DAY LABORATORY EXERCISE #6:
The Hubble Law

Name ______________________________

Lab Section: ________ Due date:_______________

Goals:
- To determine the relationship of a galaxy's distance with the redshift of its spectrum
- To examine evidence that the Universe is expanding
- To measure the rate of the expansion

Material: Galaxy photographs & spectra (provided), ruler, calculator

Methods:
- Compile a database of information on a sample of galaxies
- Graph the information to identify relationships between measured quantities

Introduction - In the first quarter of the last century, astronomy was becoming a vigorous science as new technologies and new scientific theories were developed. Due to advances in engineering, astronomers began to build large telescopes, capable of detecting extremely faint objects. Photography allowed recording of images for analysis. The development of quantum mechanics in the 1920's led to accurate descriptions of atoms so that the spectra of stars and galaxies could be understood. Armed with such new knowledge and new tools, astronomers Edwin Hubble and Milton Humason began observing galaxies.

At the time, it was unknown whether galaxies were actually outside the Milky Way or merely rotating gas clouds within our own Milky Way Galaxy. The evidence gathered by Hubble and Humason in the mid 1920s with the then-new 100-inch diameter telescope in California represented a key advance toward settling this debate, and also provided a huge leap in humanity's understanding of the nature of the Universe as a whole.

Hubble and Humason photographed a large number of distant galaxies and recorded their spectra. In addition to providing information regarding the composition of the galaxies, these spectra also allowed the determination of the velocities of the galaxies relative to the Sun. This was done by measuring the shifts of the wavelengths of the galaxies' spectra and interpreting them in terms of the Doppler effect.

In this exercise you will determine the relationship that exists between the distance to a galaxy and the redshift of its spectrum.

[Images and spectra are from the CLEA Hubble lab:
http://www3.gettysburg.edu/~marschal/clea/CLEAhome.html
Sponsored by Gettysburg College and the National Science Foundation.]

Procedures

A. Galaxy distances

Determining distances to galaxies is not easy. Galaxies beyond the Milky Way are too distant to have a measurable parallax. So, other methods need to be used. The method used in this lab is based on a critical approximation, but should suffice to yield reasonably good estimates of the distances to galaxies.

If all galaxies were same size, one could estimate their *relative* distances by comparing their apparent sizes: the ones that look smaller would be proportionately more distant. Although there is a wide range in the physical sizes of galaxies, the largest galaxies found in clusters of galaxies are roughly the same size. So, it is possible to estimate the distances to galaxy clusters by studying their largest members. The galaxies you will measure are some of the largest galaxies in a set of clusters of galaxies.

1. Measure the apparent diameter (in millimeters) of each of the three galaxies in each of the five clusters of galaxies on the page of galaxy images (Page 8). Try to measure the longest dimension, as tilts of the galaxies will cause the other dimension to appear shorter than it actually is. Write your measurements in the **Table 1** on Page 3.

2. The distance (d) to a galaxy is related to its apparent diameter (D) by the relation $\boldsymbol{d = S/D}$, where ***D* is the galaxy's diameter as measured on the image (in cm)** and ***d* is the distance to the galaxy in Mpc** (millions of parsecs). The quantity ***S* is a scale factor** that relates these two sets of distance units. For the plot scale shown on the page of galaxy images (about 4.3 arcminutes per 5 cm of linear distance), and for an assumed largest galaxy physical size of 90 kpc, ***S* = 360 Mpc cm**.

3. Using this value of S, calculate distances to the galaxies whose diameters you have measured. Put your answers in **Table 1**.

B. Galaxy radial velocities – The three pages of spectra (Pages 10-12) show a portion of the blue part of the spectrum obtained for a G-type main-sequence star residing in the Milky Way, as well as representative spectra for one galaxy in each of the five galaxy clusters. (Most galaxies have spectra similar to G stars.) You will compare the stellar spectrum to the spectra of the galaxies to determine their radial velocities – toward or away from the Sun.

The wavelength units are Angstroms (Å; 1 Å = 0.1 nm).

1. For each of the 3 indicated spectral lines in the stellar spectrum, **measure the wavelength shift $\Delta\lambda$ (in Å) by subtracting the wavelength of the line in the star's spectrum, λ_0, from the wavelength of the same line in the galaxy's spectrum, λ.** (The star is not moving relative to the Sun.) **Enter your measurement in Table 1.** Note that for some galaxies some of the lines are shifted out of the visible portion of the spectrum.

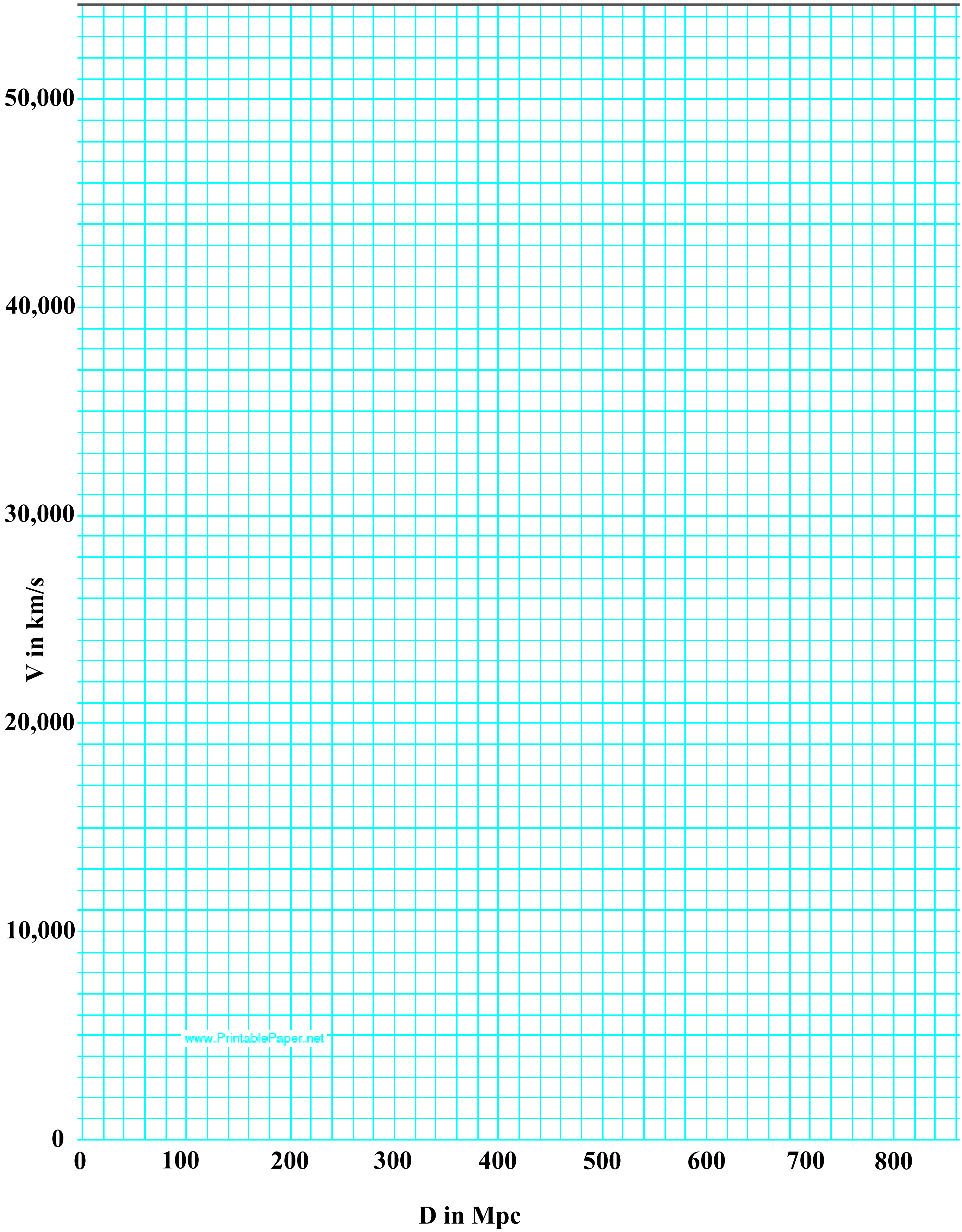
2. Find the fractional wavelength shift (F) for each spectral line using:
$$F = \frac{\Delta\lambda}{\lambda_0}$$
Enter your values in Table 1. (Assume Ca lines are at rest wavelengths of 3934 Å and 3968 Å, and the G band is at 4303 Å.)

3. Use the value of F to find the radial velocity (< 0 means toward us, > 0 means away from us) of each galaxy in km/sec; use the Doppler shift formula:
$\boldsymbol{v = Fc}$, which is valid for velocities less than about 0.2c. Here c = 3.00×10^5 km/s is the speed of light. **Enter your results in Table 1.**

Table 1
Galaxy Distances and Spectral Shifts

Galaxy Cluster	Galaxy Number	Diameter (D) (mm)	Distance (d) (Mpc)	Spectral Line	Spectral Shift $\Delta\lambda$ (Angstroms)	Fractional Spectral Shift *F*	Radial Velocity *v* (km/s)
Coma	1			CaII H			
	2			CaII K			
	3			G-Band			
Bootes	1			CaII H			
	2			CaII K			
	3			G-Band	Not present	----	----
Corona Bor.	1			CaII H			
	2			CaII K			
	3			G-Band	Not present	----	----
Ursa Maj. I	1			CaII H			
	2			CaII K			
	3			G-Band	Not present	----	----
Ursa Maj. II	1			CaII H			
	2			CaII K	Not present	----	----
	3			G-Band	Not present	----	----

Calculate the **mean** and **standard deviation** of the measurements of the radial velocity of the galaxy in Ursa Maj. I between yourself and everyone in your lab group. Show your work.


50,000
40,000
30,000
20,000
10,000
0
V in km/s
0
100
200
300
400
500
600
700
800
D in Mpc
www.PrintablePaper.net

C. The Hubble Diagram - When Hubble had collected very similar data to yours, he did what any good scientist would do: he graphed them! He found that when the observed distances of galaxies were plotted versus their apparent radial velocities, there was a simple relationship between the two.

1. **Graph your results**. Please use the grid on the previous page to make your graph. **Plot radial velocity of each cluster as the vertical axis (in km/sec) and galaxy distance as the horizontal axis (in Mpc).** If there is more than one value of *v* and/or *d* for a given cluster, **average them** to determine the value of *v* and/or *d* that you put on the graph.

2. **Draw a straight line through the data points and the origin (x=0,y=0)**. The line will not pass exactly through each data point, but it must pass through the origin. **Roughly as many data points should lie above the line as below the line**. (There are somewhat complex mathematical methods that determine the optimal line, but for this exercise your best judgment is adequate. Your line is likely to differ a bit from a classmate's line, though.)

3. The slope of this line is called the "Hubble Constant." The relationship can be expressed by the equation:

$$v = H_0\, d$$

where *v* is the radial velocity of the galaxy, *d* is the distance to the galaxy. and the **slope, H_0, is the Hubble constant, in units of km/s per Mpc [or km/(s Mpc)]**. This equation is called "**Hubble's Law**." **Calculate the slope of your best-fit line and record it in the space below.** To do this, choose any two points on the line (not actual data points unless they fall exactly on the line). **Subtract the velocity of the lower point from the velocity of the higher point to get Δv, and subtract the distance of the point farther to the left from the distance of the point farther to the right to get Δd. The slope is then $\Delta v/\Delta d$**. Show your work on the graph paper on the previous page.

Hubble constant H_0 = ______________________.

4. What is the median value of the Hubble constant found by averaging your value with the values of everyone in your group?

Group-determined median Hubble constant H_0 = ______________________.

5. The Hubble constant has strange units: km/(s Mpc). As km and Mpc are both units of distance, the units can be canceled to yield units of 1/s by dividing H_0 in km/(s Mpc) by 3.086×10^{19} km/Mpc. This gives one way to estimate the age of the Universe in seconds:

Age of Universe ≈ 1 / H_0

Calculate the approximate age of the universe based on your value for H_0 and record this answer in the space below. (Once you have the answer in seconds you should convert it to billions of years (Gyr) by dividing by 3.16×10^{16} s/Gyr):

Age of the Universe ≈ ______________________s ≈_____________Gyr_.

The Expansion of the Universe

An implication of the Hubble Law is that the more distant a galaxy is from us, the faster it moves away from us. Also, we have not detected any very distant galaxies with *blue*shifts, so *all* galaxies beyond our Local Group seem to be moving away from us. It may seem, from this lack of blueshifts, that we were at the center of an expanding universe. You can check on this possibility by considering what beings on another galaxy would measure if the entire universe – space itself – is expanding. If they would also obtain the same Hubble Law, there is no center to the universe's space!

Figures 1 and 2 on the previous page show a section of the universe simulated at two different times, Time_1 = 6 billion years and Time_2 = 8 billion years after the expansion starts (the "Big Bang"). At Time_1 = 6 billion years, we see many galaxies (galaxies A, B, and C are identified). At a later time (Time_2 = 8 billion years) we see many of the same galaxies, in different positions because of the expansion of the universe. Using Galaxy A as your reference point, measure the distances (in mm) to Galaxies B and C at both times and determine the apparent radial velocities of Galaxies B and C (in units of Mpc/Gyr). Assume that 1 mm corresponds to 0.1 Mpc.

Which galaxy is receding from Galaxy A faster?

Does this agree with the Hubble Law (from the perspective of Galaxy A)?

Now imagine that we do not live in Galaxy A, but in Galaxy B. How would the Universe appear to us then? Using Galaxy B as your reference point, measure the distances to Galaxies A and C at both times and determine their radial velocities.

Which galaxy is receding from Galaxy B faster?

Does this agree with the Hubble Law (from your perspective on Galaxy B) ?

Based on these measurements, is it possible to determine whether either Galaxy A or Galaxy B is at the center of the Universe is? If so, which one and why? If not, why not?

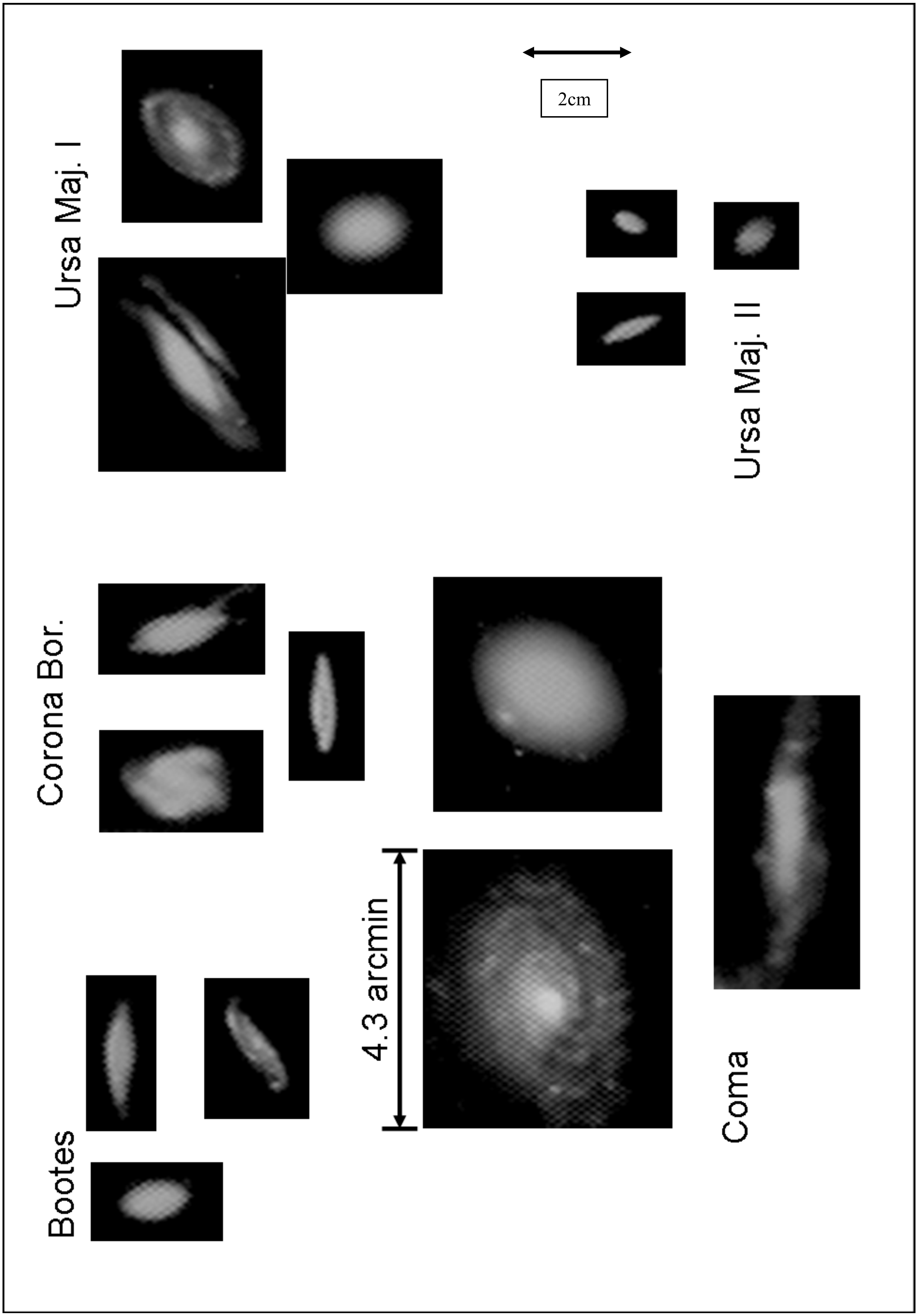
Summary Questions

1. In this exercise you determined two separate quantities: a galaxy's distance and the shift of its spectrum. Which of these two quantities is the most uncertain? Why?

2. The Gemini cluster of galaxies has a radial velocity of +23,000 km/sec. Use your graph to determine its distance. (Alternatively, you may use your value of the Hubble constant and the Hubble Law.)

3. Since light travels at a finite speed, we are seeing the distant galaxies as they appeared in the past. How long ago did the light from the galaxies in the Gemini cluster leave that cluster? (Hint: 1 pc = 3.26 light years and 1 Mpc = 10^6 pc, so 1 Mpc = 3.26 x 10^6 light years)

4. Suppose the velocity of expansion of the universe is slowing down with time; how would this affect the Hubble Law? Explain. For example, will the straight line you drew on your data plot curve up or down at larger distances, or is there no such effect? (Hint: Remember the further away you look, the further back in time you are observing).


2cm
Ursa Maj. I
Ursa Maj. II
Corona Bor.
4.3 arcmin
Coma
Bootes

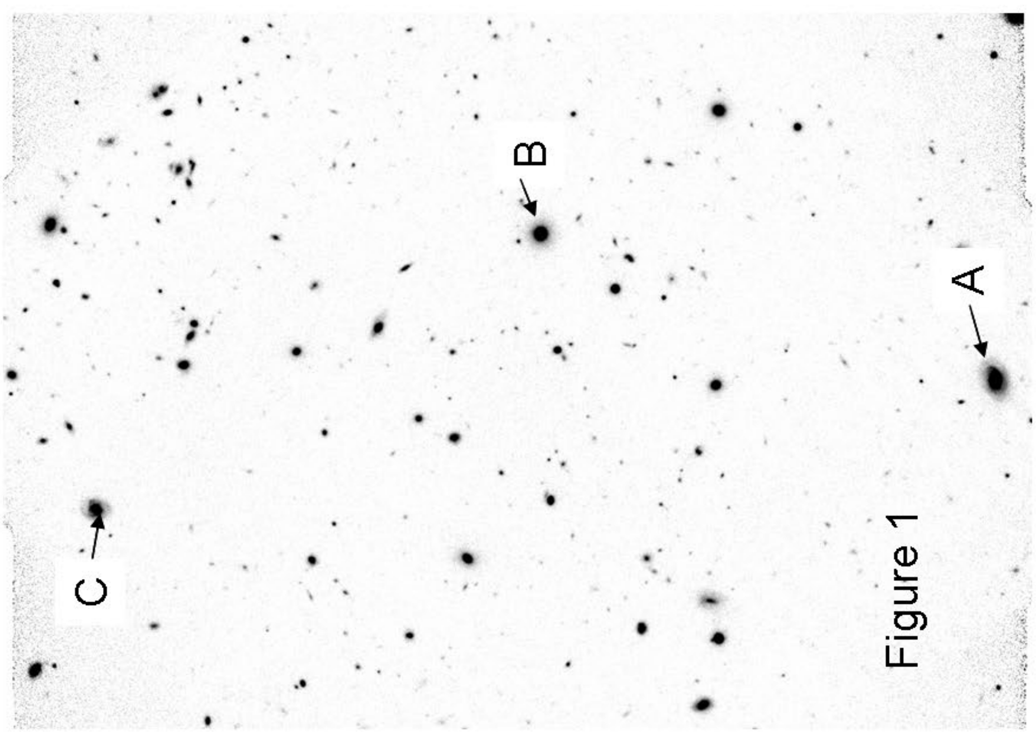


Figure 1

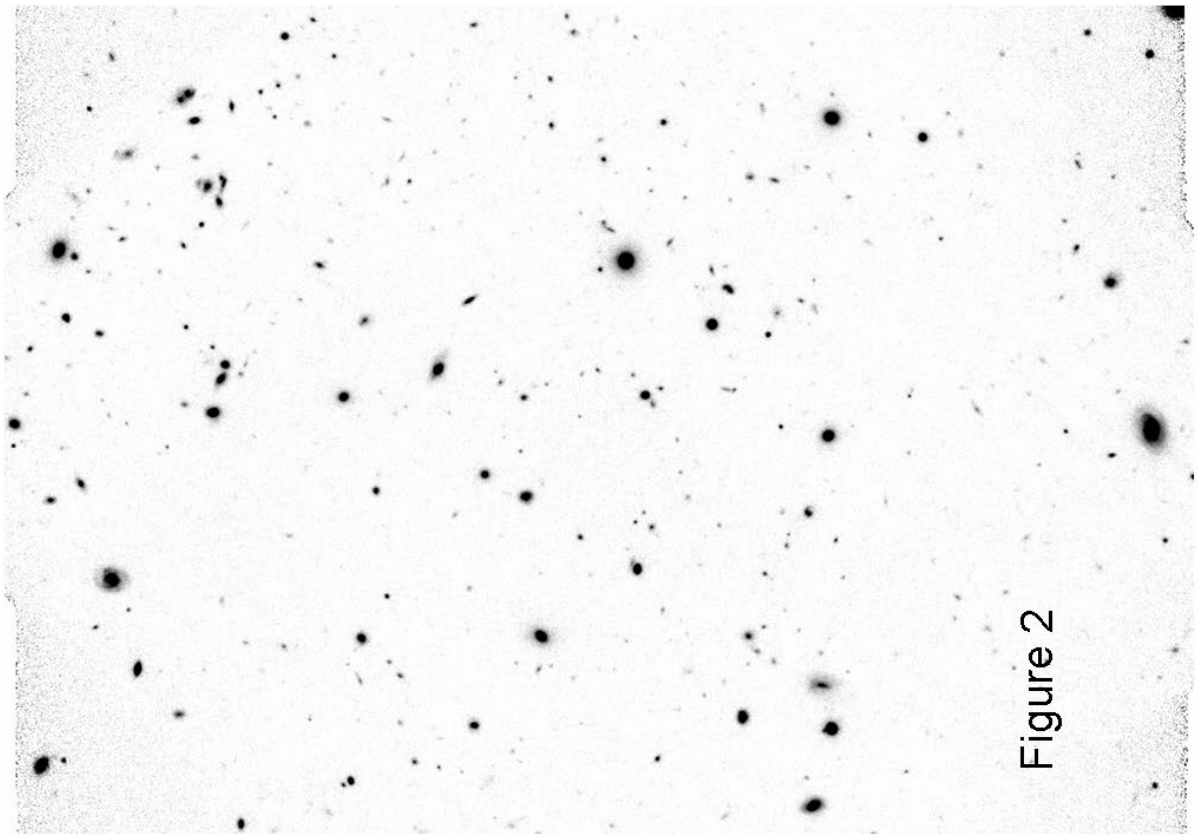
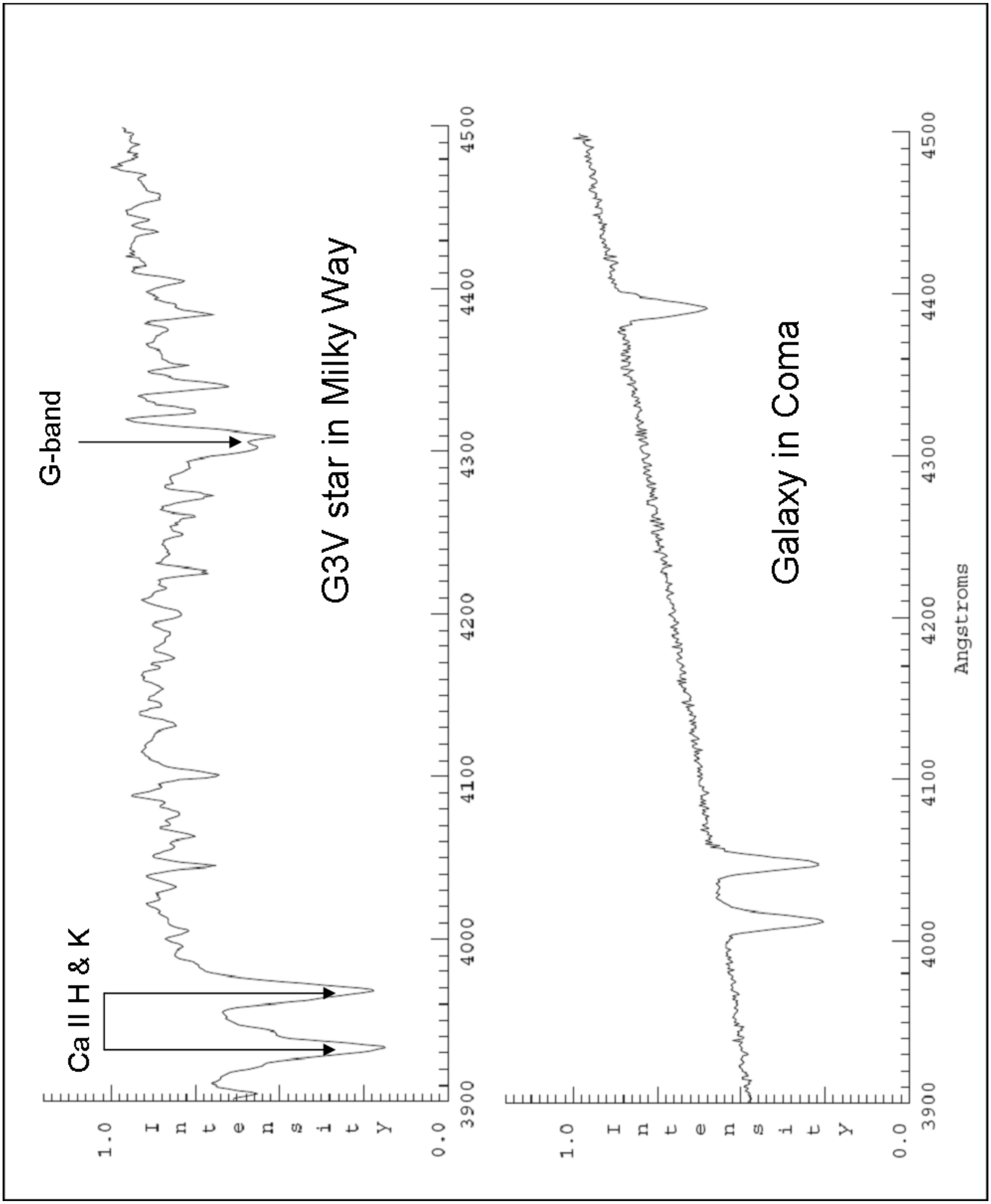
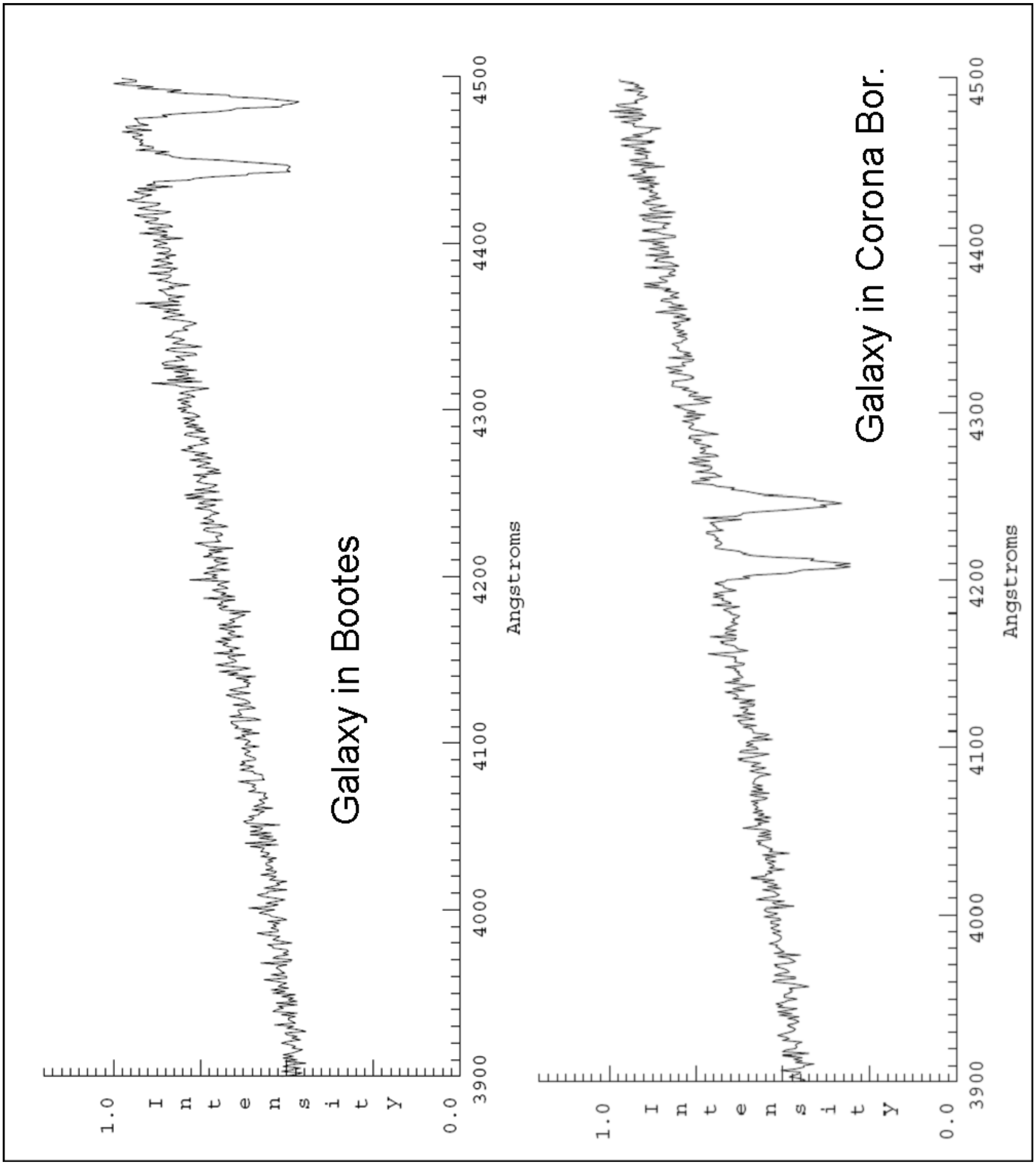
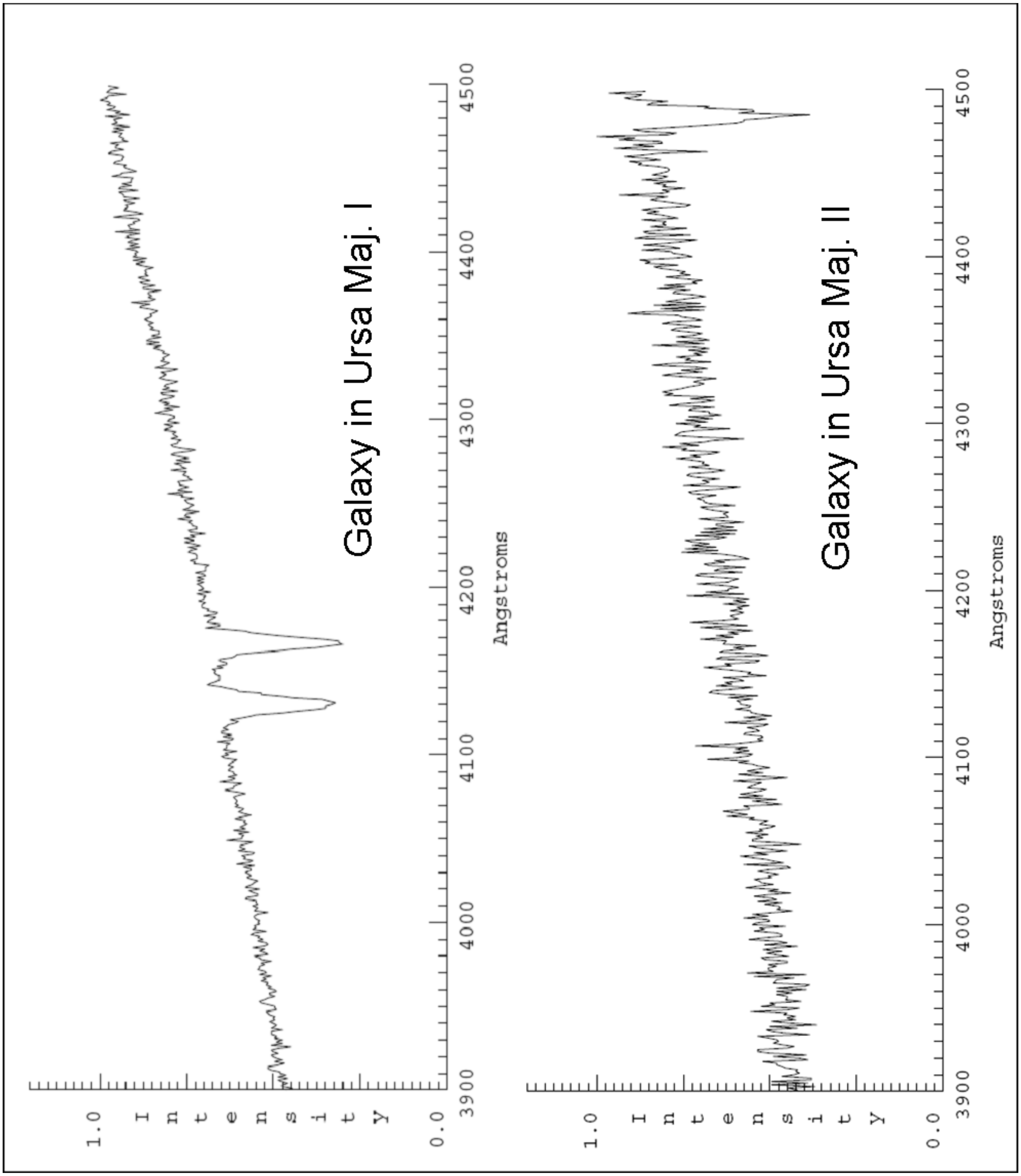


Figure 2

From Retzlaff et al. (2010). *Based on observations made with ESO Telescopes at the La Silla or Paranal Observatories under programmes 73.A-0764 and 168.A-0485.*


G-band
Ca II H & K
G3V star in Milky Way
Galaxy in Coma
Intensity
1.0
0.0
3900
4000
4100
4200
4300
4400
4500
Angstroms


Galaxy in Bootes
Galaxy in Corona Bor.
Intensity
1.0
0.0
Angstroms
3900
4000
4100
4200
4300
4400
4500


Galaxy in Ursa Maj. I
Galaxy in Ursa Maj. II
Intensity
1.0
0.0
Angstroms
3900
4000
4100
4200
4300
4400
4500