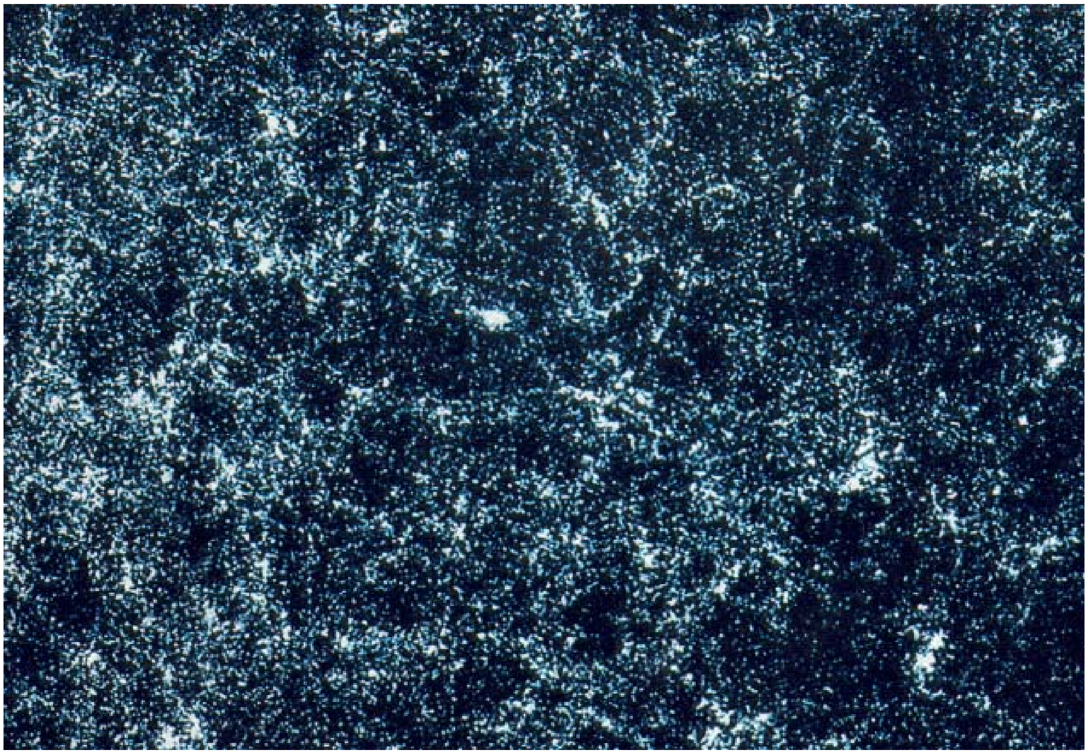
Large Scale Structure of the Universe

Student Manual

A Manual to Accompany Software for
the Introductory Astronomy Lab Exercise
Document SM 7: Circ. Version 1.1.1



Department of Physics
Gettysburg College
Gettysburg, PA

Telephone: (717) 337-6019
Email: clea@gettysburg.edu

Contemporary Laboratory
Experiences in Astronomy

Contents

Goal

You should be able to use observations of the redshifts of galaxies, along with their coordinates in the sky, to produce a three-dimensional map of a nearby region of the sky. You should understand how matter is distributed on the largest scales in the universe. You should appreciate some of the difficulties involved in making and interpreting large-scale maps of the universe.

Objectives

If you learn to.........

Find galaxies in a restricted area of the sky using a list compiled by earlier observers.
Take spectra of these galaxies using simulated telescopes and spectrometers.
Recognize the principal features of galaxy spectra.
Measure the wavelengths of principal spectral lines in galaxies.
Calculate the redshift, z, and the radial velocities of the galaxies.
Plot radial velocities and positions on a wedge diagram.
Interpret the distributions of galaxies you see on the wedge diagram.

You should be able to.........

Tabulate the radial velocities of all 218 galaxies in your sample.
Produce a map of the three-dimensional distribution of galaxies in a small part of the universe near our own Milky Way galaxy.
Develop an understanding of the typical sizes of large-scale features (super clusters and voids) in universe.
Appreciate some of the difficulties and limitations of such measurements.

Useful Terms you should review using your textbook

absolute magnitude	Declination	Hubble Constant	radial velocity	superclusters
absorption lines	distance modulus	Hubble relation	redshift	wavelength
Angstrom (Å)	Doppler Shift	local group	Right Ascension	wedge diagram
apparent magnitude	elliptical galaxy	megaparsec	spectrometer	z
Ca H and K	galaxy	parsec	spectrum	
Coma cluster	galaxy cluster	photon	spiral galaxy	

Equipment and Materials

Computer running CLEA ***Large Scale Structure of the Universe*** program, pencil, ruler, graph paper, calculator, and this manual.

Background: The Large-Scale Distribution of Matter

Drawing a map of the universe is not an easy task. Understanding why it is difficult, however, is rather simple. Consider how hard it is to determine the shape and extent of a forest when one is standing in the middle of it. Trees are visible in all directions, but how far do they extend? Where are the boundaries of the forest, if any? Are there any clearings or any denser groves, or are the trees just scattered uniformly about at random? A terrestrial surveyor might answer these questions by walking around the forest with a compass and transit (or, more recently, a Global Positioning System or GPS receiver), mapping carefully where everything was located on a piece of ruled paper. But consider how much more difficult it would be if the surveyor were tied to a tree, unable to budge from a single spot. That's the problem we earthbound observers face when surveying the universe. We have to do all our mapping (of galaxies, of course, not trees), from a single spot,—out solar system—located about 2/3 of the way between the center of the Milky Way galaxy and its edge.

Two of the three dimensions required to make a 3-dimensional map of the positions of the galaxies in universe are actually fairly easy to determine. Those two dimensions are the two celestial coordinates, Right Ascension and declination, that tell us the location of a galaxy on the celestial sphere. Over the years, by examining photographs of the heavens, astronomers have compiled extensive catalogs that contain the coordinates of hundreds of thousands of galaxies. They estimate that there are hundreds of billions of galaxies that lie within the range of our best telescopes.

More is needed, however. The two celestial coordinates just tell us in what direction to look to see a galaxy. A third number—the distance of the galaxy—is necessary in order to produce a reliable map. Unfortunately the distance of galaxies is not immediately obvious. A small, faint galaxy nearby can appear much the same as a large, luminous galaxy much further away. Except in the very nearest galaxies, we can't see individual stars whose luminosity we can use to estimate distance. How then can we determine galaxy distances reliably?

The solution to this problem is to make use of the *expansion of the universe* to give us a measure of distance. By the expansion of the universe we mean the fact that the overall distance between the galaxies is getting larger all the time, like the distance between raisins in a rising loaf of bread. An observer on any galaxy notes that all the galaxies are traveling away, with the most distant galaxies traveling the fastest.

The increase of galaxy speed with distance was first noted by astronomer Edwin Hubble in the 1920 who measured the distances of nearby galaxies from the brightness of the Cepheid variable stars he could seen in them. He measured the speeds (technically called the *radial velocities*) of the galaxies by measuring the wavelengths of absorption lines in their spectra. Due to the Doppler effect, the wavelengths of absorption lines are longer (shifted in toward the red end of the spectrum), the faster the galaxy is moving away from the observer. One of Hubble's first graphs, showing the increase of radial velocity with distance, is shown below.

Hubble's redshift-distance relation gives us the key to the third dimension. Since the distance of a galaxy is proportional to its distance, we can simply take a spectrum of it, measure the amount of the spectral lines are redshifted, and use that as an measure of distance. We plot the position of galaxies in three dimensions, two being the Right ascension and declination of the star,

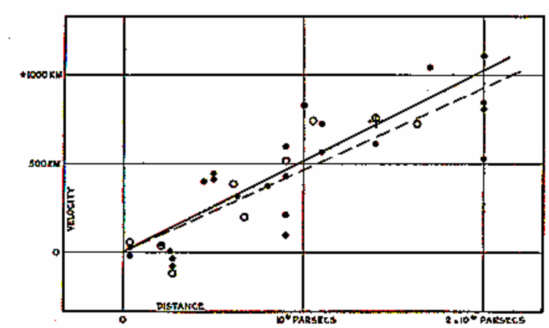


Figure 1
Radial Velocity vs. Distance

and the third being the redshift (or velocity, or distance), to create a three-dimensional map of the universe which, hopefully, will reveal the size and scope of its major structures.

Of course one needs to observe the spectra of a lot of galaxies in order to trace out the contours of the universe. This was a time-consuming process in the beginning; Hubble sometimes had to expose his photographic plates for several hours in order to get data on just one galaxy. But by the 1980's techniques of spectroscopy made it possible to obtain galaxy spectra in a matter of minutes, not hours, and several teams of astronomers began undertaking large map making surveys of the galaxies. One of the most important of these pioneering surveys was undertaken by John Huchra and Margaret Geller at the Harvard-Smithsonian Center for Astrophysics in Cambridge, MA. The CfA Redshift Survey (which provides much of the data for this exercise), surveyed all the brighter galaxies in a limited region of space, in the direction of the constellation Coma.

The maps produced by the CfA Redshift Survey and other groups revealed that the galaxies were not distributed at random, but rather were concentrated in large sheets and clumps, separated by vast expanses, or voids, in which few, if any, galaxies were found. One large sheet of galaxies, called the "Great Wall", seemed to span the entire survey volume.

Even with modern techniques, surveying thousands of galaxies takes a great deal of time, and the task is far from complete. Only a tiny fraction, about 1/100 of 1%, of the visible universe has been mapped so far. Describing the large scale structure of the universe on the basis of what we currently know may be a bit like describing our planet on the basis of a map of the state of Rhode Island. But some of the major conclusions are probably quite sound.

In the exercise that follows, you will conduct a survey of all the bright galaxies in a catalog covering the same region of the sky as the original CfA redshift survey. We've reduced the number of galaxies in our catalog, and made the operation of the instrument a bit simpler, but the fundamental process is the same as that used today to gauge the overall structure of the universe we live in.

Introduction to the Technique

Overall Strategy

The software for the *Large Scale Structure of the Universe* lab puts you in control of any one of three optical telescopes, each equipped with a TV camera (for seeing what you're pointed at) and an electronic spectrometer that can obtain the spectra of light collected by the telescope . Using this equipment, you can conduct a survey of a sample of galaxies in a restricted portion of the sky. You will obtain spectra for all the galaxies in that region, measure the wavelengths of prominent spectral absorption lines, and use the data to determine the redshift and radial velocities of each galaxy. From this, you will construct a map of the distribution of galaxies in the region. The map will show some of the major large-scale features of the universe, and you will be able to determine characteristic shape and size of these features by thoughtful examination and analysis.

The slice of sky we are surveying stretches 60 degrees in the east-west direction (from Right Ascension 12 H to 16 H) and 5 degrees in the north-south direction (from declination +27° to declination +32°). This region of the sky was chosen primarily for convenience: it is high in the sky in the northern hemisphere, and it is not obscured by gas and dust in our own galaxy.

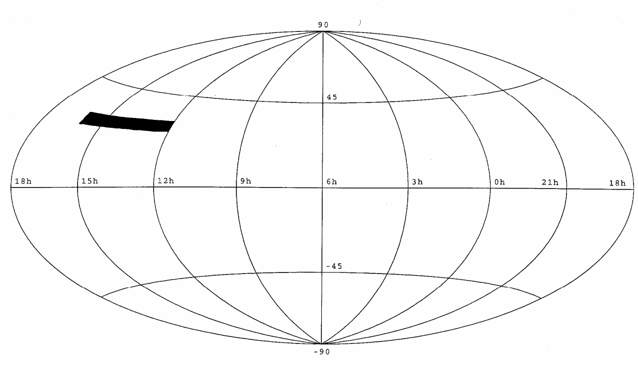


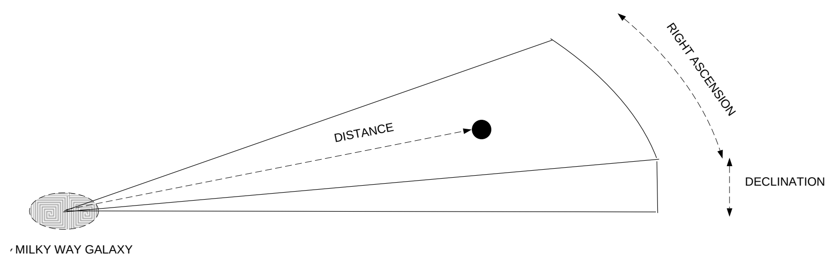
Figure 2
Portion of the Sky Used in this Survey

Moreover some of the richest nearby groupings of galaxies, in the direction of the constellation Coma, lie in this direction. A list of the target galaxies, with their celestial coordinates, is attached to the last pages of this manual as Table 2.

There are over 200 galaxies in our sample. For the purposes of this exercise, you can assume that this is all the galaxies that we can see through the telescope. In fact there are many more than this in the real sky, but we have omitted many to make the measurement task less tedious. This isn't that unrealistic, because even under the best conditions, astronomers' catalogs of galaxies never can include **all** the galaxies in a given volume of space. Faint galaxies, or ones which are spread out loosely in space may be hard to see and may not be counted. Still, our sample contains enough galaxies to show the large-scale features of the visible universe in this direction. It is your assignment to discover those features for yourselves.

Even 200 galaxies is a lot to investigate in a single class period. Your instructor may have you do the assignment in one of several ways. You may work in small groups, each group observing a 20 galaxies or so during the first part of the class. The groups can then pool their data together into one combined data set to produce a single map for your analysis. This group effort is the way most astronomers work—they collaborate with other astronomers to turn large unmanageable projects into smaller, manageable tasks. You may compile and analyze the data during several class periods. Or, you may be doing this lab as a term project or out-of-class exercise.

This write-up assumes you will be following strategy number 1, that is you'll be one of several groups working collaboratively to pool data. We'll assume you're going to obtain spectra of 20 galaxies which you will later combine with other groups to get redshifts of all 218 galaxies in our sample. Though we have provided work-sheets for only 20 galaxies in this write-up, you can still use this write-up as a guide even if you are measuring all 218 galaxies yourself.



The region you're going to be examining is shape like a thick piece of pie, where the thickness of the pie slice is the declination, and the length of the arc of crust represents the right ascension. The radius of the pie, the length of the slice, is the furthest distance included in the survey.

Technical Details

How does the equipment work? The telescope can be pointed to the desired direction either by pushing buttons (labeled **N,S,E,W**) or by typing in coordinates and telling the telescope to move to them. You have a list of all the target galaxies in the direction of Coma with their coordinates given, and you can point the telescope to a given galaxy by typing in its coordinates. The TV camera attached to the telescope lets you see the galaxy you are pointed at, and, using the buttons for fine control, you can steer the telescope so that the light from a galaxy is focused into the slit of the spectrometer. You can then turn on the spectrometer, which will begin to collect photons from the galaxy, and the screen will show the spectrum—a plot of the intensity of light collected versus wavelength. As more and more photons are collected, you should be able to see distinct spectral lines from the galaxy (the H and K lines of calcium), and you will measure their wavelength using the computer cursor. The wavelengths will longer than the wavelengths of the H and K labs measured from a non-moving object (397.0 and 393.3 nanometers), because the galaxy is moving away. The spectrometer also measures the apparent magnitude of the galaxy from the rate at which it receives photons from the galaxy, though you won't need to record that for this exercise. So for each galaxy you will have recorded the **wavelengths** of the H and K lines.

These are all the data you need. From them, you can calculate the **fractional redshif**t, **z** (the amount of wavelength shift divided by the wavelength you'd expect if the galaxy weren't moving), the **radial velocity,** v, of the galaxy from the Doppler-shift formula, and its **distance** from the Hubble redshift distance relation. To save time, however, we won't calculate distances for most galaxies. Since distance is proportional to redshift or velocity, we can plot z or v for each galaxy, which will give an equally good representation of the distribution of the galaxies in space.

You'll display your map as a two-dimensional "wedge diagram" (see figure 3 on the following page). It shows the slice of the universe you've surveyed as it would look from above. Distance is plotted out from the vertex of the wedge, and right ascension is measured counterclockwise from the right.

As you plot your data, along with that of your classmates, you'll be able to see the general shape of the clusters and voids begin to appear.

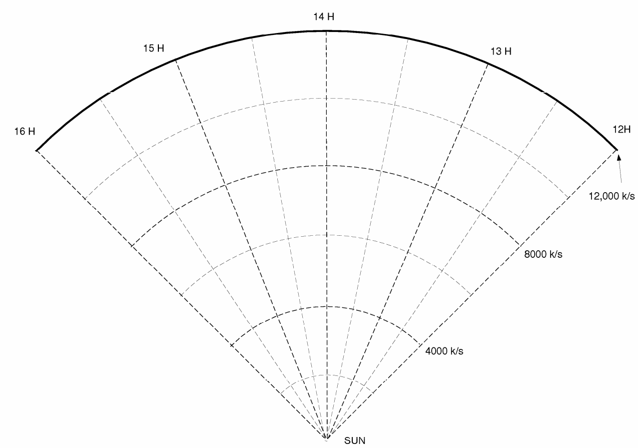


Figure 3
The Wedge Diagram

Taking Spectra With the CLEA Computer Program

First some definitions:

press Push the left mouse button down (unless another button is specified)

release Release the mouse button.

click Quickly press and release the mouse button

double click Quickly press and release the mouse button twice.

click and drag Press and hold the mouse button. Select a new location using the mouse, then release.

menu bar Strip across the top of screen; if you click and drag down a highlighted entry you can reveal a series of choices to make the program act as you wish.

scrollbar Strip at side of screen with a slider that can be dragged up and down to scroll a window through a series of entries.

Beginning Your Observations

Welcome to the observatory! The program you are going to use simulates the operation of a modern digitized telescope and spectrometer. Let's begin by obtaining the spectrum of a galaxy and measuring its redshift. You'll then be on your own as you and your classmates gather all the remaining data needed to map out your sample of the universe.

1. Open the Large Scale Structure **(LSS**) program by double clicking on the LSS icon on your computer screen. Click on **login** in the MENU BAR and type and enter your names and lab table as requested. Click **OK** when ready.

2 The only choices in the **MENU BAR** are to **run** or to **qui**t, click on **ru**n. It may take some time for the computer to set up the telescope. Be patient. In a minute the computer screen will show the control panel and view window you might see in the control room of a professional observatory. Notice the **dome status** is closed and **tracking status** is off.

3. To begin our evening's work, we first open the dome by clicking on the **dome status** button. The dome will open, and in a while you will begin to see objects in the view window.

The dome is open and the **view** we see is from the finder scope, The finder scope is mounted on the side of the main telescope and points in the same direction. It is used to locate the objects we want to measure, because the field of view is much larger than the view in the main instrument. It is displayed on-screen by a TV camera attached on the finder scope. (Note that it is not necessary for astronomers to view objects through an eyepiece.) Locate the **view** button on the control panel and note its status, i.e. finder scope. Also note the stars are drifting in the view window. This is due to the rotation of the earth and is very noticeable due to the high magnification of the finder telescope. It is even more noticeable in the main instrument which has even a higher magnification. In order to have the telescope keep an object centered over the spectrometer opening (slit) to collect data, we need to turn on the drive control motors on the telescope.

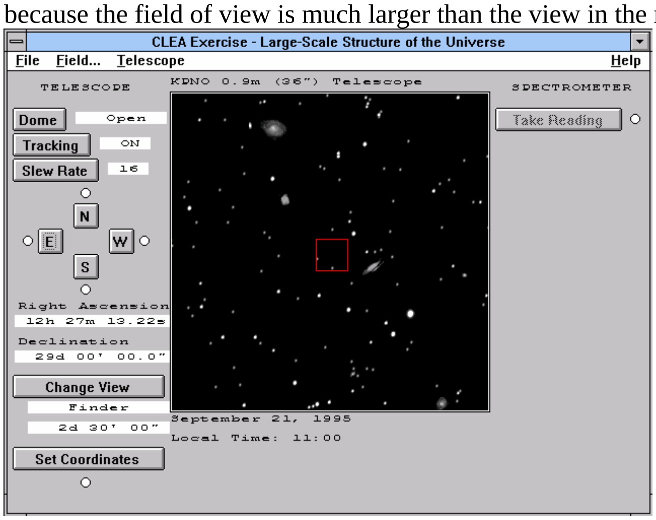


Figure 4
Telescope Screen

4. We do this by clicking on the **tracking** button.

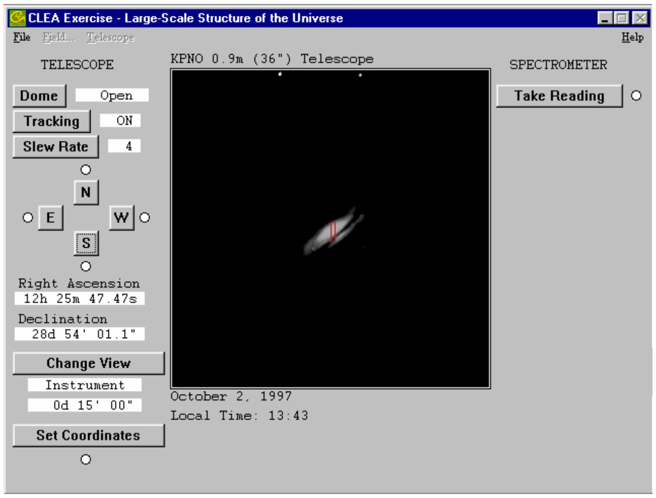
The telescope will now track in sync with the stars. Before we can collect data we will need to select a galaxy to measure. Note where the telescope is pointing by looking at the Right Ascension and Declination numbers displayed at the left of the view screen. Let's tell the telescope to point to one of our target galaxies. We'll do this by looking at the table of target galaxies attached to this write-up. Choose galaxy number 24 on the list, NGC4278, and note its coordinates. Then click on the on the **Set Coordinates** button at the lower left of the telescope control screen. Enter the coordinates of NGC 4278 and click on **OK** to tell the telescope to move. In a few seconds you will see the view screen showing the galaxy in the center. It is a small fuzzy blob of light, rather brighter at the center than at the edges. Let's look at it more closely.

Note that the view window has two magnifications.

Finder View: is the view from the small finder scope that gives a wide field of view (about 2 and a half degrees) and has a cross hairs and outline of the instrument field of view in its center.

Instrument View: is the view from the main telescope, more highly magnified (only about 15 arcminutes across). There are red lines in the center that show the position of the slit of the spectrograph. Any object positioned on the slits will send its light into the spectrograph for measurement.

5. So let's change to the higher magnification **Instrument View** by clicking on the **View** button. Then carefully position the slit directly over the center of galaxy NGC 4278 so as to get the maximum amount of light down the slit (this minimizes the time required to get a good spectrum. Center the galaxy by moving the telescope with the mouse and the **N, S, E or W** buttons. Place the arrow on the N button and press the left mouse button. Notice the red light comes on to indicate the telescope is moving in that direction.



As in real observatories, it takes a bit of practice to move the telescope to an object. You can adjust the speed or "slew rate" of the telescope by using the mouse to press the **slew rate** button. 1 is the slowest and 16 is the fastest; you will want to make fine adjustments using the slower speeds, and large moves using the faster speeds. If you have positioned the cursor accurately over the galaxy, click on the **take reading** button to the right of the view screen.

Figure 5
The Instrument View Screen

Tips and Hints for Using the Telescope

- Note that the field of view in the monitor of the telescope is flipped from what you see on a map. North is at the top, but east is to the left and West is on the right. This is because when we are looking at a map, we are looking at the outside of the globe, but when we look up at the sky, we are looking at the inside of the celestial sphere.
- Note that when you move the telescope to the east, the stars appear to move westward on the monitor screen. Think about why this is so.
- There are two ways to get a high signal-to-noise ratio for a faint galaxy. The first is to simply observe for a much longer time. The second is to use a larger telescope, which collects more light. The telescope program allows you to access two larger telescopes, as you can see if you put the telescope into the finder mode and choose Telescope form the menu choices. The telescope that comes by default is an 0.4m telescope (16in). A 0.9m and a 4m telescope are available, but on the menu these choices are light gray, which means that they are inactive for the present. Like all large professional telescopes, you must apply to use the telescopes. There is a choice in the telescope menu that allows you to apply for time on a larger telescope. You will not automatically get it, but if you do, you can use this option to cut down the time required to observe faint galaxies.
- If you are using one of larger telescopes, you will note that stars appear brighter in the monitor. That is because the larger telescopes collect more light, since they have larger mirrors.

A window should open, showing you the spectrometer display. The spectrometer breaks up the light coming in the slit into its component wavelengths and measures the number of photons (the intensity) coming in at each wavelength. If we tell the spectrometer to start counting, it will begin to collect light and display it on the graph of intensity versus wavelength that you see on the screen.

We are now ready to collect data from the object, and you can start the process by clicking on **Start/Resume Count** on the menu bar. This is what we expect to see: The spectrum of the galaxy will exhibit the characteristic H & K calcium lines which would normally appear at wavelengths 3968.847 Å and 3933.67 Å, respectively, if the galaxies were not moving. However, the H & K lines will be red shifted to longer wavelengths depending on how fast the galaxy is receding.

Photons are collected one by one. We must collect a sufficient number of photons to allow identification of the wavelength. Since an incoming photon could be of any wavelength, we need to integrate for some time before we can accurately measure the spectrum and draw conclusions. The more photons collected, the less the noise in the spectrum, making the absorption lines easier to pick out.

6. To check the progress of the spectrum, click the **stop/resume count** button. The computer will plot the spectrum with the available data. Clicking the **stop/resume count** button also places the cursor in the measurement mode. Using the mouse, place the arrow anywhere on the spectrum, press and hold the left mouse button. Notice the arrow changes to cross hair and wavelength data appears in the lower right area of the window. As you hold the left mouse button, move the mouse along the spectrum. You are able to measure the wavelength and intensity at the position of the mouse pointer.

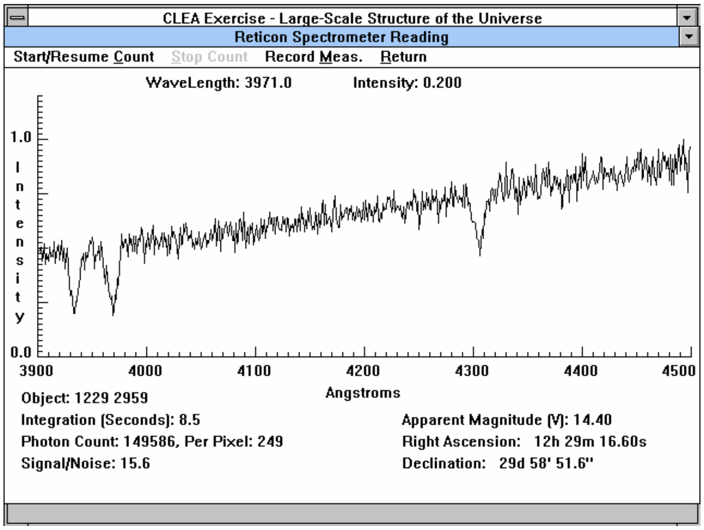


Figure 6
The Spectrometer Screen

Also notice other information that appears in the window:

Object: the name of the object being studied

Apparent magnitude: the visual magnitude of the object

Photon count: the number of photons collected so far

Integration (seconds): the number of seconds it took to collect data

Wavelength (angstroms): wavelength as read by the cursor in the measurement mode

Intensity: relative intensity of light from the galaxy at the position marked by the cursor in the measurement mode

Signal/Noise: a measure of the strength of the spectrum you have collected. In order to clearly measure the wavelengths of the calcium lines, you will need to obtain a signal to noise of about 15 or so. Judge for yourself. The higher the signal to noise, the “cleaner” and clearer the spectrum appears. You get higher signal to noise if you integrate longer; but you have a limited time, so don’t overexpose, or the spectrum will take too much of your precious observing time.

7. Click **stop/resume count** from the menu bar of the Spectrometer Reading Window. Continue to collect photons until a ***clear*** spectrum of the H & K lines of calcium is displayed. These lines are approximately 40 angstroms apart. They should stand out form the noise. If you don’t see them, continue to count photons. If you are not sure about the data, check with a lab instructor to help you interpret the data.

8. Measure the wavelength of the H and K lines by holding down the left mouse button and moving the cursor to point to the center of each calcium absorption line.

9. Record the object, S/N, apparent magnitude, and the measured wavelength of the H & K lines of calcium on the data sheet, Table 1 located at the end of this manual. The H & K lines measured should be red shifted from the laboratory values depending on the galaxy's radial velocity.

10. You will now want to use this data to calculate the velocity of this galaxy and to record it in the computer. Go on to the next step.

Note the following information:

The laboratory wavelength, λ_K of the K line of calcium is 3933.67 Å.

The laboratory wavelength, λ_H of the H line of calcium is 3968.85 Å.

1. You have now measured the wavelengths of the K and H lines in the spectrum of NGC 4278, and have entered these wavelengths into columns 6 and 7 of the data sheet, Table 1. You'll note that your measured wavelengths are longer than the "laboratory" wavelengths listed above, because the galaxy is moving away. You next want to calculate **absolute redshift**s, $\Delta\lambda_K$ and $\Delta\lambda_H$ for each line, where

(A) $\Delta\lambda_K = \lambda_{K\ measured} - \lambda_{K\ laboratory}$ and $\Delta\lambda_H = \lambda_{H\ measured} - \lambda_{H\ laboratory}$

and you can enter the results in columns 8 and 9 of your data table.

2. Next you calculate the **fractional redshifts**, z_H and z_K which are what astronomers use when they use the term redshift in general. The fractional redshifts are just the absolute redshifts divided by the original laboratory wavelengths, or, in algebraic notation:

(B) $z_K = \Delta\lambda_K / \lambda_{K\ laboratory}$ and $z_H = \Delta\lambda_H / \lambda_{H\ laboratory}$

and you can enter these results in columns 10 and 11 of your data table.

3. You can calculate he radial velocity of the galaxy of each redshift using the Doppler shift formula:

(C) $v_K = c\, z_K$ and $v_H = c\, z_H$

and you can enter these results in columns 12 and 13 of your data table.

4. Finally you can average the two velocities to get a more reliable value for the redshift.

(D) $v_{ave} = (v_H + v_K) / 2$

and you enter this value in column 14.

You now have measured and analyzed the data for one galaxy. The numbers you will want to plot in your wedge diagram, eventually, will be the Right ascension and the velocity of each galaxy. Since the slice of the universe is thin in Declination, we will assume that all the galaxies we measure lie roughly in the same plane.

Recording Data On the Computer

You can now record the data in the computer so that it can be printed out and/or plotted later. Click on **RECORD MEAS.** in the menu bar of the spectrometer window. A form will open up. You can enter the measured wavelengths of the H and K lines, $\lambda_{H\ measured}$ and $\lambda_{K\ measured}$ from columns 6 and 7 of your datasheet (Table 1), and the calculated velocities, v_H and v_K from columns 12 and 13.

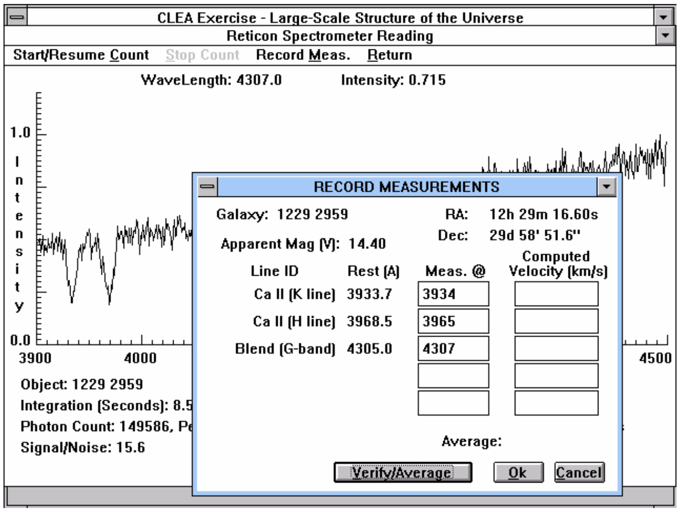


Figure 7
Recording the Data on the Computer

The recording window will check your values of the velocities to make sure they agree with your wavelength measurements and will compute the average velocity (so you can check your entry in column 14), if you push the **Verify/Average** button. Do this to make sure you've entered your data correctly. When you are satisfied with your results, press **OK** to record the data in the computer.

You can now take data on other galaxies by returning to the telescope control window. Just click on **Return** on the spectrometer menu bar. If you haven't already recorded your data in the computer for the galaxy you're looking at, the computer will remind you. You can either go back and record the data or just continue, but if you continue, make sure you've at least got a written record of your measurements, or you'll have to come back and take a spectrum all over again. (Also note that data you've recorded can be reviewed and edited from the telescope control window before printing or plotting it out, so don't worry if you've typed something in wrong. See the appendix on **Reviewing and Editing Data** (page 28) for further information.)

Collecting Data for a Wedge Plot

You are now ready to carry out your redshift survey. Your instructor will assign your table a set of galaxies to observe from the targets list attached to this write-up.
Your next step is to:

1. Enter the names and positions of your target galaxies into your data sheet for easy reference when observing.

2. Move the telescope to each galaxy in turn. (Note that you must be in the wide-field view mode of your telescope in order to use the **set coordinates** button. Obtain a spectrum of each, with enough photons to attain a reason-able Signal/Noise ratio so that the wavelengths of H and K can be measured accurately. (10 to 15 should do). Measure and record the wavelengths of the H and K lines for each galaxy.

Before you begin this, note that the fainter galaxies will require more time to attain a proper exposure. You can speed up the time to take spectra by using a larger telescope. A 1 meter and a 4 meter aperture telescope are available for your use, but as there are more astronomers wanting to use these larger telescopes than there is time available, you will have to *apply* for time using the **request time** choice under the **telescopes** menu entry. If you are granted time on a telescope, you may access it any time you wish. If you are denied time, you can apply again in a specified number of minutes. Your instructor may also permit you to borrow unused time on a telescope at another table, if one is available.

It is up to you to choose the best strategy for obtaining all your data in the shortest possible time. Larger telescopes will reduce observing time for fainter galaxies. Moving between objects that are close together takes less time than moving large distances on the sky, so the order in which you observe your sample is important, too.

3. Calculate the figures necessary to fill in the other columns of the data sheet, the absolute and fractional red-shifts, the average redshift, and the radial velocity of each galaxy.

4. Record each set of measurements in the computer as you make them.

5. When you have collected and recorded all the assigned measurements, you will want to print them out for your reference. You may also want to store them in a file that can be pooled (usually over a local network, if you have one), so that the results of others in the class can be pooled with yours. Here's how to print and save the data.

In the telescope control window, click and drag the **File** menu item down to **Dat**a. You are then given a set of choices.

- You can **Review** your data entry, and change any entries that are incorrect by pushing the **Edit** button (See the appendix on **Reviewing and Editing Data** (page 28) for additional information.)

- When you are satisfied with your data entry, choose **Print** to print the data to your local printer.

- If your class is using the computer to plot a wedge diagram (either individually or as a group over the local network), your next step is to choose **Save Results to Plot**. The computer will tell you that all your data has been saved to a file. If you have not entered all the velocities, or have left out some other data, however, it will tell you something is missing. You can then go back to the **Review** option and touch up your data table. Note that once you save data on a particular galaxy to the plot file, data on that galaxy cannot be saved to the plot file again. You can however, add data on other galaxies to your list and save that to the plot file. The computer automatically keeps track of what galaxies have been recorded already, so there's no need to worry about this.

6. When you have measured, calculated, saved , and printed the velocities for each galaxy in your sample, you are ready to pool your data with others in the class, and plot up a wedge diagram.

Plotting the Pooled Data On A Wedge Plot

There are numerous ways in which you can pool your data with others in the class and plot it on a wedge diagram. We describe one way to pool your data, and two ways to plot it, in the following sections.

Pooling your data

Here are two ways of pooling your data:

1. Each group in the class can photocopy their data table and give copies to all the other tables. Each table then winds up with all the data sheets for the class.

2. Each group in the class can post a copy of their data table at the front of the room. Members of the class can then write down the radial velocities in the blank column labeled "velocity" in the complete targets list attached to this write-up. (Table 2)

3. Your group can share data over the network. The **Save results to plot option** (see previous section) produces a file on the network that can be printed out or plotted by an entire class.

Your instructor may suggest other ways.

Plotting your data on a wedge diagram

Because our slice of the universe is relatively thin in declination, we can assume for the moment that all the galaxies lie at about the same declination. To see the large-scale structure we need only plot two dimensions, Right Ascension and velocity (which is proportional to distance according to the Hubble redshift-distance relation) Here are two ways of plotting your data:

1. By hand: We have attached a sheet of pie-shaped graph paper to this write-up. Radial lines on the graph correspond to Right Ascension, and circular arcs correspond to radial velocity. For each of the 218 galaxies you and your class have measured, you can put a dot on the graph in the corresponding position. For instance, a galaxy with a Right Ascension of 13 h 15 m 0s, and a radial velocity of 4000 k/s, would appear at the position in the graph shown below.

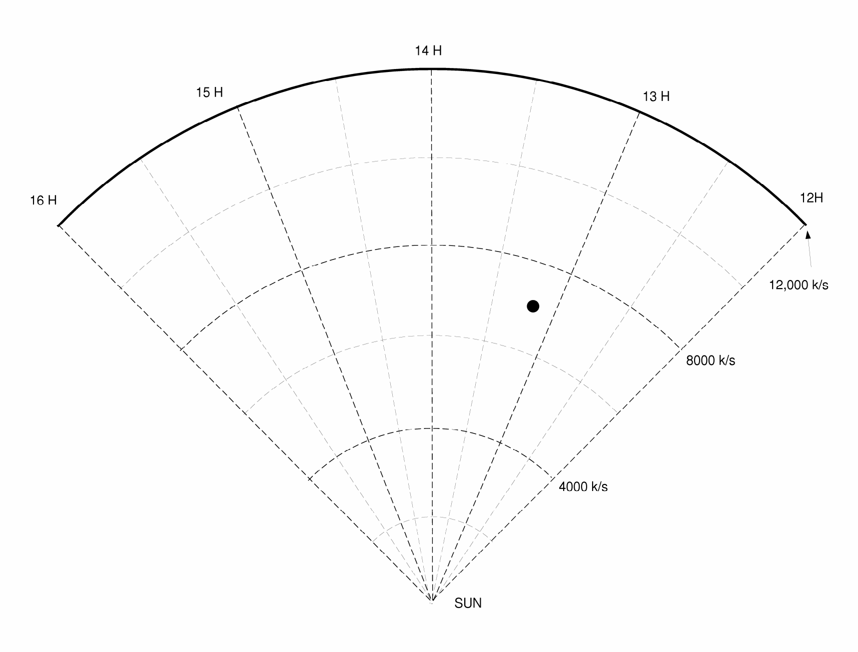


Figure 8
The Wedge Diagram

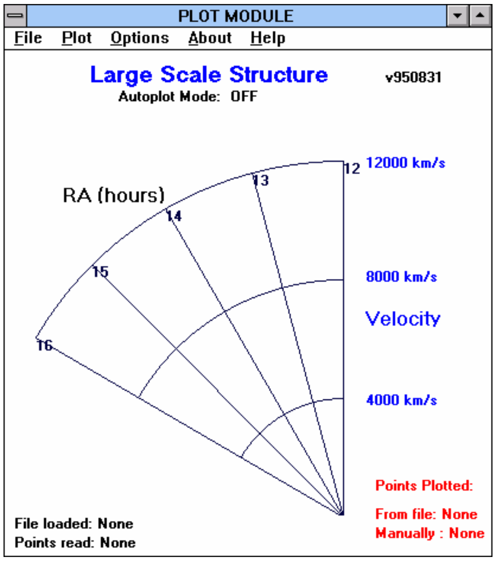
As you enter the dots for every galaxy in your survey the shape of the large-scale distribution of matter should gradually appear.

2. Using the wedge-plot utility program: The LSS software has the capability of producing a wedge-plot on the screen of your computer, and the plot can be printed, after it is displayed, on a laser printer attached to your computer.

To do this, you simply run the plotting utility program. The program, called *Wedge Plo*t, can be run from the menu of the ***Large Scale Structure*** lab. When it is run, a window will open (see Figure 9). To read in your data file, choose the **File** menu bar and open your data file. (The instructor will tell you its name, such as “plot.txt”.) It is usually the name that appears by default when you open the **File Open** menu. When the file is open, you can display the file on a wedge plot, by pulling down the **Plot** menu and choosing the **plot data file** option. You can print the file, should you choose, by choosing print file located under **File** in the menu .

The **Options** pull-down menu lets you choose what color , the size, and the style (filled or open circles) that you want to assign to the plotted points, and lets you superimpose coordinate grids on the plot. You can also add points to the plot manually, by choosing **manual data entry** under the **Plot** menu.

When you are satisfied with the appearance of the plot, you can print it out on the printer by choosing **Print the Plot** under the Plot pull-down menu. You will now want to examine the plot and see what it reveals about the large-scale structure of the universe.



Note that if your class is not pooling the data over a network, the wedge plot program will display the data from an individual's table if the data has been saved to a plot file.

Figure 9
The Wedge Plotting Program

Interpreting the Wedge Plot

Carefully examine the wedge diagram you and your classmates have produced. Though you have only plotted 200 or so representative galaxies, the features you see are distinctive. Based on your plot, answer the questions below.

1. Does matter in the universe appear to be randomly distributed on the large scale, or are there clumps and voids?

2. The most densely populated region of the diagram (which appears like the stick figure of a human), is the core of the Coma Cluster of galaxies. What are the approximate Right Ascension and velocity coordinates of this feature?

3. You can use Hubble's redshift-distance relation to determine the distances of objects in the chart.

v = H D

where H is the Hubble constant which tells you how fast an galaxy at a given distance is receding due to the expansion of the universe. The value of **H** is not well known, and there is a great deal of dispute about it, but a value of 75 kilometers/sec/megaparsec is a reasonable figure. **(1 megaparsec = 10^6 parsecs**).

Using this value of H, calculate the distance to the Coma Cluster.

4. Using the redshift-distance relation, how far is the farthest galaxy included in this study? How much smaller is this distance than the limit of the observable universe, which is about 4.6 x 10 9 parsecs?

5. Discuss the problem of completeness of the sample, which is based on a catalog of galaxies identified on photographs. What sorts of objects might be missing from our survey? How could we improve the complete-ness?

6. Beyond the Coma cluster there is a loose band of galaxies stretching from east to west across the entire survey volume. It is called the “Great Wall”.

a. Using the Hubble redshift-distance relation, calculate the distance to the Great Wall.

b. One can use simple trigonometry to estimate the length of the Great Wall. If D is the distance of the Great Wall, and Θ is the angle it spans in the skies (in degrees), then

Length of the great wall = $2\pi D (\Theta /360)$

Use this formula to estimate the length of the Great Wall (which is just a lower limit, since it may extend beyond the boundaries of our survey.) Give your answer in megaparsecs and light years (3.26 1y = 1 parsec).

c. What other observations do astronomers need to make to confirm that the Great Wall is indeed a wall and not just a line or filament of galaxies?

7. Attach your wedge plot to this write-up when you turn it in.

Concluding Remarks

Although it represents only a minuscule sample of the universe, astronomers believe it is typical of the large-scale structure that pervades the universe. To confirm this, they have extended the surveys to other regions of the sky and outward to include fainter and more distant galaxies. Automated telescopes, capable of taking scores of spectra at one time are being developed. As more and more of the universe is mapped, the same types of clusters and voids appear throughout. One of the greatest puzzles of modern cosmology is to explain how such large structures could form from the nearly featureless soup of material that existed at the time of the Big Bang.

Useful References

Cornell, James, ed., *Bubbles, Voids, and Bumps in Tim*e, Cambridge University Press, Cambridge, 1988.

Chaikin, Andrew, “Great Wall of the Cosmos”, *Omn*i, August, 1991, p. 35

Geller, Margaret J., “Mapping the Universe”, *Mercur*y, May/June, 1990. p 66.

Schramm, D., “The Origin of Cosmic Structure,” *Sky and Telescop*e, Aug 1991, p. 140

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
1	1202+3127	12	2	10.2	31		20		
2	NGC 4080	12	2	18.5	27	16	15		
3	NGC 4104	12	4	6	28	27	10		
4	NGC 4131	12	6	12	29	35	0		
5	NGC 4132	12	6	30	29	31	0		
6	NGC 4134	12	6	36	29	27	0		
7	1206+3151	12	6	36	31	51	0		
8	NGC 4136	12	6	48	30	12	0		
9	NGC 4150	12	8	0	30	41	0		
10	NGC 4173	12	9	48	29	29	0		
11	NGC 4174	12	9	54	29	25	0		
12	NGC 4175	12	9	59.1	29	26	48		
13	NGC 4185	12	10	48	28	47	0		
14	NGC 4196	12	11	54	28	42	0		
15	NGC 4211A	12	13	4.2	28	27	18		
16	1214+2900	12	14	12	29	0	27		
17	NGC 4245	12	15	6	29	53	0		
18	NGC 4251	12	15	36	28	27	0		
19	NGC 4253	12	15	55.6	30	5	26		
20	IC 777	12	16	54	28	35	0		
21	NGC 4274	12	17	18	29	53	0		
22	NGC 4272	12	17	18	30	37	0		
23	NGC 4275	12	17	24	27	54	0		
24	NGC 4278	12	17	36.2	29	33	31		
25	NGC 4283	12	17	49.8	29	35	12		
26	1217+3127	12	17	54	31	27	0		
27	NGC 4286	12	18	12	29	38	0		
28	NGC 4308	12	19	24	30	20	0		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
29	NGC 4310	12	19	54	29	29	0		
30	NGC 4314	12	20	0	30	10	0		
31	NGC 4359	12	21	42	31	48	0		
32	NGC 4375	12	22	30.6	28	50	6		
33	NGC 4393	12	23	18	27	50	0		
34	NGC 4414	12	24	0	31	30	0		
35	IC 3376	12	25	18	27	16	0		
36	NGC 4448	12	25	48	28	54	0		
37	IC 3407	12	26	30	28	4	0		
38	NGC 4475	12	27	18	27	32	0		
39	NGC 4495	12	28	54	29	25	0		
40	1229+2959	12	29	18	29	59	0		
41	NGC 4514	12	30	6	30	0	0		
42	NGC 4525	12	31	18	30	34	0		
43	NGC 4556	12	33	18	27	11	0		
44	NGC 4559	12	33	30	28	14	0		
45	NGC 4585	12	35	42	29	13	0		
46	IC 3651	12	38	18	27	0	0		
47	1240+2800	12	40	36	28	0	0		
48	1242+2845	12	42	11.7	28	44	35		
49	NGC 4670	12	42	49.9	27	23	56		
50	NGC 4673	12	43	7.6	27	20	3		
51	IC 821	12	45	0	30	4	0		
52	1245+2715	12	45	15.6	27	15	12		
53	NGC 4692	12	45	28.8	27	29	48		
54	1250+2839	12	50	24	28	39	0		
55	NGC 4789	12	51	54.8	27	20	18		
56	NGC 4793	12	52	16	29	12	30		
57	NGC 4798	12	52	36	27	41	0		
58	NGC 4807	12	53	6	27	47	0		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
59	NGC 4816	12	53	48	28	1	0		
60	NGC 4819	12	54	0	27	15	0		
61	NGC 4827	12	54	18	27	27	0		
62	1254+3059B	12	54	36	30	59	0		
63	NGC 4839	12	54	59.4	27	46	0		
64	1255+2749	12	55	0	27	49	0		
65	NGC 4841A	12	55	7.2	28	44	48		
66	NGC 4841B	12	55	9	28	45	6		
67	NGC 4848	12	55	42	28	31	0		
68	NGC 4853	12	56	10.3	27	52	0		
69	NGC 4860	12	56	39.6	28	23	36		
70	NGC 4865	12	56	55	28	21	12		
71	NGC 4872	12	57	10	28	13	9		
72	NGC 4874	12	57	10.8	28	13	48		
73	NGC 4892	12	57	36	27	10	0		
74	NGC 4889	12	57	43.5	28	14	46		
75	NGC 4895	12	57	52.8	28	28	12		
76	IC 842	12	58	12	29	17	0		
77	NGC 4907	12	58	24	28	25	0		
78	NGC 4911	12	58	30	28	3	0		
79	NGC 4921	12	59	0	28	9	0		
80	NGC 4923	12	59	7.2	28	6	54		
81	NGC 4926	12	59	29.4	27	53	36		
82	NGC 4929	13	0	20	28	18	48		
83	NGC 4931	13	0	36.6	28	18	2		
84	NGC 4944	13	1	25.9	28	27	13		
85	NGC 4952	13	2	36	29	24	0		
86	NGC 4957	13	2	48.6	27	50	12		
87	NGC 4961	13	3	24	28	0	0		
88	NGC 4966	13	3	54	29	20	0		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
89	NGC 4983	13	6	0	28	35	0		
90	1306+2827	13	6	30	28	27	0		
91	NGC 5000	13	7	24	29	10	0		
92	NGC 5004	13	8	42	29	54	0		
93	1309+3146	13	9	18	31	46	0		
94	NGC 5032	13	11	0	28	4	0		
95	NGC 5041	13	12	12	30	58	0		
96	NGC 5052	13	13	12	29	55	0		
97	NGC 5056	13	13	48	31	12	0		
98	NGC 5057	13	14	6	31	17	0		
99	NGC 5065	13	15	12	31	20	0		
100	NGC 5074	13	16	6	31	44	0		
101	NGC 5081	13	16	48	28	46	0		
102	NGC 5089	13	17	18	30	31	0		
103	1318+3147	13	18	0	31	47	0		
104	1319+3137	13	19	18	31	37	0		
105	1319+3130	13	19	24	31	30	0		
106	NGC 5116	13	20	36	27	15	0		
107	NGC 5117	13	20	36	28	35	0		
108	IC 4234	13	20	42	27	23	0		
109	NGC 5127	13	21	24	31	50	0		
110	NGC 5131	13	21	37.4	31	14	53		
111	NGC 5187	13	27	29.8	31	23	17		
112	1327+3135	13	27	58.4	31	35	27		
113	1328+3153	13	28	7.9	31	52	43		
114	NGC 5251	13	35	5.2	27	40	25		
115	1337+2801	13	37	25.1	28	1	47		
116	NGC 5263	13	37	36.5	28	39	10		
117	NGC 5280	13	40	36	30	7	0		
118	1340+3036	13	40	52	30	35	19		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
119	NGC 5282	13	41	6	30	20	0		
120	1345+3035	13	45	0	30	35	0		
121	1348+2824	13	48	12	28	24	0		
122	1348+2937	13	48	12	29	37	0		
123	NGC 5375	13	54	30	29	25	0		
124	1355+2902	13	55	4	29	2	23		
125	IC 4355	13	55	48	28	40	0		
126	1357+2819	13	57	23.6	28	18	13		
127	1358+3019	13	58	30	30	19	0		
128	1358+2948	13	58	42	29	48	0		
129	1358+2946	13	58	48	29	46	0		
130	1400+2816	14	0	48.1	28	16	17		
131	1402+2809	14	2	18	28	9	0		
132	1405+3006	14	5	42	30	6	49		
133	IC 4384	14	9	36	27	21	0		
134	NGC 5512	14	10	24	31	5	0		
135	1411+2714	14	11	1	27	14	30		
136	1411+2940	14	11	30	29	40	0		
137	IC 4395A	14	15	6.1	27	5	15		
138	IC 4403	14	16	6	31	53	0		
139	1418+2705	14	18	18	27	5	0		
140	IC 4408	14	19	0	30	13	0		
141	IC 4409	14	19	18	31	49	0		
142	IC 4422	14	23	42	30	42	0		
143	IC 4425	14	24	30	27	25	0		
144	1424+3144	14	24	48.9	31	44	20		
145	IC 1012	14	25	0.5	31	10	17		
146	1426+2729	14	26	18	27	29	0		
147	NGC 5635	14	26	18	27	38	0		
148	IC 4442	14	26	34.1	29	11	16		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
149	NGC 5639A	14	26	42	30	38	7		
150	NGC 5642	14	27	0	30	15	0		
151	NGC 5641	14	27	5.4	29	2	36		
152	IC 4447	14	27	6	31	3	0		
153	1427+2745	14	27	59.1	27	45	0		
154	NGC 5653	14	28	0	31	26	17		
155	NGC 5657	14	28	30	29	24	0		
156	1428+2727	14	28	56.3	27	27	30		
157	IC 4450	14	29	54	28	46	0		
158	IC 4452	14	30	12	27	39	0		
159	NGC 5672	14	30	30	31	53	0		
160	1431+2816	14	31	29.8	28	16	22		
161	1431+2810	14	31	54	28	10	0		
162	1432+3146	14	32	12	31	46	0		
163	IC 4459	14	32	18	31	11	0		
164	IC 4460	14	32	24	30	30	0		
165	NGC 5685	14	34	0	30	7	0		
166	NGC 5709	14	36	36	30	39	0		
167	1436+3110	14	36	48	31	10	0		
168	1437+3143	14	37	54	31	43	0		
169	1438+3135	14	38	24	31	35	0		
170	1439+3151	14	39	18	31	51	0		
171	NGC 5735	14	40	12	28	56	0		
172	IC 4497	14	42	6	28	45	0		
173	1443+3038	14	43	18	30	37	54		
174	1447+2759A	14	47	6	27	59	0		
175	1447+2759	14	47	17.8	27	59	12		
176	IC 4514	14	48	42	27	46	0		
177	NGC 5771	14	50	0	30	3	0		
178	NGC 5773	14	50	18	30	0	0		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
179	1452+3025A	14	52	0	30	25	0		
180	NGC 5780	14	52	12	29	9	0		
181	NGC 5789	14	54	24	30	25	0		
182	NGC 5798	14	55	30	30	10	0		
183	1457+2719	14	57	24	27	19	0		
184	IC 4533	15	2	22.1	27	59	13		
185	1502+2711	15	2	30	27	11	0		
186	1503+3121	15	3	32.6	31	21	20		
187	1515+3052	15	15	57.1	30	52	13		
188	1517+3133	15	17	48	31	33	0		
189	1519+2844	15	19	12	28	44	0		
190	NGC 5924	15	19	54	31	24	0		
191	1520+2957	15	20	41	29	56	53		
192	IC 4546	15	24	54	29	1	0		
193	1527+3039	15	27	37.9	30	39	23		
194	1528+2716	15	28	12	27	16	0		
195	NGC 5958	15	32	42	28	50	0		
196	1533+2730	15	33	6	27	30	0		
197	NGC 5961	15	33	12	31	1	0		
198	1533+3058	15	33	15.4	30	58	0		
199	1534+3050	15	34	17.7	30	50	47		
200	NGC 5974	15	37	0	31	55	0		
201	IC 4568	15	38	0	28	19	0		
202	1538+2831A	15	38	24	28	31	0		
203	IC 4569	15	38	42	28	28	0		
204	1539+2809	15	39	18	28	9	0		
205	IC 4570	15	39	18.1	28	23	20		
206	IC 4572	15	39	48	28	18	0		
207	IC 4580	15	41	6	28	31	0		
208	1541+2835	15	41	42	28	35	0		

Galaxy #	Name	RA H	M	S	Dec Deg	‘	“	Mag	Radial Velocity
209	IC 4581	15	41	54	28	26	0		
210	IC 4582	15	43	36	28	15	0		
211	1544+3025	15	44	18	30	25	0		
212	1544+3110	15	44	44.6	31	9	53		
213	NGC 6001	15	45	42	28	48	0		
214	1546+2746	15	46	54	27	46	0		
215	1548+2847	15	48	30	28	47	0		
216	1552+3018	15	52	6	30	18	0		
217	NGC 6016	15	53	54	27	7	0		
218	1555+3011	15	55	27.3	30	11	57		

Appendix I

Reviewing and Editing Data

Once you have recorded the wavelengths of the H and K lines (and, optionally, the G lin**e),** and the velocity of the galaxy, your information is stored in the computer. You may want to review or change entries for any of the galaxies you have measured. You can do this, from the Telescope control window, by clicking and dragging the **File** choice on the menu bar down to **Dat**a, and then choosing **Revie**w. A window will open showing the data you've recorded so far. The columns list the name of the object, its apparent magnitude, and its right ascension and declination—these items are automatically entered when you saved your data. Also listed is the velocity for the galaxy that you entered. Three final columns contain asterisks to indicate (1) whether you've entered the measured wavelengths for at least two spectral lines; (2) whether you've entered a reasonable value for the velocity of the galaxy; and (3) whether you've stored the data for this star in a file for plotting up a wedge plot. This last asterisk, if present, tells you that you can't store data for this particular star in the plot file again. (That's to prevent you from storing two different values for the same object in the group plot file).

If you want to delete a record for a particular galaxy altogether, just click on it; the entry will be highlighted and then, if you click on the **Delete** button at the bottom of the review window, the entry will be deleted.

Usually, however, you won't want to delete but rather to edit. If you see an incorrect value for the velocity, or if you want to revise any of the wavelength measurements you've recorded, just click on the **Edit** button, and you'll open up a window that will let you change the data.

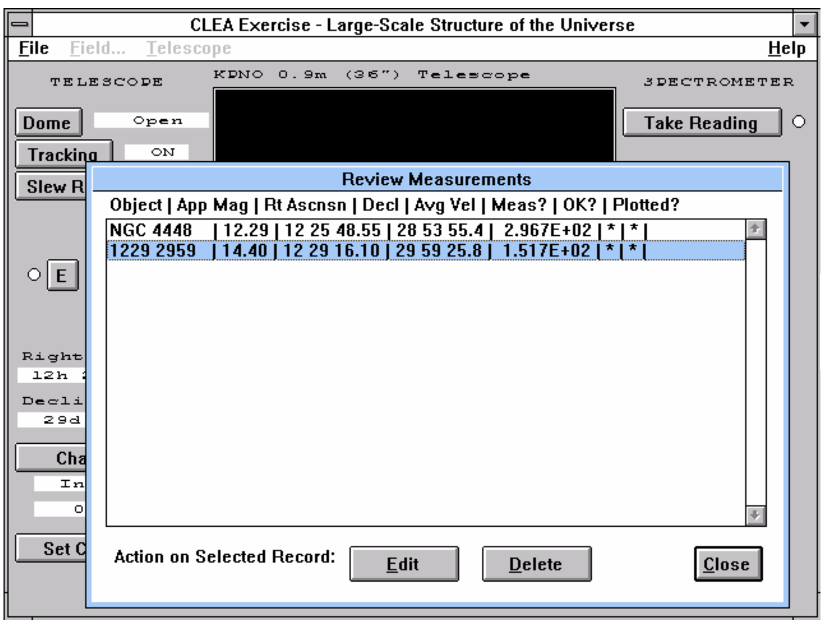
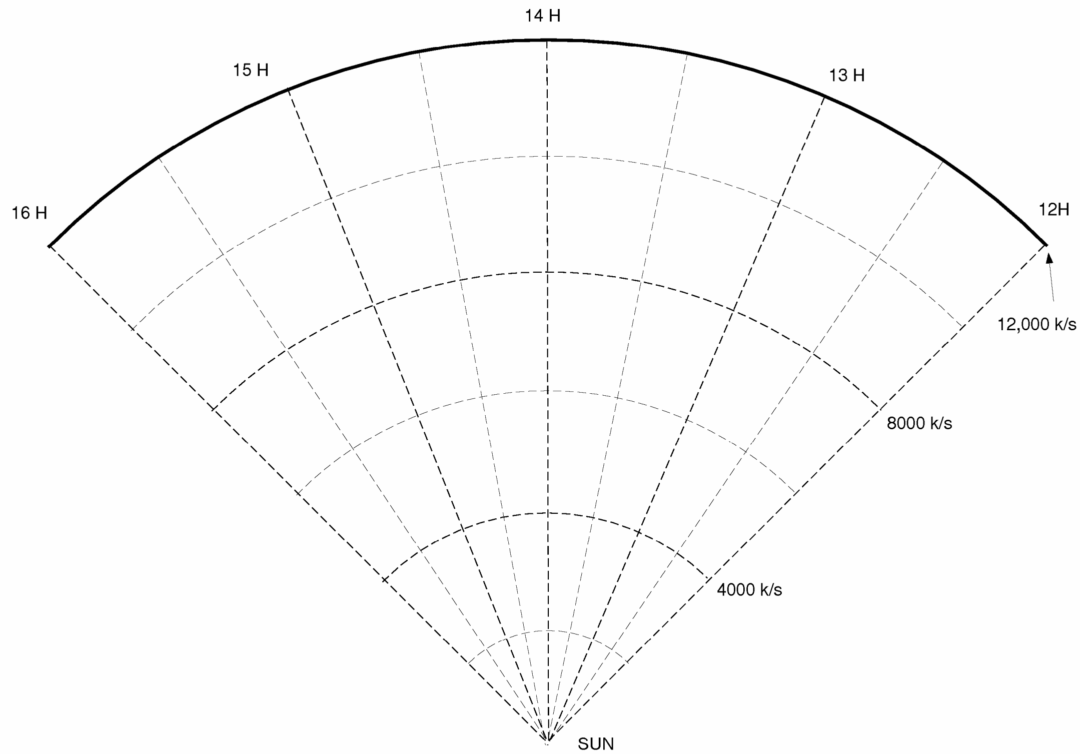


Figure 10
The Review Window


14 H
15 H
13 H
16 H
12H
12,000 k/s
8000 k/s
4000 k/s
SUN

Name	**RA**	**Dec**	**S/N**	**mag**	λ_K **meas.**	λ_H **μεασ.**	$\Delta\lambda_K$	$\Delta\lambda_H$	z_K	z_H	z_{avg}	V_K	V_H	V_{avg}
NGC 4278	**12h 17m 36.2s**	**29° 33’ 31”**												