

Galaxy 3: d = __________ pc

Galaxy 4: d = __________ pc

Galaxy 5: d = __________ pc

3. One parsec is 3.26 light years. How far away is the most distant of our galaxies in light years?

4. The light we observe from the most distant of our galaxies was emitted a number of years ago equal to its distance in light years. The solar system is about 4.6 billion years old, and life on Earth is about 3 billion years old. How does the light from this distant galaxy compare in age with life on Earth and the solar system?

III. The Hubble Law

One of the most amazing facts about observing the faraway galaxies is that the interpretation of their red shifts and distances leads us to a model for the origin and evolution of the universe of galaxies. Hubble and Slipher were the first to publish a plot of the radial velocities of galaxies versus their distances from us. The interesting thing is that there is any relationship at all between these seemingly physically unrelated quantities.

1. Using the graph paper provided, make a Hubble plot of the radial velocities you found for our five galaxies versus their distances. Convenient units to use for the axes are 10^3 km/sec for radial velocity and 10^8 pc for distance. Draw the best straight line through the data points on your graph. Make sure your line passes through the origin.

What you have found, if your work so far is correct, is that there is a good straight-line relationship between galactic distance and galactic red shift. Interpreting this relation in terms of a real radial velocity dependent on distance, Hubble concluded that for such a

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relation to hold in a uniform (homogeneous) universe that looks the same in all directions (isotropic), the universe must be expanding uniformly in all directions. That is, the galaxies are all rushing away from each other in a uniform way. An equation called the Hubble Law relates the measured radial velocities to the distances in this way:

$$V_r = H \times d$$

Here, the constant *H*, which is the slope of the line on your Hubble plot, is called the Hubble constant.

2. Find *H* from your straight line and write your answer here:

   $H =$ __________ km/sec/pc

3. Astronomers usually use the units of km/sec/Mpc (kilometers per second per megaparsec) for *H*. Write *H* here in these units:

   $H =$ __________ km/sec/Mpc

If the universe is uniformly expanding at a constant rate, then there must have been a time when all of the galaxies were very close together. This can be seen in the following way. Suppose an arbitrary galaxy has been moving away from us at a constant radial velocity for a time *t*. It will have covered a distance $d = V_r \times t$ in that time. Substituting this into the Hubble Law, we find that $t = 1/H$. That is, the galaxy would have been here, at our location, the time $t = 1/H$ ago. Because we did this for an arbitrary galaxy, the result holds for any galaxy, and all galaxies must have been together this time ago.

4. In order to evaluate when this (the Big Bang) occurred, we must convert *H* into units of 1/sec. To do this, note that 1 pc = 3.08×10^{13} km. Write *H* here:

   $H =$ __________ /sec

5. Inverting *H*, find *t* (the age of the universe, assuming that the expansion has been at a constant speed), and place your answer here:

   $t = 1/H =$ __________ sec

6. Finally, convert t to years, using the fact that 1 yr = 3.15×10^7 sec.

   t = __________ yr

Of course, in reality the expansion of the universe must be slowing because of the retarding effect of gravitation, so the galaxies have reached their present distances from us in a shorter time than if they had always traveled at their present, slower speeds. Thus, the age of the universe you have determined is a maximum value, depending on how rapidly the expansion is slowing. It is a matter of contention whether the expansion is slowing rapidly enough for the universe to stop eventually and go into contraction. (not)

That the Big Bang actually occurred, however, is supported by observation of the highly red-shifted radiation from the early condensed state of the universe (the 3° blackbody background radiation) and by the agreement of the observed hydrogen and helium abundances with calculations of nuclear reactions occurring in the Big Bang. The maximum ages of stars, the change in the density of quasars with time in the universe, and other observational facts are consistent with the Big Bang.

Table 28.1

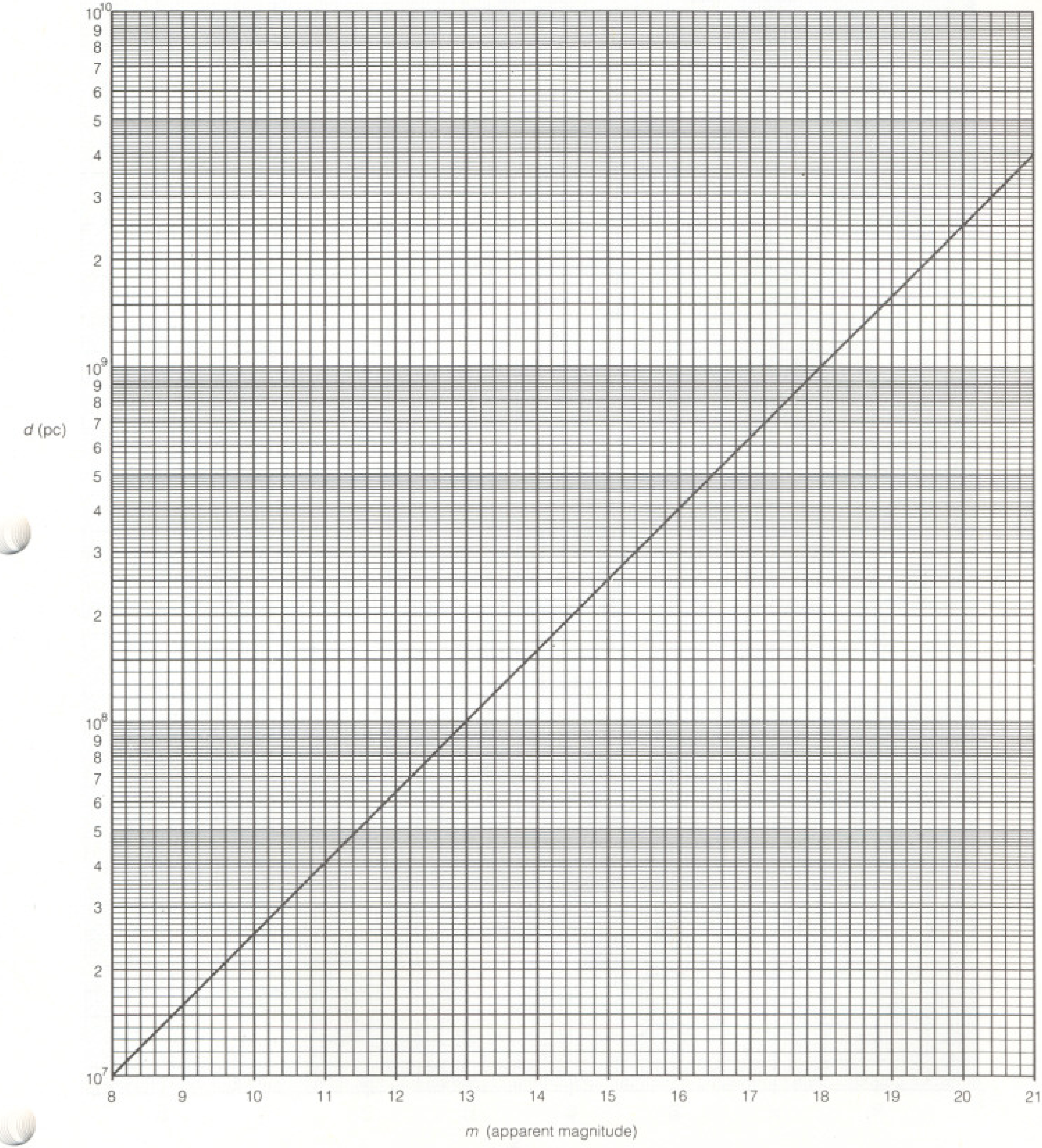
Apparent Magnitudes of Galaxies

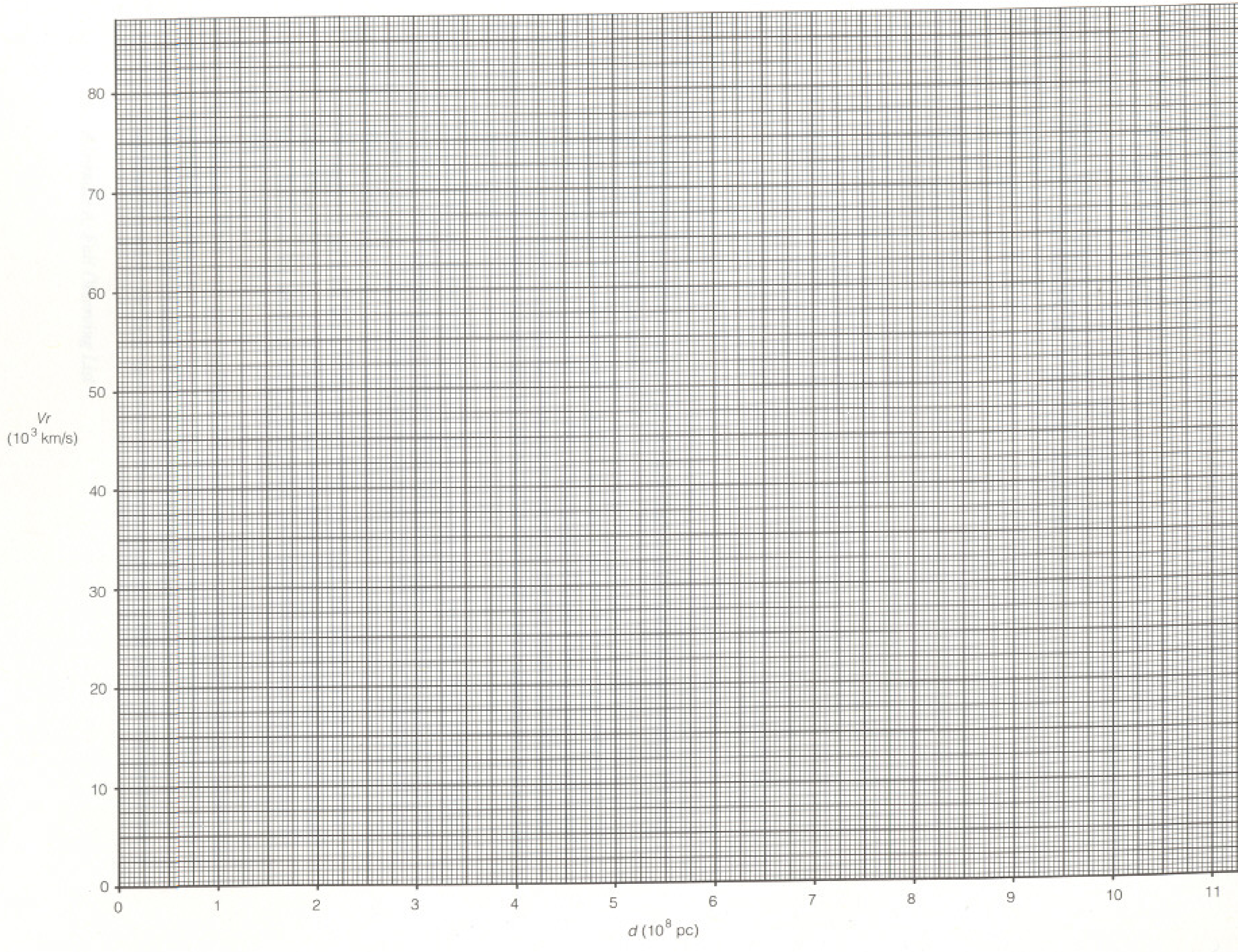
Galaxy Number	Apparent Magnitude m	H Line λ	(λ/λ_0)	V_r/c	K Line λ	(λ/λ_0)	V_r/c	Average V_r/c
1	16.0	4231.2	______	______	4266.7	______	______	______
2	9.4	3947.3	______	______	3982.8	______	______	______
3	17.2	4483.5	______	______	4522.9	______	______	______
4	15.1	4132.6	______	______	4168.1	______	______	______
5	18.2	4834.4	______	______	4873.8	______	______	______

Note: H Line of CaII λ_0 = 3933.7 Å
K Line of CaII λ_0 = 3968.5 Å
$c = 3.00 \times 10^5$ km/sec

Figure 28.1

Relationship between *d* and *m* ($M = -22.0$).




Vr
(10^3 km/s)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
10
11
d (10^8 pc)