# Hubble’s Law and the Cosmic Distance Scale

Firstname Lastname

Date

1. Replace the red text at the top of this page with your name and the date.

2. As you enter your work, please make sure that your answers stay red (like this). This will make them easier to see, and thus it will be easier for us to grade them accurately. To convert black text to red, highlight it and then click on the “A” symbol in the menu bar above, to the right of the “**B**”, “*I*”, and “U” symbols. Select the red square to turn your highlighted text red.

3. Delete these 3 initial instructions from this template as soon as you have followed them.

A Hubble Diagram for Nearby Galaxies with Cepheids

1. Complete the following statements, based on the Hubble diagram shown in Figure 7.6.

(a) The galaxy M100 is one of the most ( nearby / distant ) galaxies for which Cepheid-derived distances are shown.

(b) A galaxy lying 10 Mpc away from us should have a recessional velocity of roughly replace this text. (Please attach units to your value.)

(c) The modern value for H0 derived here is much ( higher / lower ), by a

factor of roughly replace this text, than that found in Hubble's original data (shown in Figure 7.1).

2. Figure 7.7 shows the light curve for a second Cepheid variable star in the M100 galaxy.

(a) The period of variability for this star is replace this text days (to the nearest day or two).

(b) This star is intrinsically ( brighter / fainter ) than the one shown in

Figure 7.5.

A Hubble Diagram for More Distant Galaxies with Type Ia Supernovae

1. What is the redshift *z* for the most distant galaxy shown in Figure 7.8.

*z* =

2. Figures 7.6 and 7.8 illustrate the process of deriving values for the Hubble constant (H0) from samples of galaxies containing Cepheid variable stars and supernovae. In each case, is the derived value for H0 consistent with the accepted value of 72 km sec-1 per Mpc? (Are the differences more or less than 2σ?) Please show your work.

Replace this text.

3. How many galaxies appear in Figure 7.6 and also appear in Figure 7.8? Why might even a small number of galaxies in which we had detected both Cepheid variable stars and a supernovae be of particular interest?

Replace this text.

4. How many supernovae could have been seen in the nearest 10 galaxies since the telescope was invented in 1600? How many could have been observed with modern telescopes and recording devices (over the last 30 years)?

Replace this text.

5. There is an unwritten rule of courtesy among astronomers that if a supernovae occurs nearby, anyone with time on a major telescope in the next few days observes it and circulates the images worldwide. Why do you think we do this?

Replace this text.

Measuring D-size and D-flux from Galaxy Images

1. Save a copy of the final galaxy data table and include it in your lab report.

Place PNG-format plot of table here, and replace this text.

2. Save a copy of the image for Galaxy #10 and include it in your lab report.

Place PNG-format figure here, and replace this text.

3. As you decrease the size of the elliptical aperture on a galaxy image, D-size ( increases / decreases / remains constant ) and D-flux ( increases /

decreases / remains constant ).

4. If the size of a galaxy is over-estimated (the aperture is larger than the

galaxy), D-size will be ( too large / too small ).

5. If the size of a galaxy is under-estimated (the aperture is smaller than

the galaxy), D-flux will be ( too large / too small ).

6. Most of the light from the galaxies is uniformly distributed in smooth ellipses around the cores. Why is there a second peak in the radial counts plot for Galaxy #6?

Replace this text.

7. Which of the ten galaxies posed the largest challenges to fit? Which was the easiest to analyze? Explain your choices.

Replace this text.

Measuring D-z from Galaxy Spectra

1. Save a copy of the final galaxy data table and include it in your lab report.

Place PNG-format plot of table here, and replace this text.

2. Save a copy of the spectrum for Galaxy #9 and include it in your lab report. Are you more confident in your estimates of D-z or of D-size and D-flux for this galaxy? Why?

Place PNG-format figure here, and replace this text.

3. As you increase the redshift for a galaxy spectrum, D-z ( increases / decreases / remains constant ).

4. More distant galaxies appear ( smaller / larger ) on the images, and their spectra shift to the ( left / right ) to ( shorter / longer ) wavelengths.

5. Which of the ten galaxies posed the largest challenges in determining

redshifts? Which was the easiest to fit? Explain your choices.

Replace this text.

Evaluating Distances Based on Apparent Sizes of BCGs

1. Two-thirds of the BCGs will lie within 1σ of the mean size, between replace this text kpc and replace this text kpc. For the remaining third, our D-size distance estimates would be more than 30% too low or more than 66% too high (see Example 7.5).

Evaluating Distances Based on Apparent Brightnesses of BCGs

1. Two-thirds of the BCGs will lie within 1σ of the mean luminosity, between replace this text and replace this text times as bright as the Milky

Way. For the remaining third, D-flux would be more than 16% too low or more than 33% too high (see Example 7.6).

2. ( D-size / D-flux ) is more accurate, on average.

Comparing Distance Estimators

1. Be sure to save a PNG-format copy of the plot to your computer, to include in your lab report.

Place PNG-format figure here, and replace this text.

2. Do the ten points from your data set appear to follow the same trend as the 24 additional points? If not, how do they differ, and why do you think this might have occurred?

Replace this text.

3. If all of the distance estimators were “perfect”, what values would you

expect for a slope and a *y*-intercept for each window?

Replace this text.

4. The two distance estimators ( D-size / D-flux / D-z ) had the worst rms

deviations (highest σ values) when plotted against the cluster distances.

5. Distance estimator ( D-size / D-flux / D-z ) had the best rms deviation

when plotted against the cluster distances. Do the points in this plot also

appear to follow the best-fit line most closely, just looking by eye?

( yes / no )

6. Why do you think that this technique produced the best results?

Replace this text.

The Range of BCG Properties

1. Is the most luminous BCG also the largest one? ( yes / no )

2. Is the least luminous BCG also the smallest one? ( yes / no )

3. What percentage of the 34 galaxies are either brighter and smaller than average, or fainter and larger than average?

P =

4. In general, BCGs which are intrinsically brighter than average are also

( larger / smaller ) than average, while those which are intrinsically fainter

than average are also ( larger / smaller ) than average. Explain this result, assuming that the luminosity of a galaxy is just the total amount of light emitted by all of its stars.

Replace this text.

Final (Post-Lab) Questions

1. In the 1930-1950 era the Andromeda Galaxy was thought to lie a mere 750,000 light years away, but this distance was increased to two million light years in later years. What happened? The Andromeda Galaxy did not leap and skip across the cosmos! The calibration for the Cepheid period-luminosity relationship improved, however, changing all distances which depended on it. Similar corrections occurred in the 1970-2000 era, producing large changes in cosmologically-based distances determined from measured redshifts, as the value of the important constant known as

replace this text also became more accurate.

2. How do the BCGs differ qualitatively and quantitatively from our Milky Way galaxy? (Consider galaxy sizes, luminosities, colors, types, and

environments.)

Replace this text.

3. What is the redshift of the most distant BCG that you examined? Roughly how long ago was the light captured in the image that you analyzed emitted by the galaxy?

Replace this text.

4. If it takes light a full second to travel 300,000 kilometers, how long does

it take to travel one parsec, or even 400 Mpc, in units of years? (A parsec

is equal to 3 ⤫ 1013 kilometers, and there are π ⤫ 107 seconds in a year.)

T1 =

T2 =

5. We can use the Hubble constant H0 to estimate the age of the Universe. We observe that the Universe is expanding; clusters of galaxies are all moving apart from one another. In the past the galaxies were closer together, and if we go back far enough in time we get to a point where this expansion started. We call that event -- the start of the expansion of the Universe -- the “Big Bang.” As the Universe expands, more distant galaxies are observed to be moving away faster since there is more expanding space between us and them. There is thus a correlation between the distance and the time. Let's see how that works!

If a friend says that they drove at a velocity *v* of 60 miles per hour and

covered a distance *d* of 120 miles, you instantly know their travel time *t*

(two hours). Velocity equals distance per unit time, so

v = $\frac{d}{t}$, and t = $\frac{d}{v}$,

In this case,

t = $\frac{d}{v}$ = $\frac{120 miles}{60 miles per hour}$ = $\frac{120}{60}$ hours = 2 hours.

We can perform the exact same calculation for galaxies, using the fact that

H0 = v/d.

t = $\frac{d}{v}$ = $\frac{1}{H0}$.

Until now we have expressed the units of H0 as km sec-1 per Mpc. We

need to cancel the units of length (kilometers and megaparsecs), leaving

seconds (a unit of time).

t = $\frac{d}{v}$ = $\frac{1}{H0}$= $\frac{1}{72 km per second per Mpc}$ = $\frac{1}{72}$ $\frac{Mpc - second}{ km}$.

(a) One parsec is equal to 3 ⤫ 1013 kilometers, so how many kilometers are there in a megaparsec (in 106 parsecs)?

*L* = … km.

Let's call this value *L*. We can now replace the Mpc in our expression for

*t* with “L kilometers”.

t = $\frac{1}{72}$ $\frac{Mpc - second}{ km}$ = $\frac{1}{72}$ $\frac{L km - second}{ km}$ = $\frac{L}{72}$ seconds.

(b) There are π ⤫ 107 seconds in a year, so what is the age of the Universe, in units of billions of years?

t = $\frac{L}{72}$ seconds × $\frac{year}{10,000,000 π seconds}$ = $\frac{L}{720,000,000 π }$ years.

T = … years.

(c) If the Hubble constant H0 were twice as large, the age of the Universe

would be ( twice as large / half as large / unchanged ).

Summary (300 to 500 words)

Replace this text.

Extra Credit

Replace this text.