UNIVERSITY OF WISCONSIN - MADISON

Department of Astronomy

Astronomy 113

Laboratory Manual

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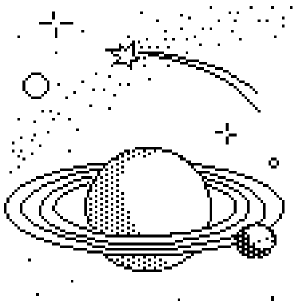
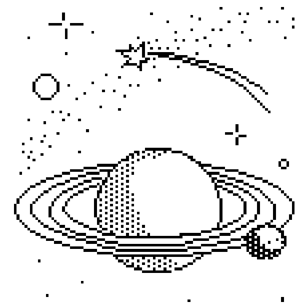


ASTRONOMY 113

Laboratory



Introduction

Astronomy is an observational science. Astronomers cannot create a star in the lab and study it, walk around it, tweak it, dissect it, or explode it. Astronomers can only observe the sky as it is, and from their observations deduce models of the Universe and its contents. Remember this as the Universe is laid out before you in Astronomy 103 - the story begins with only points of light in the sky. From this perspective, our understanding of the Universe is truly one of the greatest intellectual achievements of mankind.

The exploration of the Universe is also a lot of fun, an experience that is largely missed sitting in a lecture hall or doing homeworks. The primary goal of these labs is to bring you closer to the reality of astronomical research, and in so doing to the experience of science. Of course this would best be done at night with real telescopes, but the vagaries of Madison weather make this impractical with large classes. Fortunately, computer simulation software does remarkably well in recreating the experience of working at telescopes, including some of the largest in the world. (And we will get you to a real telescope at Washburn Observatory, promise!)

We emphasize that these labs are designed to provide you with opportunities to explore and discover. Always remember that this is **your** exploration - different students may follow different paths, all of which can lead to interesting results.

We are very anxious to have your feedback, opinions, and suggestions. Send us e-mail, stop by our offices, put notes in our mailboxes, whatever. Any part of the course is open for improvement, even during the course of the semester. Your ideas will make a difference!

The next three pages have important information on administration of the labs - please read them carefully. Then enjoy the Universe!

Laboratory development funded by the University of Wisconsin - Madison College of Letters & Science *Excellence in Undergraduate Education* program, the National Science Foundation, and the Wisconsin Space Grant Consortium.

LOCATION AND SCHEDULE

- Lab sessions will be held in 3521 Sterling Hall (3rd floor). This computer laboratory has 12 Macintosh iMac computers. Students will work in pairs at each computer.

- **Labs will start during the week beginning September 6.** Lab sessions are 2 hours long, with each lab taking 2 sessions.

- The times of lab sessions can be found in the Timetable or on the course website (http://www.astro.wisc.edu/~townsend/static.php?ref=astro-113-F10). Presumably you have registered for one of these times.

- Office hours are 1:00pm - 3:00pm on Friday in 3521 Sterling, the computer lab. The computers are open for your use then, and possibly at other times to be announced. You also may use the computers during another lab session if they are available. Additional office hours for answering questions, etc. are by appointment.

- The program of labs is given in the course syllabus. Our intent is that you will have sufficient time to complete the labs during the lab sessions; you should not have to do lab work at home.

WHAT YOU NEED TO BRING TO THE LAB

- This lab manual.

- A lab book, specifically Science Notebook 77-610 (Roaring Springs) available at the University Book Store, main floor. Each page is lined on one side and has graph paper on the other. Your name and laboratory session time should be prominently displayed on the front cover.

- Completed pre-lab assignment. If you don't have it, you will have to leave and return to another lab session.

- Pencils or erasable pen. Unless you never make mistakes (!), being able to correct errors neatly can save you a lot of rewriting.

- Scientific calculator. You don't need the state-of-the-art, one-million-function, graphical display model. But you will have to occasionally compute a tangent or a logarithm, and having a function to compute a standard deviation will be useful.

- A straight edge. A clear plastic ruler is best.

- A textbook will sometimes be useful, but is not required. Textbooks are available in the lab.

LAB BOOK

Think of your lab book as a journal of your explorations. Throughout the semester you will be making sketches, recording tables of data, creating graphs, answering questions, and writing short essays in the lab manuals. While there are certain entries in your lab book that are required for successful completion of the lab, you shouldn't feel restricted to these. Feel free to add thoughts, wonderings, musing, notes, etc. as you wish. Write everything in your lab book as you work - don't write on loose pieces of paper.

At the same time, your lab book is the means by which you communicate your results to others in the future, most importantly yourself. Research scientists must often refer to their lab books to both recover results and remind themselves of details of a procedure. You too will have to refer to your lab books, although for the somewhat less inspiring reason of answering questions on open-lab-book quizzes.

Therefore your lab book needs to be neat and reasonably well organized. **This can be achieved without rewriting if you take care as you go along.** This takes patience and some discipline, but it will save you time in the end. Some hints include:

- Organize your workspace. If you reserve space on the counter for your lab book and manual, and put your other things elsewhere, you will find it much easier to work.

- Use titles or headings to organize your lab book. Section numbers and titles from your lab manual are a natural for this.

- Write neatly, including when entering measurements into data tables.

- When the lab manual tells you to tape a table or graph into your lab book, do it right away.

- Above all else, **take your time.**

Below is a sample first page for a lab. This format isn't required, but it's one possibility.

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<u>Lab 1: Celestial Rhythms - An Introduction to the Sky</u>

January 23, 2000

Lab partner: Dylan Sierra   Computer #4

<u>Section 1: Sunset</u>

Learned how to move around in the Voyager sky.

<u>Section 2: Figures in the Sky</u>

Looked at constellations. Those Greeks had vivid imaginations, or lots of wine!

Section 3: Coordinates in the Sky, Take One

Q1: End star in the Big Dipper's handle Altitude 25˚ Azimuth 334˚

The constellation Aquila is near azimuth 90˚, altitude 0˚

The constellation of Hercules is near altitude 90˚ This is overhead!

HOME WORK

Our intention is that you should only need to do two things outside of lab: read the lab manual in advance, and complete the pre-lab assignment prior to the first session of each lab. It is essential that you read the lab manual **before** coming to the lab. Each year there are always a few students who ignore this advice and "wing it". They are always behind in the lab, get less out of the labs, and receive poorer grades. Perhaps most importantly, they are a burden to their partners.

The week prior to the first meeting of each lab you will be given a pre-lab assignment; these will be posted on the class web page. The goal of the "pre-lab" is to get you to think about the essential issues in the upcoming lab and to practice some of the skills that you will need. To do the pre-lab will require that you read the lab manual, which you should be doing in advance of the lab anyway, and occasionally read a unit or two from your 103 textbook.

At the beginning of each lab, the instructors will look over your assignment to insure that you have completed it and to provide guidance if necessary on any difficult points. To get a credit, the pre-lab **must be completed with meaningful effort**. If you do not complete the pre-lab you will be asked to leave the lab and return at a later time with the completed pre-lab assignment.

GRADING

Each lab will have an assessment component. For some labs it will be a review of your lab book; for others it will be an in-class assessment. The assessment will be based entirely on what you accomplish in lab. All of the quizzes will be open (lab) book.

Because these labs are meant to be a time of discovery and exploration, your work cannot be assessed solely on the basis of whether answers are correct. The basis for grading will be a <u>combination</u> of:

> *Depth of thought* - careful thinking, thoughtful interpretation, creative ideas
> *Quality of results* - this reflects care and effort as well as technical proficiency
> *Neatness and organization* - clear communication of results is essential to the scientific process

Each individual assessment will be based on a 0-5 scale. It is our desire to promote collaborative learning in the lab. Hence the course grade scale is set in advance, as defined in the syllabus. The course is not curved - every student can receive an A. So you are not in competition with your classmates and **we strongly encourage working together**, except of course during quizzes.

On weeks when lab books will be reviewed for evaluation, we prefer that they be turned in at the end of the lab. You don't need to take them home and rewrite or improve them. However, should you choose to make use of the Friday open lab, lab books must be turned in by 2:55pm of the week they are due. **Lab books turned in late will not be graded.**

IMPORTANT ADVICE

- **Read the lab manual carefully before coming to the lab.** When you sit down at the computer terminal, you should be familiar with the overall goals and strategy of the project. The pre-lab assignment will help you in identifying the more important issues. **NOTE: Pre-lab assignments will be reviewed by your instructor at the beginning of lab. If your pre-lab does not show quality effort, you will be asked to leave the lab and return at another lab session.**

- Don't hesitate to ask questions of the instructor, your lab partner, or anyone. That's how you learn!

- **Relax and have fun!** The labs are designed to be completed within the lab sessions, typically with no further work outside of lab. If you have extra time, your instructor can show you other software to explore with.

- If you aren't experienced with computers, don't panic! The software is very user-friendly and the lab exercises are designed to ease you into computer usage. We've also included in this introduction a primer to some computer terminology called **Macintosh Basics**.

Macintosh Basics

Macintosh computers are among the easiest computers to use. Even so, there are a few bits of jargon that you will need to know in order to understand the lab manuals.

Cursor: The small, black arrow (usually) on the computer screen that moves when you move the mouse.

Clicking: To click on something, move the mouse until the cursor is over the object. Then press and release the mouse button. The term "click" comes from the sound the mouse button makes when it is pressed and released. Uses: pressing buttons and icons.

Double-Clicking: This is when you click on something twice in rapid succession. It is most commonly used to start programs. If you double click an icon, it will either start a program, open a file or open a folder, depending on what kind of icon it is. Uses: starting programs, opening files and folders.

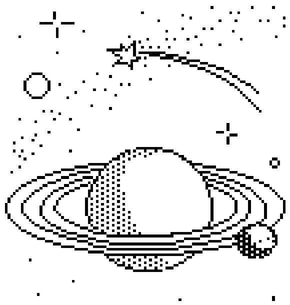
Dragging: To drag something, move the mouse until the cursor is over the object. Then press and hold the mouse button, move the mouse a little ways, and then release the button. It is as if you are "grabbing" something when you press the button, pulling it along as you move the mouse, then releasing it when you release the button. Uses: moving windows, selecting items from menus.

Windows: Windows are rectangles on the screen that can be "opened" or "closed" (created or destroyed) to show different information. They typically have the same border around them: a "titlebar" on top to identify the window, a "close box" in the upper left to make the window go away, and a "zoom box" in the upper right to make the window large or small. Many windows also have scrollbars (described below) and resize boxes. Resize boxes are in the lower right corner; if you drag it, you can make the window larger or smaller.

Scrollbars: The scrollbars are gray strips with arrows on each end located on the right and bottom sides of a window. They are used when the window is too small to allow you to see all of its contents at once. Pressing the scrollbar arrows allows you to move around within a window. In the middle of each scrollbar is a button with a few lines on it. You can drag this button back and forth to scroll more quickly than with the arrows. The location of this button tells you how much you can scroll in each direction. When the button disappears and the scrollbar turns light gray, the whole window is being displayed.

Menus: On the top of the screen is a row of words. If you position the cursor on one of the words and press and hold the mouse button, a short window with a list of options (called a menu) is opened. If you drag the cursor to one of the options and release the button, the option will be activated. For example, you can usually quit a program using Quit in the File menu.

This summary makes the most sense if you read it while you are sitting in front of the computer!



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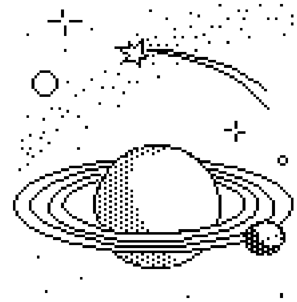


Celestial Rhythms:
An Introduction to the Sky

Introduction and Goals

The sky is a beautiful and fascinating stage upon which celestial dances are performed nightly. The sky is also our window on the Universe; mankind's first cosmological inquiries were inspired by these motions of the heavens. Over the centuries we have become more and more disconnected from the sky, even as our understanding of the Universe becomes greater. The goal of this lab is to reintroduce you to the sky, and to develop in you a deeper knowledge of its arrangement and motions.

Of course, this lab would best be done under the real night sky. Unfortunately we cannot guarantee clear skies in Madison, nor do we have the luxury of many years or the wherewithal to fly to distant lands. However, we do have the virtual reality of Voyager II, an electronic planetarium providing a rich array of observing opportunities.

We encourage you to explore with Voyager beyond the instructions of the lab. Don't worry if you go off on an exploration and get "lost" - the TA can easily bring you back to any point in the lab. And you are encouraged to ask questions during the lab about anything you may find.

Format

The format of the text in this lab is designed to clearly distinguish different purposes:

Text in normal font guides you through the lab.

• Text in bold provides instructions for operating Voyager.

Underlined text identifies key words or concepts to be learned.

Text in italics is supplementary information for your pleasure.

Q1: Questions in boxes must be answered in your lab book.

Before You Come to Class ...

Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.

Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in **two** lab sessions. You should be well into if not completed **Section 4** in the first lab session.

Section 1: Sunset

It is dusk, and the Sun has just set. You are standing in a meadow, looking toward the northern horizon. Above you is the sky (no stars yet!) and below you is the ground. Curiously, there are letters on the horizon indicating which direction you are facing (north, south, east and west). You turn your head to look in different directions:

- **Move the horizontal scrollbar with the left and right arrows, or by dragging the scrollbar tab. (Note that when you grab the scrollbar tab, a compass appears to show the present direction.) You can also maneuver on the sky with the arrows on the keyboard.**

- **Return to looking North.**

As the sky gets darker, more and more stars appear in the sky:

- **Turn on the stars. The button for the stars is among the small set of buttons near the lower left corner of the screen.**

- **Go to Define Horizon in the Control menu. Click OK.**

Now you tilt your head back to look at the stars overhead:

- **Move the vertical scrollbar with the up and down arrows, and by grabbing the scroll bar. When you grab the scroll bar, an indicator appears to show the angle above the horizon at which you are looking.**

- **Find the point in the sky marked "zenith."**

The zenith is the point directly overhead. Of course, you will never see it marked in the real night sky!

- **Lower your head (move the vertical scrollbar) so that the "North" is just above the bottom of the screen.**

Section 2: Figures in the Sky

At first glance, the stars appear to be scattered at random in the sky. But it is the nature of humans to organize, and archeological records show that all civilizations have seen patterns in the stars, or constellations. The stars were thought to be in the realm of the gods, and often the constellations were linked to religion and myth. In Western cultures the constellations typically derive from Greek and Roman mythology, such as Aries, Leo, Andromeda, Orion, Hercules and Gemini. These patterns gave an organization to the sky that was essential for its study. Indeed, some people believe that many myths were made up for the sole purpose of remembering star patterns. Today, while few give any spiritual significance to the constellations, every culture still uses constellations to guide their way through the sky.

Since the constellations are simply mnemonics, there is no "right" way to group stars. Different civilizations have created different sets of constellations from the same night sky. However, there are certain groupings of stars that are so distinctive that every civilization has grouped them together - although not always representing the same thing. One such group of stars is the one we call the Big Dipper, also seen as a Starry Plough in England, as a Wagon in Europe and Israel, and as the Government in ancient China! Find the Big Dipper in the Voyager sky. Once you have found it:

- **Turn on the constellation lines. The button for the constellations is among the small set of buttons near the lower left corner of the screen.**

- **Turn on the constellation figures. Go to Constellation Figures in the Display menu.**

- **Turn on the constellation labels. Display menu to Sky Labels to Constellations.**

The Big Dipper is actually the body and tail of Ursa Major, the Large Bear.

- **Use the scrollbars to wander around the sky.**

How many constellations do you recognize?

In ancient times the 48 constellations catalogued by Ptolemy were widely accepted, but as astronomy became more precise (and as the skies of the southern hemisphere were included), many more constellations were added. There are now 88 constellations, as established by the International Astronomical Union in 1930. At that time boundaries were established for each constellation, so every star in the sky falls in exactly one constellation. If you wish to see them, turn on Constellation Boundaries (in the Display menu). Be sure to turn the boundaries off again!

Section 3: Coordinates in the Sky

Constellations are a reasonable system of organization for "naked eye" observations, but suppose that you wanted to direct someone to a faint comet that you just discovered in your telescope. It would hardly do to tell her to point her telescope just to the left of the nose of Pegasus! Astronomers have developed several coordinate systems to solve this problem. We'll introduce you to one in this lab - the altitude-azimuth coordinate system

Altitude and azimuth are just more sophisticated versions of your natural inclinations. The position of a star can be described by its <u>altitude</u> angle above the horizon and its <u>azimuth</u> angle around the horizon (analogous to a compass direction, like "southeast"). Altitude is measured from 0˚ at the horizon to 90˚ at the zenith. Azimuth is measured around the horizon from north to east. So north has an azimuth of 0˚, east has an azimuth of 90˚, south has an azimuth of 180˚, and west has an azimuth of 270˚.

- **Look north again, with the "North" just above the bottom of the screen.**

- **Turn off the Constellation Figures. (Display menu to Constellation Figures)**

- **Open the Chart panel. (Control menu to Chart Panel)**

The bottom two numbers on the Chart Panel are the azimuth and altitude of the cursor. Note that both are measured in degrees and arcminutes. There are 60 arcminutes in 1 degree.

To get a feeling for the alt-az system, move the cursor around the sky and watch the azimuth and altitude values. For example, move along the horizon from due north to the east and to the west. How do the altitude and azimuth change? Now move from the "North" straight up. How do the altitude and azimuth change? Notice that the azimuth changes abruptly by 180˚ at the zenith.

Q1: What are the altitude and azimuth angles of the end star in the handle of the Big Dipper?

What constellation is nearest to azimuth 90˚, altitude 0˚? What constellation is nearest to an altitude of 90˚?

- **Turn on the coordinate grid. The button for the grid is among the small set of buttons near the lower left corner of the screen.**

The grid makes it evident that every star has its own unique altitude and azimuth. Note that the "pole" of this grid is the zenith.

While the "alt-az" coordinate system is very intuitive and has many valuable applications, it does have two notable weaknesses. First, the azimuth and altitude of every star are always changing with the passage of time. Second, the altitude and azimuth of a star at any given time depend on the location of the observer on the Earth. So it is a bit of a trick to tell your friend the altitude and azimuth of your faint comet if she happens to be elsewhere in the world. Later in the course we will introduce you to a celestial coordinate system in which a star's position is always the same (almost!).

Section 4: The Polaris Experiment

Polaris, the North Star, has long shown the way to travelers. At sea the only "landmarks" are celestial. It was Polaris that guided sailors around the globe, and not only by showing the way North. Using a sextant a European captain sailing to the New World could also accurately find the ship's latitude on any clear night by observing Polaris. While it is seldom still needed today, Polaris remains ever present to guide the lost or the adventurous. To find Polaris ...

- **Turn off the coordinate grid by clicking on the button. Look north again, with the "North" just above the bottom of the screen.**

People often have the misconception that Polaris is a particularly bright star. It is not, but it is easy to find nonetheless. The trick is to first find the Big Dipper. Then locate the two stars in the bowl which are farthest from the handle. These are the "Pointer Stars", Dubhe and Merak. Now imagine a line beginning at Merak (the one at the bottom of the bowl) and passing through Dubhe. This line passes through Polaris at about five times the distance between the Pointer Stars. There are no bright stars near Polaris, so it is hard to miss once the Pointer Stars show you the way.

To find out if you have correctly identified Polaris, put the cursor on the star and click. A window will pop up with the star's name and information about it. If the star is not Polaris, keep looking. (Put the window away by clicking on the white box in its upper left corner.)

Q2: In which constellation is Polaris? Make a sketch of the stars in the constellation and identify Polaris. Include the Big Dipper in your sketch.

The brightest stars in each constellation are named by a letter of the Greek alphabet and the Latin genitive form of its constellation name. The brightest one gets Alpha, the next brightest gets Beta, then Gamma, Delta, Epsilon, and so on. For example, Polaris is Alpha Ursae Minoris. The brightest star in the sky is Sirius, the Dog Star, which is also known as Alpha Canis Majoris. (The constellation Canis Major is the Large Dog.) There are many more stars than Greek letters, however, so this system only applies to the 24 brightest stars in any constellation.

Now it is time for your first measurements - in particular, you will measure the altitude of Polaris from a number of different locations on the Earth. You can measure altitude by putting the cursor on Polaris and looking at the Chart Panel.

But first, how can you transport yourself around the globe with the click of the mouse?

- **Open the Control Panel. (Control menu to Control Panel)**

The Control Panel gives all the information you could ever want about the time and your position on the Earth. Look beneath the heading of Location on the Control Panel. It should say "Washburn Observa", along with the longitude and latitude of Washburn Observatory at the top of Observatory Hill on campus. To travel elsewhere,

- **Open Location Lists. (Control menu to Set Location to Location Lists)**

You can select any city in the list (use the scrollbar to see more of them) and then click Select to go there. Now you are ready to travel the world!

Q3: In your lab book, make a table formatted like the one below. Measure and record the altitude of Polaris as seen from Washburn Observatory (where you are at now). Next, travel to Calcutta and record its latitude and longitude, and the altitude of Polaris. Do the same for a number of other cities having a range of longitude and latitude. (Hint: Stick to the northern hemisphere for now.)

Location	**Latitude**	**Longitude**	**Polaris Altitude**
Washburn Observatory	43° 05' N	89° 24' W	
Calcutta, India			

Table 1: Observations of the Altitude of Polaris

(Copy this table into your lab book and use it for the Polaris Experiment.)

Q4: In your lab book, make a graph of Polaris Altitude versus Latitude. Next make a separate graph of Polaris Altitude versus Longitude. Do you see any patterns in either graph? What conclusions can you draw about any relationships between the altitude of Polaris and the latitude and longitude of an observer on Earth. Could a sea captain measure his latitude by observing Polaris? His longitude?

Q5: Explain why any relationships exist, perhaps drawing a diagram showing the Earth, Polaris and an observer on the Earth.

Now suppose you were to travel to the southern hemisphere. Santiago, Chile has a longitude of 71˚ W and a latitude of 33˚ S.

Q6: What do you predict will be the altitude of Polaris as seen from Santiago, Chile?

- **Set Location to Santiago, Chile.**
- **Turn horizon translucent. (Control menu to Define Horizon, click Translucent and OK)**
- **Find Polaris, and measure its altitude.**

Q7: What do you measure for the altitude of Polaris as seen from Santiago, Chile? Could Magellan have measured his latitude by observing Polaris as he sailed around South America? Why not?

The sky looks very different when viewed from the southern hemisphere. Orion stands on his head, the Sun is high in the sky in December, and there are stars and constellations that are never seen from the northern hemisphere. The southern skies are especially spectacular in the summer when Sagittarius and the center of the Milky Way pass overhead. Of course, for astronomers the southern sky also represents new and unique stars to be studied, and many of us travel to mountain tops in the Chilean Andes to observe the sky.

- **Turn horizon opaque. (Control menu to Define Horizon, click Opaque and OK)**

Section 5: Motions of the Sky - Diurnal or Daily Motion

So far we have been looking at the sky at only one moment in time. In fact the sky is constantly changing with the passage of time; the Sun, the planets, the stars all move to their own celestial rhythms. Unfortunately today these rhythms pass most people by without notice. The goal here is to teach you what your ancestors knew well.

But first, how can you travel in time with the click of the mouse?

- **Set the location back to Washburn Observatory. (Control menu to Set Location to Location Lists. In Location Lists, click on the menu labeled Major Cities and choose Observatories. Select Washburn Observatory.)**

- **Look north again, with the "North" just above the bottom of the screen. Close the Chart Panel by clicking in the white box in its upper left corner. The Control Panel should still be open.**

We will use the Control Panel to control time. At the top of the panel are five buttons. The long middle one (now labeled "4 min") sets the time step, the interval by which we can change time (forward or backward). This "time step button" is actually a menu in which you can change the time step; click on it to see how it works (but leave it at 4 min when you are done).

The lower two buttons, labeled with a plus and minus sign, step the sky forward or backward in time. Try clicking each of them to see what happens.

The top two buttons are marked with arrows in addition to a plus and minus. These are the animation buttons for continuous motion forward or backward in time. To stop the animation, just click the mouse. Try animating the sky forward and backward in time.

Now, let's begin to explore the motions of the heavens:

- **Press the animate forward button and just watch for a while.**

Q8: In your lab book, *sketch* what you observe, noting in particular the directions of the stars' movements. Write your location (Washburn Observatory) and the direction you are looking (North) by your sketch.

Note the emphasis on the word sketch! You don't need to make works of art with all the stars and constellations neatly drawn. Arrows showing the general directions of stellar motions are quite sufficient.

If you watch the Voyager clock, you will notice that the northern stars complete a circle once in (nearly!) 24 hours. (Check this.) In fact all objects in the sky - including of course the Sun - complete such circles in a day, but for most stars the Earth gets in the way of our view during much of the cycle. (Hence they set and rise.) This daily motion of the stars is called <u>diurnal motion</u>, and results from the spin of the Earth.

Note that as seen from Madison, stars near Polaris never set - these stars are called <u>circumpolar</u>. The stars of the Big Dipper are circumpolar as seen from Madison.

Q9: Face East, animate, and sketch what you observe. Do the same for South and West.

At any given time, stars can be rising anywhere along the eastern horizon (and be setting anywhere along the western horizon). Roughly, where a star rises and sets along the horizon depends on how far it is from Polaris. Notice that as seen from Madison the stars do not rise "straight up" nor set "straight down".

Now let's do the same from a place near the equator. Care to go to a warm Tropical Island?

- **Set the location to Tropical Island. (Control menu to Set Location to Location Lists. In Location Lists, click on the menu labeled Observatories and select Special Locations. Select Tropical Island.)**

Q10: Animate looking North and East, and sketch what you observe. Write your location and the direction you are looking by your sketches.

Compare the motions of the stars as seen from Madison and from Tropical Island. Is the Big Dipper circumpolar from Tropical Island?

Now let's go to the North Pole! Where will Polaris be in the sky?

- **Use Location List to travel to North Pole.**

Q11: Animate looking North and sketch what you observe. (Remember, Polaris defines the direction North.) Write your location and the direction you are looking by your sketches.

Look to the horizon and sketch what you observe.

Compare the motions of the stars as seen from the North Pole with those seen from Madison or Tropical Island. Which stars are circumpolar, i.e. never rise or set? Where is Polaris in the sky?

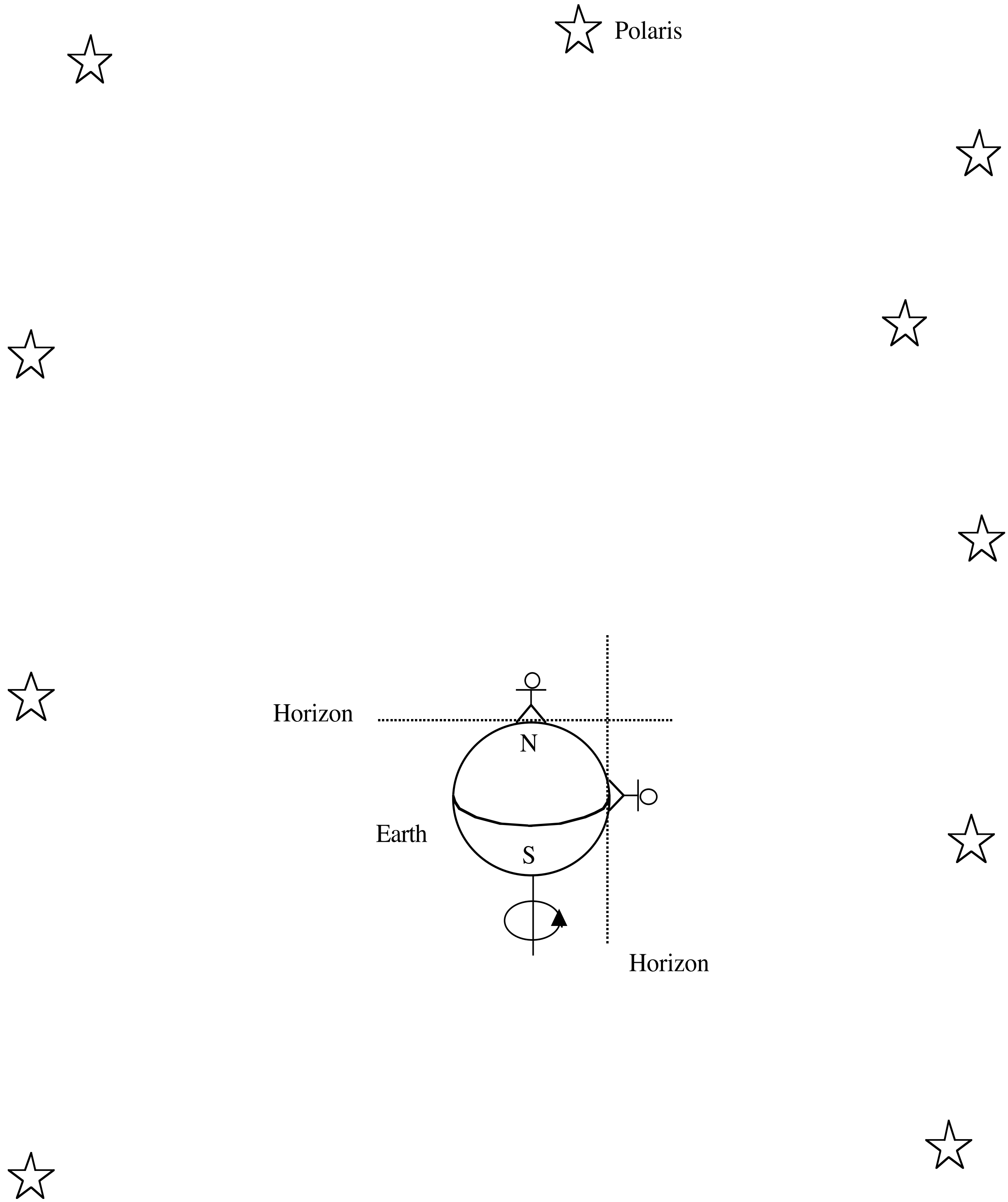
Q12: Using the figure on the next page if it helps, explain the motions of the stars which you observed at the North Pole (Q11) and at the equator (Q10).

Section 6: Motions of the Sky - Solar

In some ways the motions of the sky can be compared to those carnival rides where one rides in spinning chairs which themselves rest on a spinning platform which ... it can be hard to figure out what is moving where! In the same way, everything in the sky takes part in the diurnal motion, since it is we who are spinning. But some celestial objects have additional motions of their own. For example, the Sun ...

Let's take a long vacation on Tropical Island at the equator. Every evening at the same time, you sit on your verandah and watch the sunset. Being an observant, as well as romantic, person, you notice that the view is a little different each night:

- **Use Location List to travel to Tropical Island.**
- **Open Planet Panel. (Control Menu to Planet Panel)**
- **Turn on the Sun. (Click Sun symbol in upper left corner of Planet Panel, then close Planet Panel by clicking on white square in upper left corner)**


Polaris
Horizon
N
Earth
S
Horizon

- **Set the date and time to December 21, 1995 at 5:30 pm. (Click Local Time on the Control Panel)**
- **Face West, with the "West" at the bottom of the screen, and find the Sun.**

Q13: Make a *precise* sketch of the few stars right next to the Sun. Note the time and date by your sketch.

- **Animate forward exactly one day (watch the clock).**

As you likely expected, after one day the Sun is in (nearly) the same position with respect to the horizon. But is it in the same position with respect to the stars?

Q14: Make another careful sketch, again noting the time and date. Compare your sketches. Did the relative position of the Sun and the stars change? What direction did the Sun move with respect to the stars? What direction did the stars move with respect to the Sun? If you are not sure that you detected any motion, feel free to animate forward another day or more.

You have observed the apparent solar motion, or the motion of the Sun with respect to the stars. It might seem strange to call this solar motion, when you have observed the Sun to be in the same place in the sky and the stars to have moved toward the west. However, watchers of the sky have always seen the stars as the fundamental fixed reference against which the sun, the moon, and the planets move.

One implication of the solar motion is that the stars which we can see in the evening depend on the time of year. If we always look at about the same time each night, say an hour after sunset, then with each passing day we see the stars move further to the west in the sky. Eventually they move into the evening twilight and are lost to view behind the Sun. It is this effect which makes Orion a "winter constellation" and Sagittarius a "summer constellation", for these are the seasons when these constellations are visible in the evening.

To see this, let's watch the solar motion over many months. To speed things up a bit:

- **Set the time step to 1 day. (Click on the long time step button at the top of the Control Panel)**

Q15: Look to the zenith. Record in your lab book the constellations that are overhead, along with the date.

- **Look back to the western horizon and animate forward for three months.**

Remember, you are looking at the sky at the same time each day - think of it as time-lapse photography where you take a picture every time the Sun is at the same altitude above the horizon. Thus the motions of the stars with respect to the horizon that you are now observing are *not* diurnal motion. It is the result of the solar motion with respect to the stars.

Where are the December constellations now? Now which constellations are near the zenith?

Q16: Look to the zenith. Record in your lab book the constellations that are overhead, along with the date.

Face west again and animate forward for 3 months. Record the constellations that are overhead and date, and repeat until the Sun has returned to its position in Q15.

You have seen that as a result of the solar motion the stars that are visible at any given time of night change throughout the year. (Why is it essential to write "any given time of night" in the previous sentence?) You have also seen that the Sun and the stars complete their motions with respect to each other in 1 year. This is the essential clue that links the solar motion to the orbital motion of the Earth around the Sun.

In the same way that the diurnal motion of the Sun and stars provides a daily clock, the annual motion of the Sun with respect to the stars provides a calendar. One of the fundamental tasks of priests in early civilizations was to watch the Sun's motion so as to foretell the changes of season that were so essential to life. Indeed, early watchers of the sky used certain constellations in much the same way that we use pages on a calendar.

- **Animate forward through a year and notice the constellations through which the Sun passes. In what constellation is the Sun on your birthday?**

Do you recognize the constellations that you have listed? The ring of constellations through which the Sun appears to move over the course of the year is called the <u>Zodiac</u>, which some historians think comes from Greek for "circle of animals." There are 12 "signs" of the Zodiac and the Sun passes through any one of them in about a month. Believers in astrology say that the constellation in which the Sun was on the day of your birth tells something about what kind of person you will be and what your future holds. Actually, on your birthday the Sun may not be in the constellation of your astrological sign. This is because the astrological signs were set several thousand years ago, and an effect called precession has since shifted the constellations with respect to a given date. Modern astrologers still use the original positions of the zodiacal constellations to make predictions, so your "sign" is about one month off from the real sky.

While today astronomers give no significance to the Zodiacal constellations, the path of the Sun through the stars is an important reference point in the sky. This path is called the <u>Ecliptic</u>.

- **Turn on the Ecliptic (Display menu to Coordinate Lines to Ecliptic)**

- **Animate the Sun again and observe its motion with respect to the Ecliptic.**

Q17: Use sketches of the Earth, the Sun, and the stars to explain solar motion. Include text as necessary to make clear what the sketches are showing.

Section 7: Motions of Sky - Planets

The first people who kept track of the night skies over long periods of time noticed that there were certain "stars" which wandered slowly among the constellations. The Greek word for these wandering stars was "planetos" - the origin of the modern word "planet".

- **Open the Planet Panel (Control menu). Click on the symbols in the top two rows, and the two leftmost symbols in the third row. (The Sun should already be on and the Earth can't be turned on.)**

The symbols represent (left to right, top to bottom) the Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto.

- **Search the sky for all of the planets which are visible on whatever date and time you are at. Click on their symbols to identify them. For fun, click on the picture box for images.**

Q18: Did you find planets everywhere in the sky? If not, is there a pattern to where they are located?

Did you find 8 planets in the sky? If not, why not? How might you check your answer? Do so!

Each of the planets moves in its own way, but broadly speaking the planets can be divided into two groups with quite different patterns of motion. The first group consists of Mercury and Venus:

- **Face west, with the "West" at the bottom of the screen. The time should still be 5:30 pm, the Sun should be visible near the horizon, and the time step should be 1 day.**

- **Animate forward and watch the motions of Mercury (orange triangle) and Venus (pink diamond).**

You will see that Mercury and Venus never travel far from the Sun. You will also see that at times Mercury or Venus or both are not visible at sunset.

- **Animate forward to a date when neither Mercury or Venus are visible at sunset.**

Q19: Why aren't they visible at sunset on this date? At what other time of the same day might they be visible? Check your prediction by changing to that time. At what time were you able to see them? What direction did you have to look?

Why is Venus sometimes called the "Evening Star" and sometimes called the "Morning Star", but never the "Midnight Star"?

The remaining planets have motions very different from Mercury and Venus. Most of the time they travel to the east with respect to the stars, circling the ecliptic just like the Sun. However, occasionally these planets do an unusual motion which caused great consternation among learned men for several thousand years and ultimately contributed to the downfall of the Ptolemaic cosmology. Let's watch Mars perform this maneuver:

- **Use Local Time button to set the sky to September 1, 1992 at 1:00 AM.**

- **Find Mars low in the eastern sky.**

- **Set the time step to 14 days.**

Q20: Tape the star chart on the next page into your lab book.

Carefully mark the position of Mars on the star chart. (Use the constellations to orient yourself.) Step forward 14 days (one time step) and again mark the position of Mars. Repeat until March 16, 1993, when Mars can no longer be observed. Occasionally note the dates of points on your figure.

Note: To keep Mars in your field of view as the months pass, you will have to adjust the direction you are looking in the sky with the scrollbars.

Q21: During what dates were Mars in <u>prograde motion</u> (west-to-east) and during what dates were Mars in <u>retrograde motion</u> (east-to-west)?

While Mars did its cosmic loop against the stars, it also moved from low in the eastern sky to low in the western sky. How do you explain this motion?

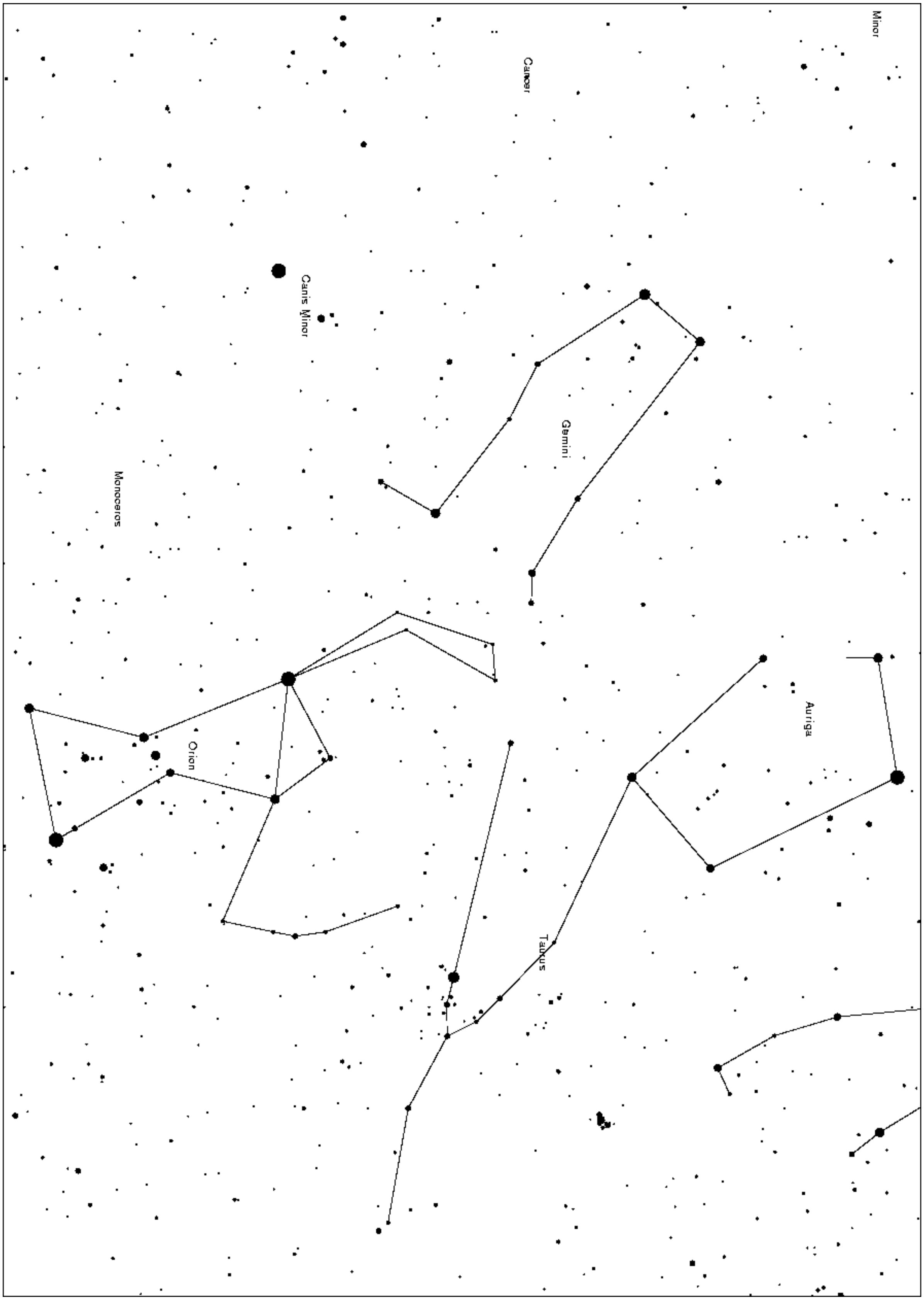


Figure 2: Star Chart for the Motion of Mars

The dances of the planets could best be seen if we could make the Earth transparent and the Sun less bright. Then we could watch the motions of the planets against the stars for 24 hours a day, 365 days a year. Of course, with Voyager nothing is impossible!

- **Change the screen to an all-sky view. (Chart menu to Chart Coordinates to Star Atlas - Equatorial)**

- **Set the Zoom to 360 degrees. The zoom menu is among the set of buttons near the lower left corner of the screen.**

- **Click on the "box-in-a-box" square in the upper right corner of the Control Panel.**

- **Turn off Zenith. (Display menu to Reference Points to Zenith) Turn off the Constellation Labels. (Display menu to Sky Labels to Constellations) Turn off the stars. The constellation lines should still be on.**

You are now seeing the entire Celestial Sphere, much like a flat map of the entire Earth. Thus if you see the Sun and Mars half a screen away from each other it means they are on opposite sides of the celestial sphere (much like Australia is half a page away from Madison on a world map). In this view of the sky, the stars remain fixed in time, making it much easier to see the motions of the Sun and planets. (Note that east is to the left and north to the top.)

- **Set the time step to 3 hours.**

- **Animate forward in time.**

If the simulation runs too slow or too fast, feel free to adjust the time step. Watch the movements of the Sun and Mars for several years. Now you can easily see the Sun's motion to the east with respect to the stars. Mars also travels to the east most of the time, but once in a while it makes its retrograde loop.

Q22: Search for patterns in the positions of the Sun and Mars when Mars makes its retrograde loop. For example, is Mars always in the same place with respect to the stars when it goes retrograde? What about its position with respect to the Sun? Can you predict when a planet will do its retrograde loop? Describe how you make your prediction.

One of the primary goals of science is to find patterns that generalize from one case to many others. Can you predict when other planets will make a retrograde loop? Does your prediction method work for all of the other planets? If not for all, then for which ones does it work?

Section 8: The Copernican Model

So far we have only observed the motions of the Sun, planets and stars. We have not made any attempt to explain them, nor have we dared to derive from our observations the true arrangement of the planets in the Universe. These are the ultimate goals of any cosmological model. In this lab we shall take on the challenge using the Copernican model for the Solar System.

- **Animate forward in time, sit back, and watch the "Dance of the Planets".**

Observe each planet over the course of a few years. There is a lot of action here! Which planets move the fastest in the sky? Which planets show retrograde motion? Are the retrograde loops of all the planets the same size? Is the prograde motion of the Sun faster or slower than the motions of the planets?

Q23: Make sure that you and your lab partner can explain the motion of *every* planet at *any* time in the context of the Copernican model. Call on your TA to check your understanding. This may require several iterations as he/she asks probing questions. Don't be dismayed - the goal is to teach by challenging you to think about astronomy, not to simply provide rote answers. When done, have the TA initial your lab book.

A goal of this lab is to leave you with the ability to walk outside on any night, observe the positions of the planets in the sky, and from your observations be able to visualize where they are located in the Solar System at that time. Of course, with your naked eye you can't see Uranus, Neptune or Pluto.

- **Open the Planet Panel (Control menu). Turn off Uranus, Neptune and Pluto. Close the Planet Panel.**

- **Set the date to June 4, 1995.**

- **Return to a local-horizon view (Chart menu to Chart Coordinates to Local Horizon - Altazimuth). Make the ground opaque (Control menu to Define Horizon) !**

- **Set the Zoom to 150 degrees. The zoom menu is among the set of buttons near the lower left corner of the screen.**

Q24: The ultimate challenge: Deduce the positions of the planets in their orbits from observations of them in the sky.

Based on what you see in the Voyager sky, figure out where all the planets are in their orbits. Tape the figure on the next page into your lab book. Use the figure as a scratch pad to help you try out ideas.

You are free to change the time of day as you wish; you may also change the date, but remember that you are trying to determine the planets' locations specifically on June 4, 1995. And of course you can look anywhere in the sky that you wish.

With Voyager you can check your map by voyaging above the Solar System and looking back!

- **Go into the Control menu and choose Observe from Point ... Make the heliocentric latitude 90^{o} and the distance from the Sun 100 a.u.**

- **Choose a zoom of 15°.**

Q25: How does your map compare to the actual configuration of the planets? If there are differences, note them and discuss how you got to your answer. Was your reasoning incorrect, or was it not possible to distinguish between your answer and the actual configuration based on what you see in the sky?

You can return to the Earth by choosing Return to Earth in the Control menu, and setting the zoom to 120°.

Success with these last questions is the ultimate achievement of the Copernican Revolution - every position and motion of the planets in the sky can be understood in the context of one reasonably simple heliocentric model. Of course there are complexities in the celestial motions, which in turn require complexities in the model. But these should not obscure the beauty of the synthesis achieved by the Copernican vision, nor lessen your pleasure in understanding the celestial rhythms above you every night.

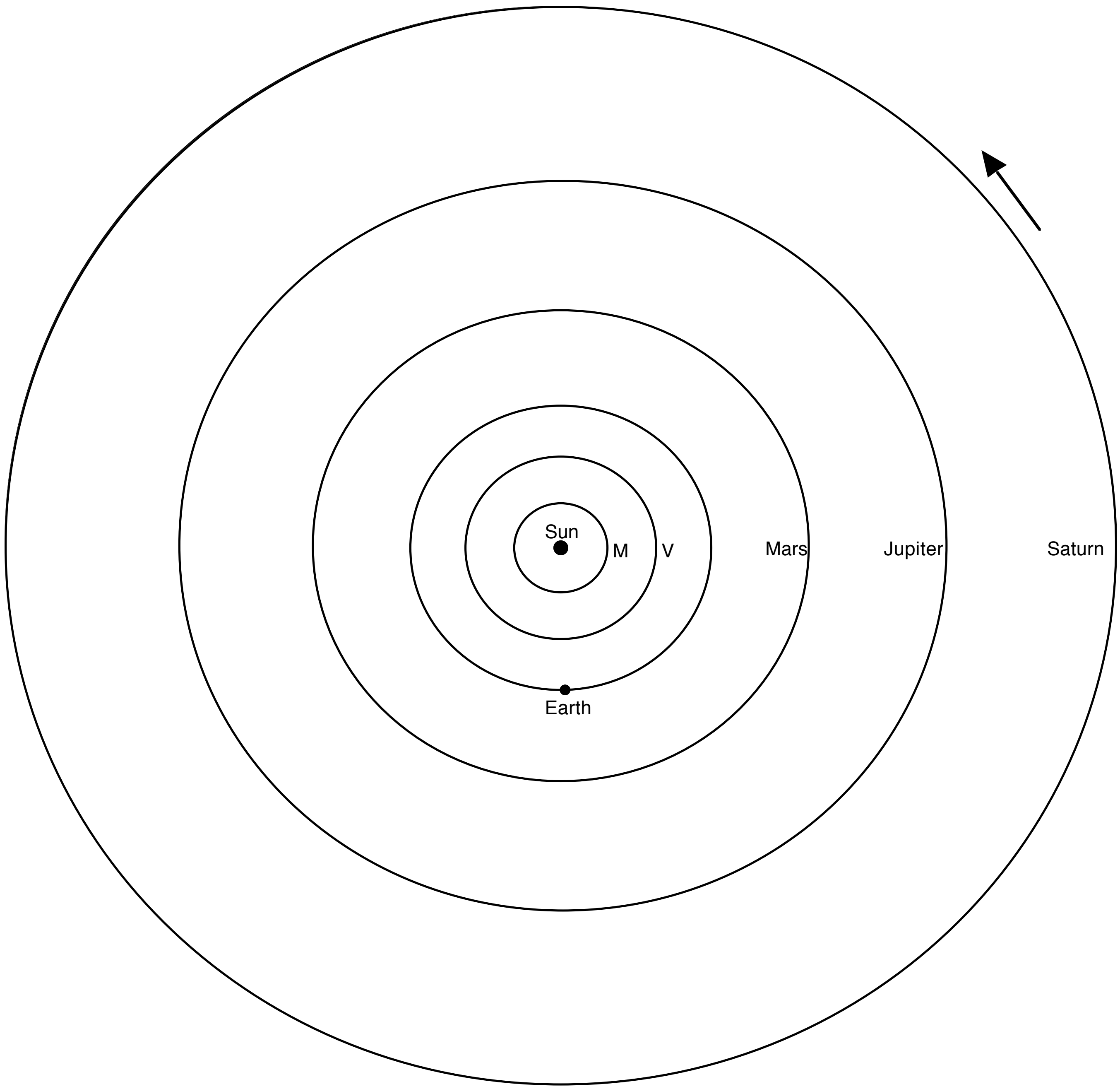


Figure 3: The Orbits of the Planets - for use with Q24

This is **not** to scale!!!!

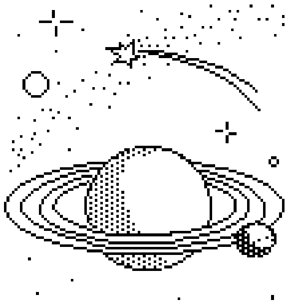
Study Guide

Key Words

Altitude
Apparent Solar Motion
Arcminute
Azimuth
Circumpolar
Constellations
Diurnal Motion
Ecliptic
Maximum Elongation
Prograde Motion
Retrograde Motion
Zenith
Zodiac

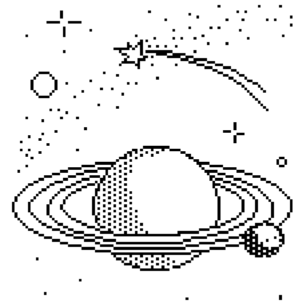
Key Concepts

Altitude-Azimuth coordinate system
Altitude of Polaris and significance for navigation
Diurnal motion of the sky, as seen from different locations on Earth
Solar motion and the annual motions of the stars
Planetary motion - Mercury and Venus
Planetary motion - prograde and retrograde motion of Mars, Jupiter, Saturn, Uranus, Neptune and Pluto
The Copernican model and its application



ASTRONOMY 113

Laboratory



Lab 2: The Moons of Jupiter

Introduction and Goals

In 1609, Galileo Galilei heard of the invention of a new optical instrument by a Dutch spectacle maker, Hans Lippershey. By using two lenses, one convex and one concave, Lippershey found that distant objects could be made to look nearer. This instrument was called a telescope. Without having seen one, Galileo was able to construct his own telescope with a magnification of about three. He soon greatly improved upon his first instrument, and his best telescopes reached a magnification of about thirty.

Galileo immediately began observing the sky with his technological breakthrough. He was a careful observer, and soon published a small book of remarkable discoveries called the *Sidereal Messenger*. Galileo found sunspots on the Sun and craters on the Moon. He found that Venus had phases, much like the Moon. He was able to see that the Milky Way was a myriad of individual stars. He noticed that there was something strange about Saturn, but his small telescope was not able to resolve its rings. Very suddenly the Universe had become quite a different place!

One of Galileo's most important discoveries was that Jupiter had four moons revolving around it. Galileo made such exhaustive studies of the motions of these moons that they are known as the Galilean satellites. This "miniature solar system" was clear evidence that the Copernican theory of a Sun-centered solar system was physically possible.

Because he was developing a world view which was not easily reconciled with the religious dogma of his period, Galileo was compelled to neither "hold nor defend" the Copernican hypothesis. Nevertheless, in 1632 he published his *Dialogue on the Great World System* which was a thinly disguised defense of the Copernican system. This led to his forced denunciation of the theory and confinement to his home for the rest of his life.

In this lab you will repeat Galileo's observations, without threat of government condemnation! The goals of this lab are to:

i) Measure the periods and semi-major axes of the orbits of Jupiter's moons, and to use these results and Kepler's Third Law to measure the mass of Jupiter.
ii) Experience the scientific process in a world of limited resources, in particular telescope observing time.
iii) Develop a deeper understanding of the concept and significance of uncertainty in science.

Before You Come to Class ...

Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.

Complete the pre-lab assignment.

Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in **two** lab sessions. You should be able to complete at least two observing sessions in the first lab, and have the orbits for at least 1-2 moons determined.

This lab incorporates software developed by the Contemporary Laboratory Experiences in Astronomy project of Gettysburg College, funded in part by the National Science Foundation.

Section 1 - A Bit of Technical Background

Kepler's Third Law

At about the same time that Galileo was observing the sky, Johannes Kepler was deriving his three laws of planetary motion. The most powerful was Kepler's Third Law, which stated that the square of a planet's orbital period was proportional to the cube of the planet's distance from the Sun. Later, Newton used his Law of Gravitation to show that Kepler's Third Law could be generalized to *any* two objects in orbit about each other. Newton also showed how the period and semi-major axis of an orbit depended on the masses of the orbiting objects. With the addition of Newton's insights, Kepler's Third Law can be stated as follows:

$$M1 + M2 = \frac{A^3}{P^2}$$

where

M1, M2 are the masses of the objects in orbit about each other, **in units of the mass of the Sun (M_O).**

A is the length of the semi-major axis of the elliptical orbit**, in units of the Earth-Sun distance or an "Astronomical Unit" (AU).** If the orbit is circular (as is the case for the Galilean moons) the semi-major axis is the same as the radius of the orbit.

P is the period of the orbit **in units of Earth years**. The period is the amount of time required for a body to complete one orbit.

If one object, say M1, is much more massive than the other, then M1 + M2 ≈ M1. ('≈' means 'very nearly equal to'). Kepler's Third Law then simplifies to

$$M1 = \frac{A^3}{P^2}$$

The power of Newton's version of Kepler's Third Law lies in its generality. It applies to any planet orbiting about the Sun (check: for the Earth A = 1 AU and P = 1 yr, giving M1 = 1 M_O for the Sun), to a satellite orbiting the Earth, to a moon orbiting around a planet, to two stars orbiting each other, or to a star orbiting the Galaxy. In this lab you will be determining A and P for each of the Galilean moons of Jupiter, and from these you will use Kepler's Third Law to derive the mass of Jupiter.

The Galilean Moons of Jupiter

The four Galilean moons are named Io, Europa, Ganymede and Callisto. These are names of mythological characters admired by Jupiter, occasionally to their detriment. You can remember the order by the mnemonic "**I E**at **G**reen **C**arrots", in order of increasing distance from Jupiter.

If you were to observe Jupiter through a small telescope, the view might look like this:

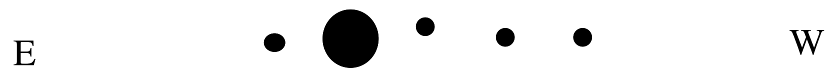


Figure 1. Jupiter and the Galilean Satellites

The moons appear to be lined up because we are looking nearly edge-on to their orbital planes around Jupiter. In fact some are closer to us and some farther from us, depending on where they are in their orbits. Note that when looking through a telescope, **west** is to the **right** and **east** is to the **left**.

Needless to say, nature has not created neon signs identifying each moon, so at a given time it will not be obvious which moon is which. Only by following their motions over time - or by traveling to Jupiter - can one tell them apart. In this lab you will observe Jupiter's moons at times of your choosing; indeed one of the challenges of the lab - and of much observational astronomy - is to determine the best interval of time between your observations. At every time of observation you will measure the distance of each moon from Jupiter. The only readily available measuring scale is Jupiter itself, and so your measurements will be in Jupiter diameters (JuD); later you will convert these to AU. Ultimately you will obtain enough measurements to puzzle out which moon is which, and derive each moon's period P and semi-major axis A.

If every measurement could be perfectly precise, then observation of the period P and semi-major axis A of each moon of Jupiter should give the same value for Jupiter's mass. But every measurement must have some error, however small, and consequently two experiments will not give exactly the same results. Indeed, it is the differences between the results of several repeated experiments which give the best estimate of the uncertainty in an answer. Consequently, you will observe all four Galilean moons and derive four measures of Jupiter's mass.

Section 2 - Observations of Jupiter's Moons

The *Jupiter's Moons* program simulates the operation of a telescope on which is mounted an electronic camera. The camera provides a video image to the computer screen. You control the telescope's magnification. The computer is also equipped with software for measuring precise positions on the image.

Start-up Procedure

- **Double-click on the icon *Jupiter's Moons*.**

After the program is activated it will request a Start Date and Time for your observing session. Your Start Date and Time can be obtained from your TA.

Q1: Copy the table below into your lab book and fill in the information given to you by your TA.

Year of First Observation:	______________________
Month:	______________________
Day:	______________________
Universal Time (UT):	______________________
Interval Between Observations:	12 hours

Enter this information into the computer.

Note: Universal Time, or UT, is the time in Greenwich, England. Universal Time has been adopted by astronomers for communicating times of astronomical events.

The Telescope Field of View and Readouts

After you have entered this information into the computer, it will point the telescope at Jupiter and provide a display similar to that shown below. Jupiter is displayed in the center of the screen. To either side are the Galilean moons. Even at high magnifications they appear only as points of light with no visible surface.

The date and the Universal Time are displayed in the lower left corner. There is also a number labeled JD, which stands for Julian Day. This is the number of days (and fractions of days) since noon on Jan 1, 4713 BC, and is the standard system astronomers use to record and communicate dates. This may seem like a bizarre way to measure time, but it works well. To see why Julian days are useful, try to figure out how many days have passed between noon on Oct 13, 1971 and June 15, 1995. You have to take into account the number of days in each month, the leap years, etc. But it's easy if you know that those dates are Julian Days 2441238 and 2449884, respectively. Then you can tell quite easily that I was 8646 days old on the day I wrote this!

There are four buttons on the screen marked 100x, 200x, 300x, and 400x. The magnification of the telescope can be controlled by clicking these buttons. Try clicking on them to see how it changes the view. The current telescope magnification is shown at the upper left corner.

The "Next" button steps ahead one time interval.

To end your observing session, select QUIT from the File menu. **You cannot continue where you left off if you QUIT the program.**

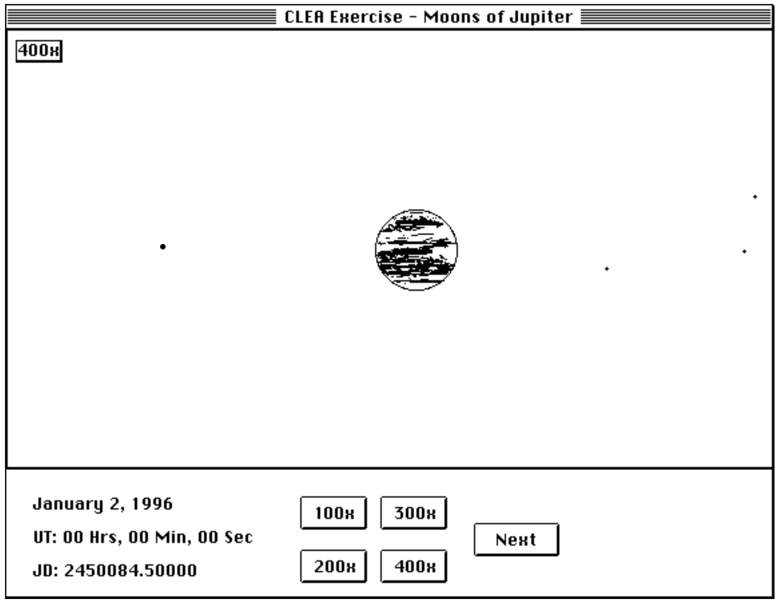


Figure 2. Jupiter and its Four Galilean Moons

Position Measurement

Precise determination of the orbital periods and semi-major axes of the Galilean moons requires observing the motions of each moon over at least one orbital period. In order to obtain quantitative results the positions of each moon must be measured with the passage of time. Specifically, observations in this lab consist of measuring the distance of each moon from Jupiter at regularly spaced intervals of time.

In order to measure a moon's position, move the cursor into the telescope field of view, then press and hold the mouse button. The cursor becomes a cross and the measurement software is activated. Carefully center the cross on a moon and read the value next to the lower 'X' in the lower righthand corner. The number is the distance of the cursor from the center of Jupiter, measured in JuD. (To make sure that you are clear on this, check that the edge of Jupiter is 0.5 JuD.) The direction of the moon is given by an E or W for east and west.

For best precision it is a good idea to use the highest magnification possible. However, when the moons get too far from Jupiter you will have to reduce the magnification to keep them in your field of view.

Sometimes a moon will be "missing". In this case, first go to the lowest magnification and largest field of view. If you don't see four moons, then go to the highest power to see if one is in front of Jupiter.

(This is called a transit.) If the missing moon is not in front of Jupiter, it must be behind the planet. In this case, record its distance as zero. Of course, this measurement could be in error by as much as 0.5 JuD.

Once you have measured the positions of all four moons, click "Next" to advance in time by one time step.

Recording Data

The word "data" has taken on many meanings, but in astronomy it refers to measurements of any sort. In this lab your data are your position measurements for the moons. On the next page is a table for recording your data; additional copies will be available in the lab room. **Use this page and tape it into your lab book, or create a table of the same form on a clean lab book page.** You may need more than one page for your data, so save space in your lab book. Record your observations as follows:

Column 1: Write down the Julian Day. Since you likely will not be observing for more than a year in time, you can just record the last few digits. For example you could put down 9883.43 instead of 2449883.43 to save some writing.

Columns 2 through 5: Record each moon's position, in the order that you see them from east to west (left to right). Remember to specify if they are east (left) or west (right) of Jupiter. For example, you could write 2.21W to mean one moon was 2.21 JuD west (right) of Jupiter's center.

You may run into cloudy weather. Be sure to record cloudy dates as well, and write "Cloudy" in columns 2 through 5.

<u>Data Table</u>

(1) **Julian Day**	**(2)**	**(3)**	**(4)**	**(5)**
2449883.00	9.81E	3.75E	1.72W	2.11W

Data Presentation - Graphical

More often than not, the graphical display of data makes trends and correlations readily apparent. Often the basis of a discovery is simply recognizing what to plot against what! Given the data in this lab the proper plot is evidently the position of each moon versus time, specifically Julian Date.

The last page in this lab is a grid conveniently labeled for your use; additional copies will be available in the computer lab. The number of days since the first observation is along the x-axis and distance from Jupiter is along the y-axis.

Q2: After each observing session is completed, plot the four measurements from each day on which an observation was made. An example is shown in Figure 3.

It is unlikely that the data gathered in your first observing session will suffice to clearly identify the orbital paths of each moon. After extracting what information you can from the data in hand, you will need to return to the telescope. However, analysis of the data in hand should reveal some trends and give you guidance in your choice of interval between observations in your next observing session.

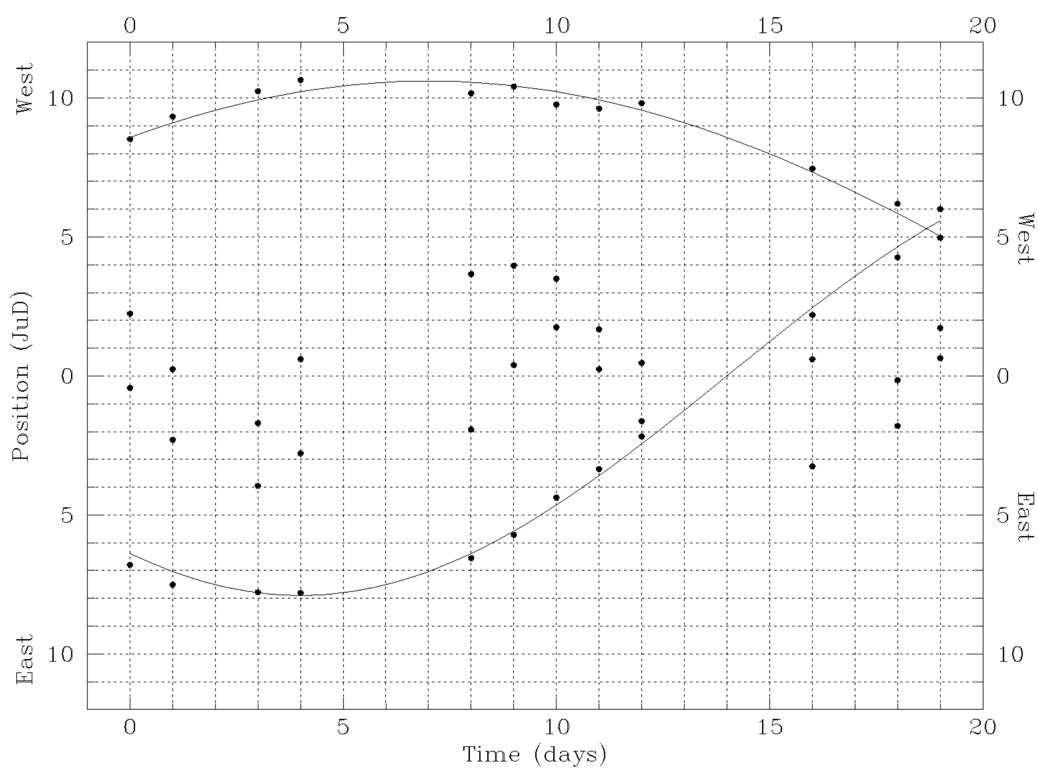


Figure 3. Sample Graph of Moons' Positions

Telescope Observing Time

There is a catch in the real world of observational astronomy. There are too few telescopes for all of astronomers' ideas, and telescope time is dear. Thus telescope time is allocated via a competitive process in which proposals are submitted, reviewed by peers, and ranked. The best proposals get telescope time, the rest do not. As an example, on the largest telescope at Kitt Peak National Observatory the requested time exceeds the available time by a factor of 3 - most proposals don't get done!

The situation is similar for the telescope which you are using. You have initially been allocated enough telescope time for 10 observations separated by time intervals of 0.5 days. After you have completed 10 observations, **Stop Observing. You need to write a short proposal to be granted your next 10 observations.** The allocation of additional telescope time is not guaranteed! A good proposal must demonstrate results from previously allocated observing time, describe the outstanding questions to be addressed, and propose an observing plan designed to answer those questions. For this lab, designing your observing plan consists of choosing the Start Date and the Time Interval for your next 10 observations. Note: your proposed Start Date can not take you back in time!

There is a proposal form at the end of this lab, and additional copies will be available in the computer lab. Confine your proposal to just the one side of the paper, although you may add graphs and figures if you wish. Submit your proposal to your TA, who will take it to an anonymous referee for review and consideration. If you are not granted time, you will need to develop your proposal further and resubmit it. You may submit as many proposals as you wish, but the proposal/observing cycle takes time and you must "publish" your results before the end of the second lab period.

If you are granted time, go to **RESTART** in the **FILE** menu and set the date of first observation and observation interval to that which you proposed.

Section 3 - Data Analysis

Collecting sufficient high-quality data is essential for successful research, but it is only the beginning. With data in hand, the analysis begins.

Identifying Moons, and Determining Orbital Periods and Semi-Major Axes

Before you can determine the periods and semi-major axes of the moons' orbits, you need to figure out which measurement goes with which moon at any given time. Since nature doesn't label the moons for us, this can only be done by looking for patterns in the data. Fortunately, the orbits of the Galilean moons are circular so that **the path of each moon in your graph of position versus time will look like a sine curve**. For any one moon the sine curve will be symmetric, with all maxima and minima the same distance from 0; see Figure 4 for an example.

Q3: Find four sine curves that together incorporate every data point. Remember that the four sine curves will have different periods and different amplitudes (maximum deviations from 0).

Note: Read the next two paragraphs first!

Once you feel that the orbital motions of all of the moons are clearly determined in your figure, tape your graph into your lab book.

To get you started, consider again the data in Figure 3. It is not too hard to see the pattern in the motions of the outer two moons, and we have sketched preliminary orbit curves through them. But these orbit curves are incomplete, so longer time coverage is needed. And the rest of the points look rather jumbled; it would seem that the intervals between the first ten observations were too long to follow the rapid change in motion of the inner moons. So we should write a proposal to obtain more data!

As you will see, data collection and analysis play symbiotic roles with each other. Very rarely does one simply gather data for a period of time, analyze it after the fact, and get to the answer. Rather one gathers data, analyzes it to obtain a new but incomplete understanding, obtains more and better designed data, further analyzes it, and so on until the result is clear. In this lab you need to continue to gather data until you can determine the periods of all four moons. It is up to you how well you want those periods to be determined - more precision requires more data and more time but gives a better result.

Determining the Mass of Jupiter – Four Times!

Now you can derive the essential quantities - period P and semi-major axis A - from your observations, and from them derive the mass of Jupiter. For each moon you will have a curve something like the one below. (The data are for an imaginary moon named Ganef and is different from the moons in the lab.)

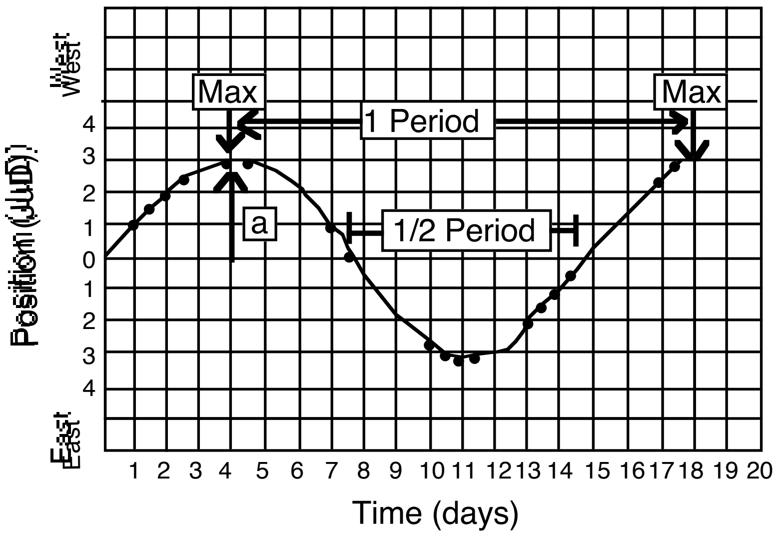


Figure 4. Complete Orbit Curve for the Imaginary Moon Ganef

Each dot in the figure is one observation of Moon Ganef. Note the irregular spacing of dots, due to poor weather and other problems on some nights. The sine curve drawn through the points is the smooth curve that would be made by Ganef if you had observed it constantly.

Using the data from Moon Ganef, it is possible to determine the semi-major axis and period of the orbit. The period is the time it takes to return to the same position in the orbit. Thus the time between two maxima, for example, is the period. Alternatively, the time between crossings at 0 JuD is equal to 1/2 the period because this is the time it takes to get from the front of Jupiter to the back of Jupiter, or 1/2 way around. If you have observed several orbital cycles of a moon, you can find a more accurate period by taking the time it takes for a moon to complete, say, 4 orbits, and then dividing that time by 4.

The semi-major axis of the orbit is given by the maximum distance from Jupiter at which you observed the moon. Equivalently, the semi-major axis is given by the maximum or minimum value of your sine curve. Of course, since your measures are in JuD, so will be your value for the semi-major axis of the orbit.

Finally, your measures are in days and JuD, while Kepler's Third Law requires years and AU. To convert your period in days to a period in years, simply divide by 365.25 days in a year. To convert your semi-major axis in JuD to a semi-major axis in AU, divide by 1050 Jupiter diameters in an AU.

For Ganef, the results are:

P	= ____14___ days	a	= _____3___ JuD
	= __.038___ years		= __.0028__ AU

Q4: Copy the information below into your lab book. Fill in the blanks with your results. (Remember, Io is the moon closest to Jupiter.)

Pay attention to how many digits you give, for that is a statement of your estimated uncertainty. Do you think you know the period to a precision of 1 day? Then give the period as 5 days, not 5.32 days. To a tenth of a day? Then give the period as 5.3 days.

The same is true of computed values. If you think you only know the period as 5 days, then you can't know the period as accurately as 0.01369 years. To see this, note that 5.5 days computes to 0.01507 years, so clearly the '69' digits in 0.01369 years are meaningless.

Io

P (period) = _________ days A (semi-major axis) = ________ JuD

P (period) = _________ years A (semi-major axis) = ________ AU

Europa

P (period) = _________ days A (semi-major axis) = ________ JuD

P (period) = _________ years A (semi-major axis) = ________ AU

Ganymede

P (period) = _________ days A (semi-major axis) = ________ JuD

P (period) = _________ years A (semi-major axis) = ________ AU

Callisto

P (period) = _________ days A (semi-major axis) = ________ JuD

P (period) = _________ years A (semi-major axis) = ________ AU

Q5: Using a full page in your lab book, make a plot of period P versus semi-major axis A.

Describe qualitatively the relation between period and semi-major axis. Qualitatively, are your data consistent with Kepler's Third Law? For example, do your data describe a line on your graph? Should they?

We now have all the information we need to use Kepler's Third Law to derive Jupiter's mass. For Jupiter's moons revolving around the much more massive Jupiter, Kepler's Third Law takes the form:

$$M_J = \frac{A^3}{P^2}$$

where P is in units of years
A is in units of AU
M_J is in units of solar masses M_O.

Q6: Calculate four values for the mass of Jupiter, using your results from each of the four moons. Record your four results as a table in your lab book. Be sure your table includes units!

Again, pay attention to how many digits you use. For example, if we measured P = 1.00 year and A = 1.00 AU for the Earth, would it be better to write the mass of the Sun as 1, 1.00, or 1.00000000 solar masses?

The Final Answer

Computing a number for the mass of Jupiter is, relatively speaking, easy. If you insert values for period and semi-major axes into Kepler's Third Law, you will assuredly obtain a value for the mass of Jupiter. Far more difficult – and far more important - than obtaining this result is determining the quality, or uncertainty, of the result. The only thing you know with absolute certainty is that the derived value is not the true value. However, if the uncertainty is properly determined, the true value will lie within the interval of uncertainty around the measured value.

Q7: Derive a value and uncertainty[1] for the mass of Jupiter from your data and analysis.

You have four measures which must be reduced to one value and an uncertainty. Along the way decisions must be made. How to combine the four measures? Are all four measures equally valid? What properties of the four measures provide insight into their uncertainties?

[1] This would be a good time to review the section on Measurement Errors in the Introduction.

Section 4 - Publication

It is often said that scientific research is not completed until the results are communicated. In the time of Galileo and Kepler communication was via books. Today results are typically communicated in scientific journals. In Astronomy 114, publish or perish in your lab book**.**

Q8: Write up a concise but complete conclusion drawn from your research. Most importantly, discuss and justify how you went from four measures of the mass of Jupiter to one value with an uncertainty.

Q9: It is standard scientific procedure to compare results with other independently derived results. Look in your textbook to find the best available mass of Jupiter. Is your answer right or wrong?

This is not a straightforward question. Spend some time thinking and talking to your partner about what it means for a result to be right or wrong.
Include your thoughts with the discussion of Q8.

The concept of uncertainty is absolutely fundamental to experimental science. Imagine, for example, that an experimental result is reported without an uncertainty. If the result is taken as absolutely true, then there would no longer be any purpose in repeating or improving the experiment – clearly this would be a foolish, dead-end path for science. On the other hand, if the result is taken as not absolutely true and the experiment is repeated, then necessarily the second result will not be the same as the first at some level of precision. Does this mean that the two results disagree? That critical question cannot be answered without knowing the uncertainties of both results. *And so one finds that a result without an uncertainty is truly worthless*.

This is a truth that too often is lost on the general public and the media. And thus the results of science are presented and accepted as truths, at least until the next results are presented. Perceptions change with the most recent headline, sometimes radically, when in fact what is actually known may have changed little given the uncertainties. For yourself, always remember that your four measurements of Jupiter's mass yielded four different answers, and that this is necessarily so in all experimental results. Wisdom and truth derive from recognizing *both* what is known and what is not known.

Study Guide

Key Words

Accuracy
Astronomical Unit (AU)
Data
Galilean moons
Julian Date
Mass
Period
Precision
Semi-major Axis
Solar mass ($M_{\odot}$)
Uncertainty
Universal Time

Key Concepts

Kepler's Third Law
Scientific uncertainty, precision, and accuracy

Observing Proposal Form

Sterling Hall Observatory

I) Previous Observations and Results:

II) Proposed Observations: (give start date, time interval between observations, and number of observations requested; justify your choices!)

ASTRONOMY 113

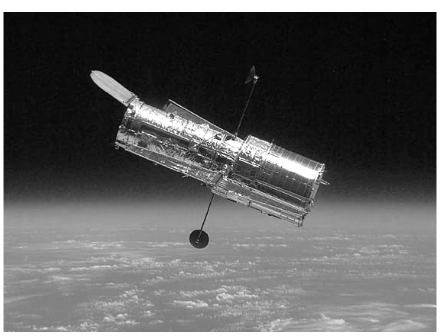
Laboratory

Lab 3: Telescopes

Perhaps no scientific instrument is as closely associated with a field of study as is the telescope to astronomy. And yet arguably the telescope is also the most misunderstood of scientific instruments, so closely associated is the telescope with the word “magnification”.

First and foremost, an astronomical telescope is a “light bucket” designed to collect light. A celestial object, such as a star, emits light in all directions. After traveling for thousands of years across billions of kilometers, a tiny portion of that light rains down on the hemisphere of the Earth facing that star. Almost all of that light does nothing more than be absorbed by the atmosphere or the ground, ever so slightly heating up the Earth. An infinitesimal portion of the star’s light strikes the lens or mirror of a telescope and is directed into an eye, or onto a piece of film, or through a spectrograph. The bigger the diameter of the lens or mirror, the more light that is guided to the detector, and the more knowledge that is gained about the Universe. This is the basic fact that underlies astronomers’ never-ending quest for telescopes of larger diameter.

Considered broadly, telescopes are all around you in optical devices of other names – cameras, eyes, binoculars, eyeglasses, and more. The details of the optics in each of these telescopes dictates how effectively the collected light is used. The goal of this lab is to give you a feel for optics through recreation of that marvelous device of Galileo, the telescope.



Before You Come to Class ...

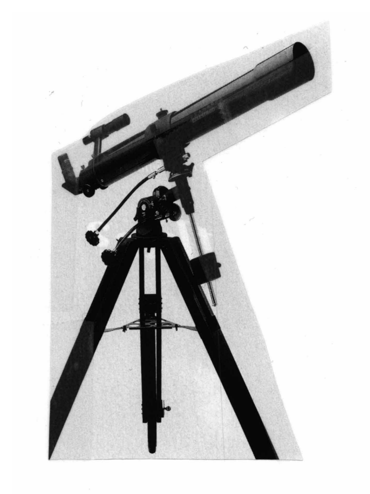
Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.

Complete the pre-lab assignment.

Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in **two** lab sessions.



Section 1 – The Simple Telescope – A Primer

To make a telescope all you need is one lens[1], appropriately curved. This objective lens receives light from a distant object – perhaps a student across the classroom, a sailboat on Lake Mendota, the Moon, the planet Jupiter, or a galaxy - and creates an image of that object behind the lens on a flat plane called the "Image Plane".

Before working with celestial objects, let's consider two headlights on a car on the far side of Lake Mendota at night. The car is far enough away that each headlight appears simply as a point of light. In Figure 1 the headlights are shown as points A and B. To start, Figure 1 shows only the light rays coming from headlight A. There are several important things to notice in this simple picture.

a) The light rays that strike the lens are bent (refracted) in such a way that they all pass through the same point in space. This place is the focal point for headlight A. If you were to put a piece of paper here, you would see a point of light on the paper. This point of light is called the real image of headlight A.

b) The light rays don't stop at the focal point.

c) Most of the light from the headlight misses the lens and thus is never sent to the focal point.

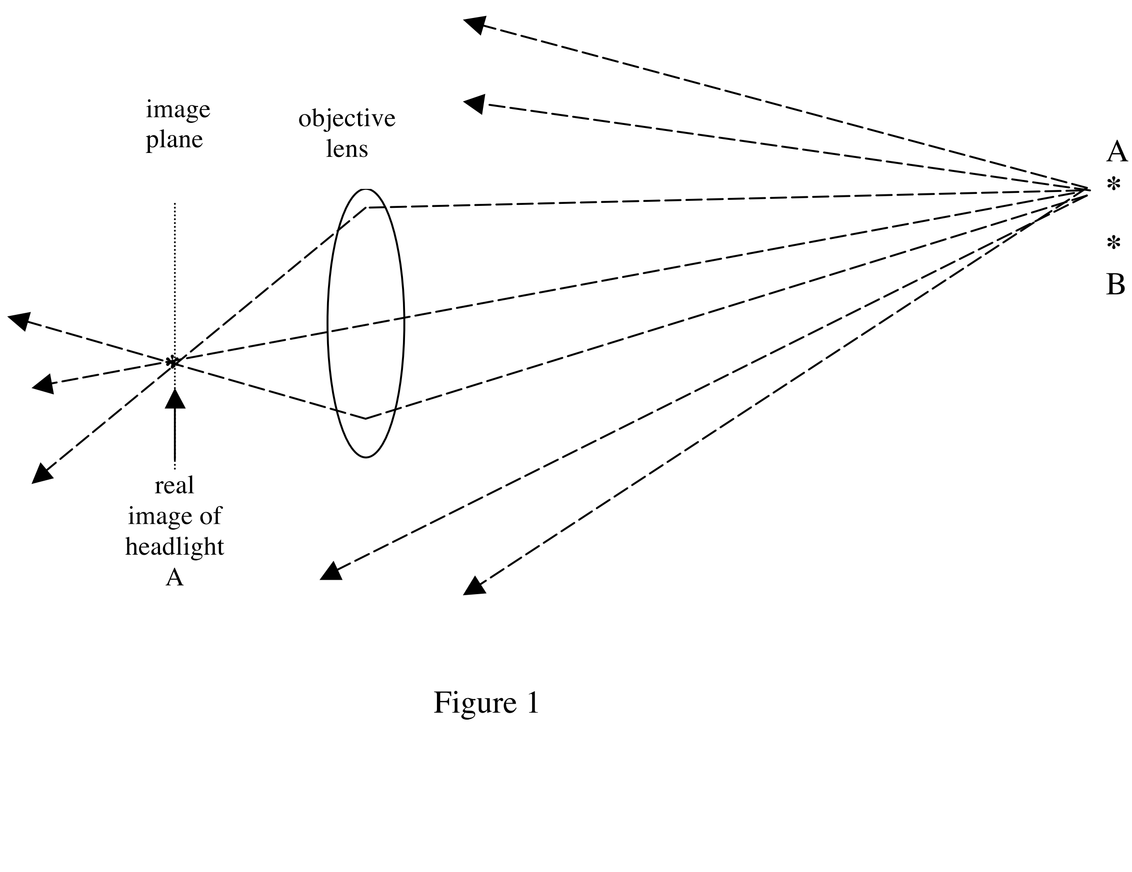


Figure 1

[1] Either a lens or concave mirror will do, and in fact most astronomical telescopes use a mirror. Since in this lab you will be using lenses, we will continue to talk in terms of lenses.

Of course, light is also arriving at the lens from headlight B. As shown in Figure 2, because the light from B is coming from a different direction, the focal point of B is located at a different place in space.

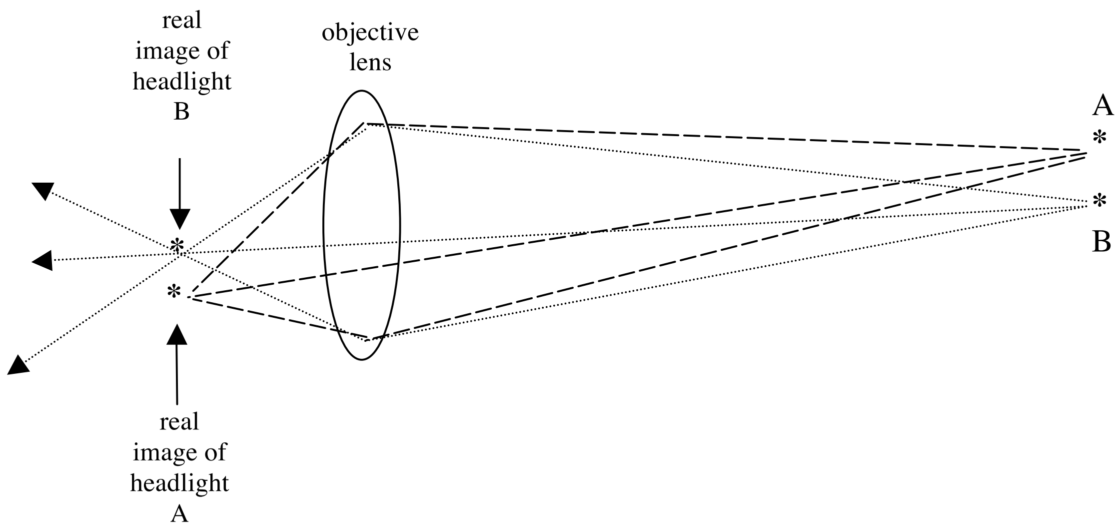


Figure 2

If you were to hold a piece of paper at the appropriate distance behind the lens, you would see two points of light on the paper, one at the focal point of headlight A and one at the focal point of headlight B.

Now, instead of headlights, imagine a fluorescent Texaco sign on the other side of Lake Mendota. Just like the two headlights, light from every point on the sign comes to a focus at a different place behind the lens. And the ensemble of all these points of light become an image of the Texaco sign! This image behind the objective lens is a two-dimensional reproduction of the object suspended in space, and as before is called a <u>real image</u>. Perhaps this phrasing might now make more sense – optically speaking, the real image of the Texaco sign is no different than the sign itself. The real image can be looked at and examined with no loss of information compared to looking at the sign itself (with the exception of optical imperfections). In a sense, the sign has been "beamed" to the focal point of the lens!

Once a real image is created by the objective lens, it can be carefully inspected in a variety of ways. For example, one could project the real image onto a piece of white paper, which in fact is an excellent and safe way to observe the Sun with a telescope. Alternatively, the real image can be examined by eye, perhaps with a magnifying glass. More traditionally the magnifying glass is called an eyepiece, and most likely this is how you have used telescopes. However, it is almost never the way professional astronomers use a telescope, simply because the eye is a very insensitive light detector. One could also record the image by placing photographic film or a light-sensitive silicon chip (called a charge coupled device; CCD) at the position of the image. In this case the telescope is a high-end camera – indeed, your digital camera is simply a single lens and a CCD. Or the spectrum of the light from the object could be measured by placing the entrance of a spectrograph at the position of the image.

- **Why do astronomers prefer these latter two uses of the telescope and almost never look at the image with their eye?**

Section 2 – Becoming Familiar with Lenses

FINDING IMAGES, OR SEEING SPOTS

Your lab group has been supplied with an assortment of lenses, lens holders, a white screen, and a lens rail onto which the lenses and screen can be mounted. In this section you can explore creating and finding real images. There is no need to write anything in your notebook for this section.

- **Place the "blue" lens near one end of the lens rail, tighten the lens holder onto the lens rail, and aim the rail as accurately as you can toward one of the "double stars'' located on the far side of the room. To aim up or down, you may need to shim one end of the rail with something, such as a book or block of wood.**

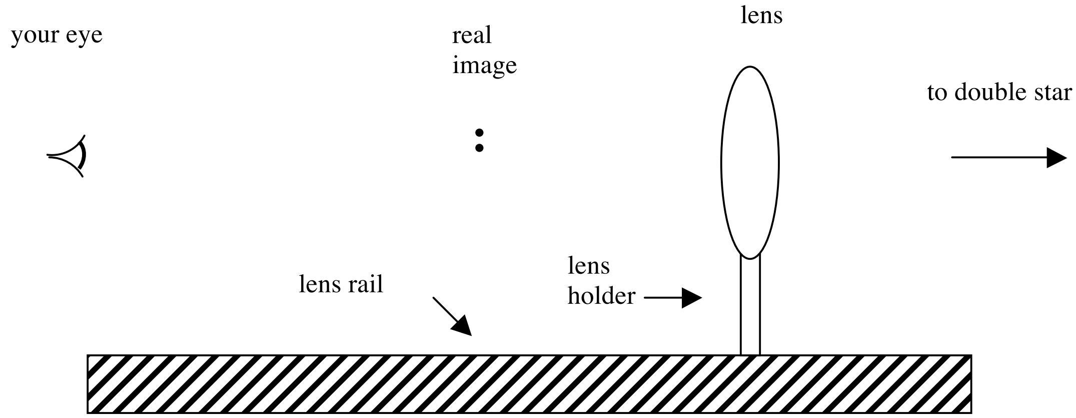


Figure 3

Now find the real image of the "double stars". The image will be located 50 cm or so behind the lens along a line from the "stars" through the center of the lens.

Try finding the image in a couple of different ways:

- **Place the white screen on the rail behind the lens. Slide the screen back and forth until the image of the two stars appears on the screen. In this situation the light that creates the image hits the white screen and scatters in all directions, making it possible to see the image easily from any direction.**

- **Stand about 1 m behind the lens and look toward the stars through the lens. Can you see an image of the stars suspended in space just in front of you? (Note: some people can and some people can’t – even professors! This is the result of eyes and brains, not the existence of the real image.)**

Section 3 – Focal Lengths and Image Size

When looking at an object very far away, the distance between the lens and the real image of the object is a property of a lens called its focal length.[2] The focal length is a measure of how much the lens bends light. Typically, the greater the curvature of the surface of the lens, the more that light is bent and the shorter is its focal length.

- Q1: The four lenses supplied for this lab have different focal lengths. Observe a "double star" with your screen to measure the focal length of each of your lenses. Record your results in Table 1 (copied to your labbook), listing each lens and its focal length in mm. BE SURE TO OBSERVE THE SAME "DOUBLE STAR" WITH ALL OF YOUR LENSES. Also measure the separation in mm between the two star images. When you make your table be sure to leave room for the extra column for "magnifier distance", which you will fill in later.

Table 1

lens	focal length	separation of the two star images	magnifier distance
White			
Yellow			
Blue			
Orange			

Q2: Make a graph, plotting separation (distance between the two star images) on the vertical axis and focal length on the horizontal axis. What qualitative relationship do you find between focal length and the separation between the two star images? Show this relationship in a graph.

Q3: Examine the lenses. What physical property of the lenses accounts for their differing focal lengths?

Q4: Suppose you want to take photographs of the sky with pieces of film that are 35 mm square. Which of your lenses would be best for taking a photograph of a large field of view, e.g. a photograph of the entire constellation Orion? Why?

Which of your lenses would be best for taking a photograph that reveals fine detail, e.g. of group of craters on the Moon? Why? The ability to distinguish fine detail is called the resolution of a telescope.

[2] See Appendix A for more detail on focal lengths of lenses and ray tracing.

Can a telescope provide both a wide field of view and superb resolution? Why or why not?

For a given diameter, telescopes of different focal lengths have very different capabilities. When designing telescopes astronomers must make design decisions very similar to the ones that you have just made, depending on their scientific goals. Of course, astronomers cast those design decisions into multi-million dollar facilities!

Q5: Consider Figure 2 carefully. Recreate it in your lab notebook.

Imagine replacing the lens in Figure 2 with a longer focal length lens. On your figure, redraw the light rays after they pass through this longer focal length lens. It helps to know that the ray that passes through the center of a lens is always unbent, whatever the focal length of the lens.

With your drawing, explain the relationship that you have discovered between focal length and separation.

Section 4 – A Better Light Bucket

When used for astronomy, one of the telescope's most important characteristics is the size of its objective lens.

- **While projecting the double star onto the white screen, have one of your lab partners decrease the usable area of the objective lens.**

A piece of paper with a hole in it (a "mask") can be held just in front of the lens, for example. Start with a mask that has a hole about 1/2 the diameter of the objective lens. Try another with about 1/10 the diameter.

Q6: In a few sentences, explain why the brightnesses of the images depends upon the diameter of the objective lens.

Q7: Suppose an astronomer has used the UW 3.5m-diameter telescope (located in Arizona!) to just barely detect brown dwarf stars in a nearby star cluster. She believes that if she could detect objects 10 times fainter, she could discover Jupiter-like planets in the star cluster. If she submits a proposal to use the Keck Observatory 10m-diameter telescope for this project, would you award her observing time?

Note: Justify your decision with sound arguments. This is an obligation of every Time Assignment Committee Member, and a pillar supporting the peer-review system of science.

Section 5 – The Simple Magnifier

Hopefully by now you are convinced that the critical component of a telescope is the objective lens (or mirror). The diameter of the lens determines the brightness of images, or equivalently the faintest celestial objects that you can observe. The focal length of the lens determines the field of view that can be observed with the telescope and the ability of the telescope to resolve fine detail. From the point of view of a professional astronomer, this largely completes the story.

But for the rest of the human race who will be observing through a telescope by eye, there is more to be said. In principle you can simply look at the real image of an objective lens with your eye, as you have already done. But more typically the view of the real image is enhanced by using a magnifying glass. Which ultimately will bring us to the subject of magnification.

Your four lenses can also be used as magnifiers. Hold each of the lenses (one at a time) **close to your eye** and then examine your finger tip, the page of your notebook, or the graduations on a ruler, How close to the lens do you have to bring the object in order to see a clear, magnified image of the object?

Q8: Measure this distance for each lens and record it in your Table 1 under "magnifier distance."

How does this distance compare to the focal length of the lens listed in Table 1?

Do you find a relationship between the focal length and the magnification? That is, if lens A has a focal length smaller than that of lens B, do objects look bigger when viewed through lens B or through lens A?

To better understand how the magnifier works, see Appendix B.

Section 6 – Making a Visual Refracting Telescope

Now you are ready to use what you have learned about lenses to make a visual refracting telescope. (That is, a telescope comprised of lenses for use by eye.) Simply use one of the lenses as a magnifier to examine the real image formed by an objective lens.

- **Try it!**

Usually the trickiest part of making a telescope is simply getting the objective lens and the magnifier lens (or "eyepiece") properly aligned with each other. If you are having trouble, here's a trick:

> Place one of the short focal length lenses on the lens rail behind the real image formed by one of the long focal length lenses (in this case, the objective lens). Place the white screen at the position of the real image of the objective lens. Now look at the back of the screen through the short focal length lens (in this case, the eyepiece). Move the eyepiece back and forth along the rail until a clear, magnified view of the back of the screen appears. At this point the eyepiece is acting as a simple magnifier for objects located at the position of the screen. Since the real image from the objective lens is also at the position of the screen, you need only remove the screen to see a magnified image of the real image of the "stars". The two lenses are now operating as a telescope. (Be sure the

centers of the lenses are at the same height above the rail and that the telescope is pointed directly at the stars.)

Q9: Sketch your telescope in your labbook, indicating distances between lenses, focal lengths of the lenses, and the distance of each lens to the real image. Be sure to label which lens is the objective lens and which is the eyepiece.

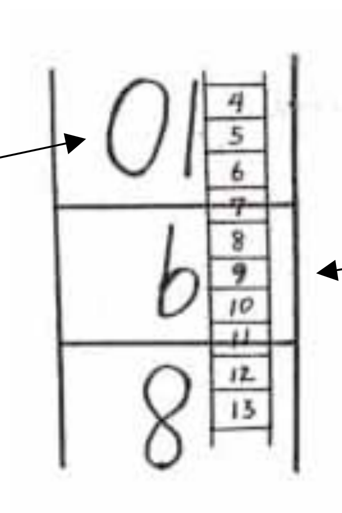
Section 7 – Measuring the Magnification of a Telescope

Magnification has many definitions, but for our purpose we will define it as the ratio of the size of an object as seen with a telescope to the size of the object as seen with the unaided eye.

- **With one eye looking through the telescope at a double star and the other looking at the double star directly, estimate the magnification of the telescope.**

- **A more accurate measure of the magnification can be made by looking at the large numbered illuminated boards positioned around the room. With one eye looking through the telescope and the other looking directly at the board, you should see something like that displayed below. In this example, the magnification of the telescope is about 4.**

Inverted image as seen through the telescope.



White board as seen directly with the other eye.

Figure 4

Q10: Make telescopes using different objective lenses and eyepieces.

Record your results in Table 2 (copied to your labbook).

Can you find a relationship between magnification and the focal lengths of your lenses? Think of a systematic way to explore this question.

Table 2

Focal length objective	Focal length eyepiece	Magnification

Q11: Explain your findings.

Hint: Consider the objective lens and the eyepiece lens separately. What is each lens doing, independent of the other?

Section 8 – Astronomical Seeing

Despite the advertising for WalMart telescopes, magnification is a vastly overrated property of telescopes. It turns out that when looking at stars and planets through a telescope, after a certain point, more and more magnification does not result in seeing the object in better and better detail. For example, no matter how much magnification your telescope has, it will never allow you to see individual grains of sand on the surface of Mars.

The blurring by the earth's atmosphere, called "atmospheric seeing" by astronomers, is one of the limiting factors.

- **While looking at a "double star" with your highest magnification telescope, take a heat gun and blow hot air across the light path in front of the objective.**

Notice that the stars become noticeably blurry due to the churning hot and cool air through which the light must pass. Ground based telescopes must also look through such a churning atmosphere, although the effect is not so dramatic as with a heat gun. This churning of the air is what makes the stars twinkle in the night sky.

Remember that stars (except the Sun) are much too distant to be able to visually resolve them. Thus effectively stars appear as perfect points of light. However, if one takes a photograph of a star its IMAGES will have a measurable size because of the atmosphere moving the point of light around during the exposure. This is also true for your eye, which also has an exposure time, albeit brief.

The measure of such image sizes are called astronomical seeing, and is the limit of detail that can be resolved on any celestial object. The best seeing is typically about 1 arc second (1" = 1/3600 degree). High magnification simply allows one to see a magnified view of these blurred images. This means that a ground-based telescope cannot see detail on Mars (when it is 8×10^7 km from Earth) any smaller than 390 km across -- no matter how much magnification the telescope has.

If your telescope were placed above the atmosphere, and if the objective lens (or mirror) were very accurately made, then the amount of detail that the telescope could reveal might improve dramatically. However, even in space there is a limit to the clarity of the image, set by the fact that light behaves as a wave. If you reach the point where the image quality is being degraded by the wave nature of light, then your telescope is said to be working at its "diffraction limit." That is the sharpest image that it can have. The larger the telescope's objective, the smaller (better) is its diffraction limit. For example, the Hubble Telescope (2.4 m diameter objective) is working at its diffraction limit, corresponding to 0.05 arc seconds of smearing in the real image formed at its focal plane. This means Hubble can resolve objects as small as 12 miles across on Mars --very good, but still a long way from seeing that grain of sand!

The diffraction limit of a telescope is given approximately by the formula

$$\theta = 1.2\ \lambda/D$$

where θ is the angular size of the blurring due to the wave nature of light, λ is the wavelength of the light (about 0.5 μm for visible light) and D is the diameter of the objective lens. (1 μm = 10^{-6} m; 1 mm = 10^{-3} m).

Note: the angle θ is measured in radians (see the hand-out on scientific calculators for a brief discussion of degrees and radians). Astronomers like to express angles in arc seconds. For future reference, note that there are 57.3 degrees or 206,000 arc seconds in a radian and that there are $4.85*10^{-6}$ radians in an arc second.

Q12:
a) Using the equation above, what is the diffraction limit of your eye in arc seconds (your pupil diameter is about 3 mm)?

b) For what size telescope (objective diameter) is the smearing by the Earth's atmosphere (1 arc second) and the smearing due to diffraction about equal?

For ground based telescopes that are larger in diameter than that calculated in b), the image does not get any sharper. Is there any advantage to having a telescope larger that this?

Section 9 – For Life Closer to Home … The Lens Formula (Extra Credit)

Considered broadly, telescopes are all around you in optical devices of other names – eyes, cameras, binoculars, eyeglasses, and more. In practice, astronomical telescopes are the simplest of all optical devices, since celestial objects are so far away that for the purposes of optical design they can all be considered to be at the same distance – infinity! The engineering of your eyes does not have that luxury. Your eyes must be able to place a real image on your retina whether you are reading your lab manual or looking at a distant star.

In the first part of this lab in which you constructed a telescope, the object being looked at (the "binary star") was far away and you found that the real image was located at the focal length of the lens. But for objects closer to the lens, the distance to the real image will be located at a greater distance from the lens than the focal length.

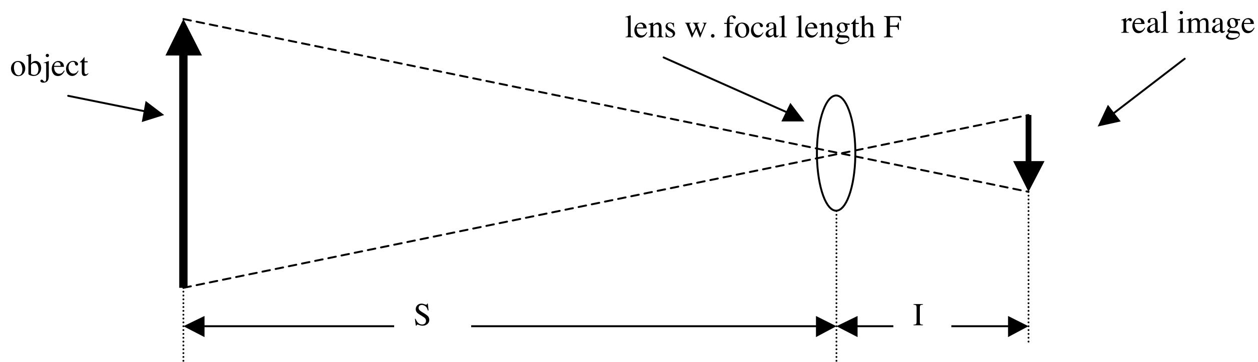


Figure 1

Specifically, the distance I from the lens to the real image is related to the distance S from the lens to the object by the **lens formula**,

$$\mathbf{1/I + 1/S = 1/F} \ ,$$

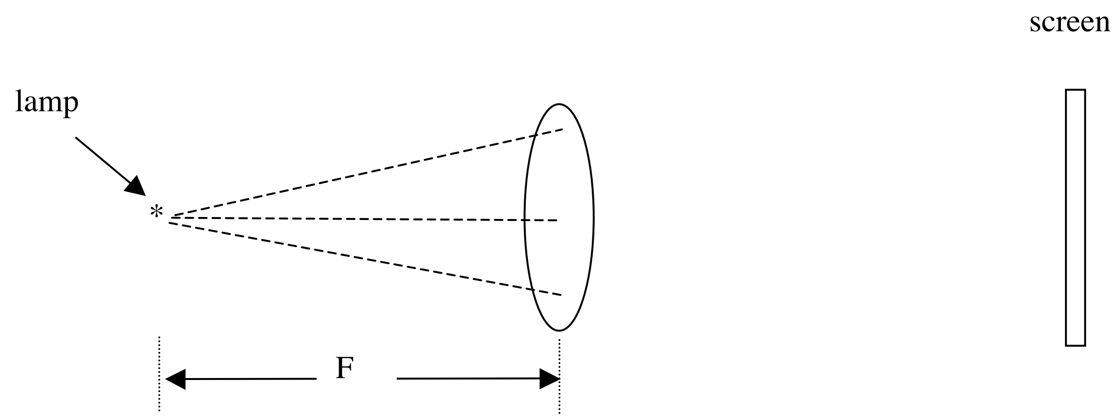
where F is the focal length of the lens.

Q13: Earlier in the lab you found that for light sources at very large distances (e.g., across the room, or at cosmic distances), the real image of the object is located behind the lens at the distance of one focal length. Show that this equation is consistent with that finding.

Q14: The focal length of the orange lens is 100 mm. Use the bright lamp on your optical bench as the object for the lens. (Make sure that the lamp is at the same height as the center of your lens.) Place the lamp at a few positions and verify the lens formula. NOTE WELL: Unless S is very large, the distance I to the real image is NOT the same as the focal length of the lens. The real image lies more distant than the focal length.

Q15: Place the lamp in front of the lens at the distance of one focal length. Describe what you observe. If you have done this accurately, you have created a searchlight!

Use the figure below to show what is happening.



Guide

Key Words

Astronomical seeing
Field of view
Focal length
Lens formula (extra credit)
Magnification
Objective lens
Real image
Refracting telescope
Resolution

Key Concepts

Light collection and telescope diameter
Formation of a real image
Focal length, field of view, and resolution
Eyepieces and magnification
Visual refracting telescopes
Lens formula (extra credit)

Appendix A - Ray Tracing

Figure A shows photons traveling radially away from a star. Some photons will travel toward the objective lens of a telescope. You know from experience that light travels on straight lines (called rays) through air or vacuum. It turns out that there are some simple rules governing this light-deflection that make it easy to draw a diagram of how lenses produce images.

The concept is simple: follow individual light rays on their straight lines until they hit the lens. Then bend them according to the rules of light-ray bending. This process is called ray tracing. These are the rules and regulations regarding ray tracing:

- Light paths can only change direction where they pass through a lens; everywhere else they are just straight lines (see in the figure below how light travels on straight lines until it gets bent by the lens). Use a ruler or straightedge to draw the rays. It is obvious that light rays missing the lens do not get bent and do not contribute to the image (ray 4 in Figure A is an example of that).
- A ray passing through the very center of a lens does not bend (ray number 1 in the figure below)
- Any ray entering (or exiting) the lens parallel to the lens axis (the lens axis goes through the center of the lens and is perpendicular to the lens surface – see figure) will go through the focus on the opposite side of the lens (rays 2 and 3).

Additional helpful rules:

- All other rays coming from the object point and going through the lens must also go through the image of the point (ray 5 is an example of that). These rays do not help in finding the location of the image through ray tracing.
- Note that the two focal points of a lens are at the same distance F from either side of the lens (see the two points marked F in the figure).

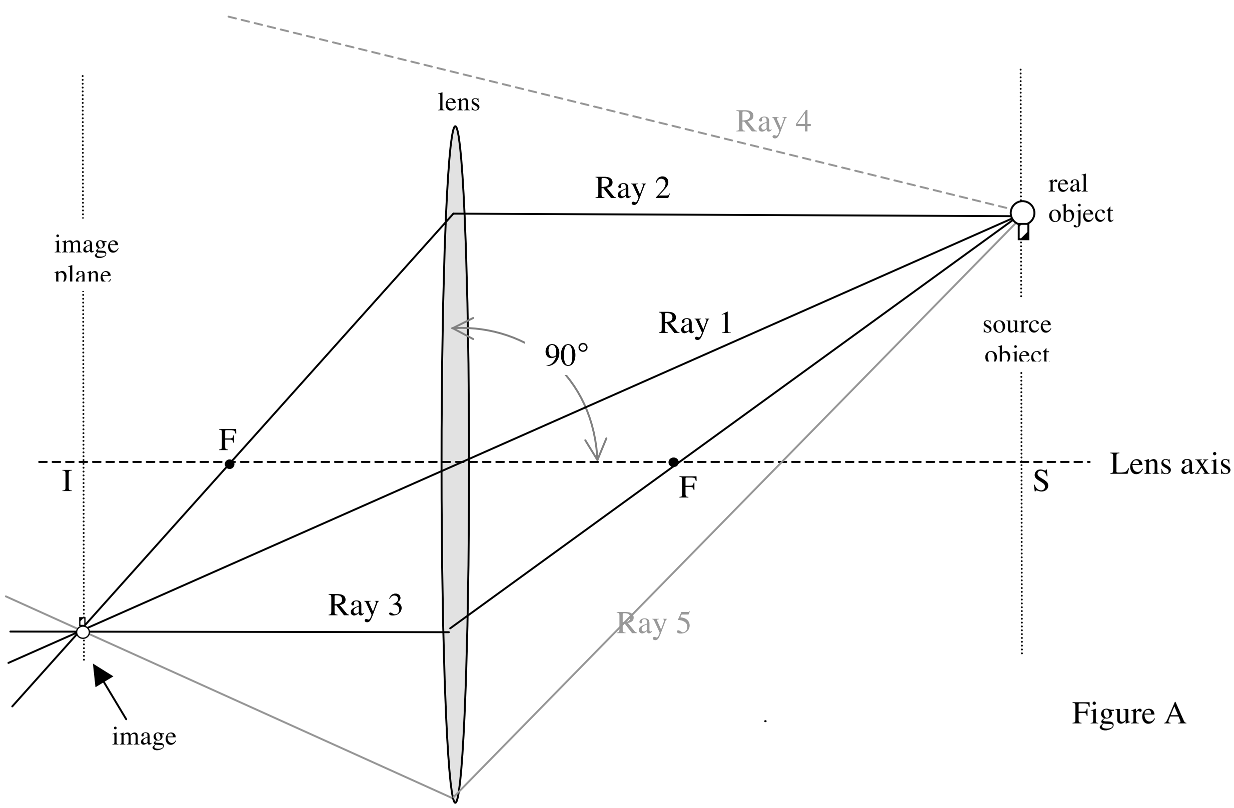
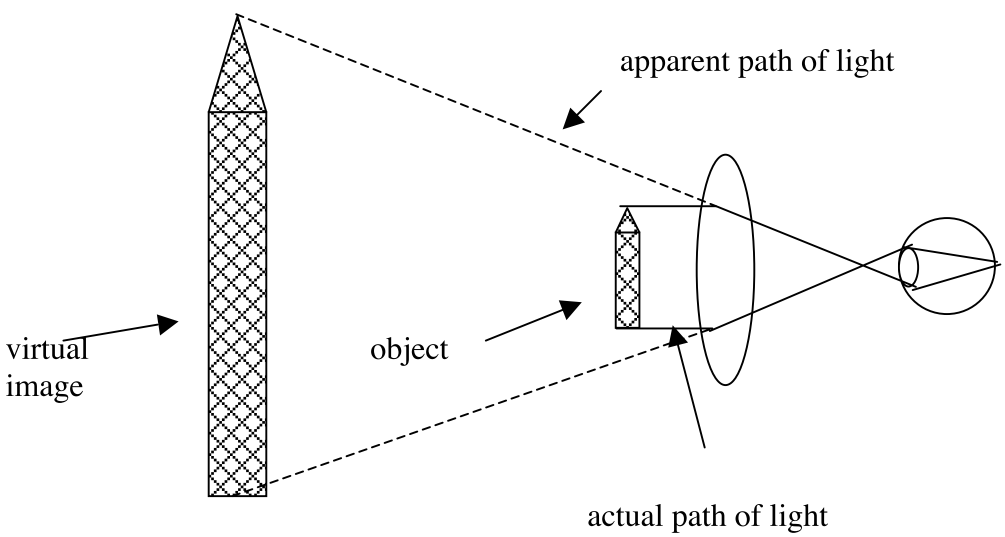


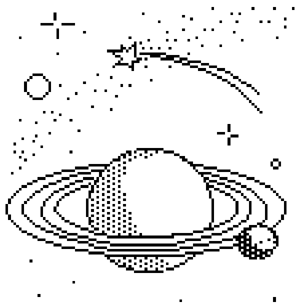
Figure A

Appendix B – A Magnifying Glass

The magnified image of the object that you see when looking through a magnifying lens is not a real' image. There is no actual point in space onto which light rays are being focused. Rather the light *appears* as if its coming from a much larger object located behind the object being examined. Thus images seen through a magnifying lens are called virtual images.

Of course, all the eye knows is the direction of light rays entering it. Thus the light enters the eye as if it were originating in the virtual image. Then the lens of they eye forms a real image of the virtual image on the surface of the retina --which is what allows the brain to "see" a magnified image.





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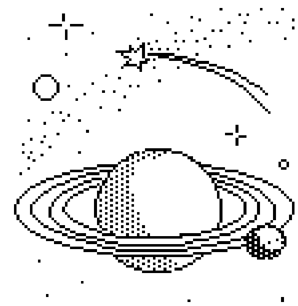


Lab 4: The Distances to the Stars - Parallax

Introduction and Goals

One of the most fundamental - and difficult - goals of astronomy is to measure the size of the Universe. At the end of the semester you will approach this goal and measure the distances to remote galaxies. However, the journey begins here with the measurement of the distances between the Sun and the very nearest stars. For all of its cosmic grandeur, the measurement of the distances to stars is founded in the most classic surveying technique - triangulation - and the most ancient astronomical observation - astrometry.

<u>Astrometry</u> is the careful measurement of the positions in the sky of celestial objects *with respect to each other*. Of course, with respect to the horizon the positions of stars are constantly changing due to the rotation of the Earth. But with respect to each other the positions of stars change very little. Thus the relative positions of the stars in the bowl of the Big Dipper or of the stars in the Belt of Orion do not appear to change from year to year.

In fact, though, very precise astrometric measurements reveal that stars do move with respect to each other. A change in position might be due to the <u>tangential velocity</u> of a star (that is, its motion across your line of sight). Alternatively, the change in position might be due to the motion of the Earth itself around the Sun. The resulting *apparent* motion of the star is known as the <u>parallax effect.</u>

Parallax is the apparent change in the direction of an object resulting from the motion of the observer. Hold your pencil at arm's length. Close first one eye, and then the other. The pencil seems to move back and forth with respect to a mark on the more distant wall. This is the parallax effect. Of course the pencil has not moved; it is actually the location of the "observer" which is changing. Now move the pencil closer to your face and repeat the experiment. You will see that the pencil seems to move a greater distance than before. Thus the amount of the parallax motion depends on the distance of the pencil from your face. In fact, by measuring the amount of the parallax motion of the pencil you could derive the distance to the pencil. Surveyors use this same technique to measure the size of fields, the heights of mountains, etc.

Exactly the same effect should happen due to the Earth moving in orbit about the Sun. The effect is shown in Figure 1. As seen from Earth, the target star seems to shift position with respect to the more distant reference stars over the course of one year. In fact the target star is not moving at all. It is the Earth which is moving, and as a consequence the direction of the target star as seen from the Earth changes over the course of one year. This apparent motion of the target star in the sky is called its parallax motion.

As can be seen in Figure 1, *the change in direction to the target star is an angle*. The parallax angle, called p and measured in arc seconds, is defined as *half* of the change in direction over 6 months. (The reason for using half the angle will be seen later.) By measuring the parallax angle p of a star and using a bit of geometry, we can measure the distance D to the star in units of the Earth-Sun distance. Thus the radius of the Earth's orbit about the Sun becomes our yardstick for measuring the size of the Universe. The Earth-Sun distance is so fundamental that it has been given the name of Astronomical Unit or AU.

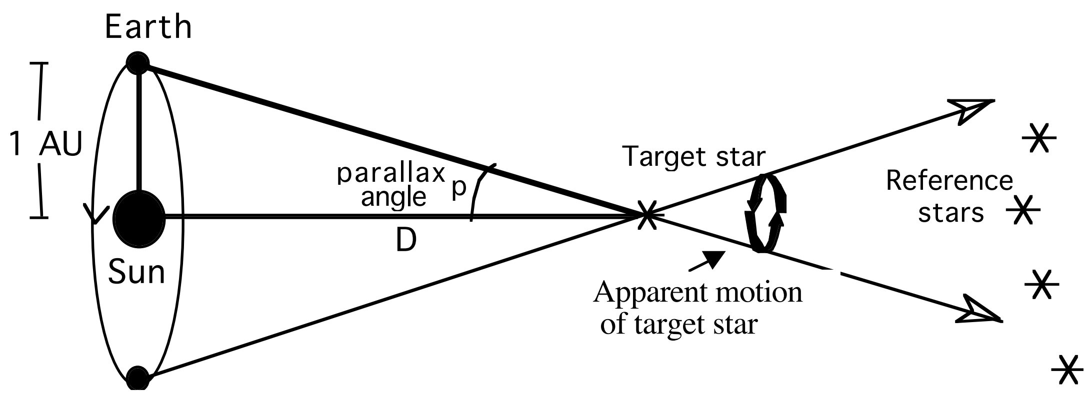


Figure 1: Geometry of parallax motion.
(Not to scale!!)

Note that measuring such motions requires the existence of a fixed reference frame, provided by celestial objects whose motions are not detectable. Usually very distant stars will do, but for the most accurate astrometry astronomers use distant galaxies or quasars as reference points.

Two thousand years ago, Greek Astronomers realized that if the Earth were moving then they should be able to observe the parallax motion of the stars. As no such motions were seen, they concluded the Earth was at rest. Their logic was absolutely correct. However, the stars are vastly more distant than they realized so that their parallax motions are too small to be seen with the naked eye. In this lab, you will observe a small portion of the sky through a telescope. You will search for stars whose positions in the sky are changing with time.

The goals of this lab are to:

i) Use astrometry to measure the parallax angles of several stars.
ii) Determine the distances to these stars.
iii) Observe the tangential velocities of several stars.

Before You Come to Class...

- Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.
- Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in **two** lab sessions.

Section 1 - Observations

The computer screen will show a window with the application "Parallax".

- **Double click on the application "Parallax".**

You will see a view of the sky like that in Figure 2.

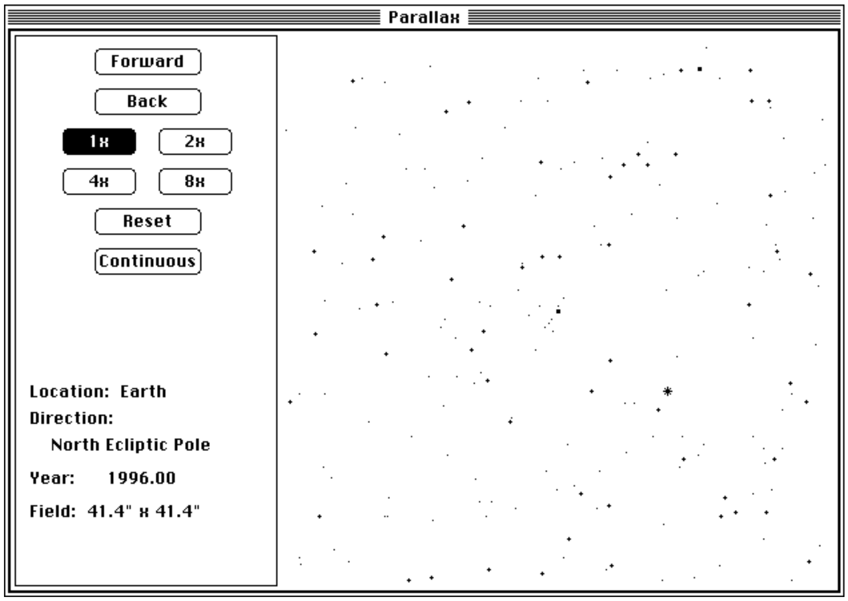


Figure 2: Sample Parallax screen

The display shows the image obtained from the telescope, and a console with several control buttons and readouts. The readouts show the location of the telescope in the Solar System, the direction in which the telescope is pointing, and the Earth date in years and decimal fractions of a year.

This telescope can only point in certain directions: in the ecliptic plane ("Ecliptic"), toward the ecliptic poles (e.g., "North Ecliptic Pole"), and at an angle 45^{o} above the ecliptic plane (e.g., "North Mid-Latitude"). Initially the telescope should be pointing toward the North Ecliptic Pole; if not, ask your TA for help.

The buttons at the top of the console give you control over time and telescope magnification. The **Forward** and **Back** buttons move time one-step forward and backward, respectively. The time step is one tenth of a year. The **Continuous** button moves time forward continuously. The magnification buttons (**1x, 2x, 4x, 8x**) change the telescope magnification. Try them out - notice that increased magnification necessarily reduces the size of the field of view.

Now that you are comfortable with the telescope, begin your observations.

- **Click the Reset button to set the date to the current year.**
- **Make sure you are on Earth looking toward the North Ecliptic Pole.**
- **Click the Continuous button to move forward in time.**

You will see that time is continuously (and rapidly!) passing. Just watch the stars for a while.

- **Click the Continuous button to stop the advance of time.**

Q1: Tape the star chart at the end of the lab manual (Figure 4) into your lab book. Identify all of the stars whose positions are changing with time. Mark them on the star chart; you may need to do a Reset if any of the stars have moved a long way from their original positions.

These will be your "target stars" for observation. Name each moving star with a name of your own choosing.

- **Click on magnification 8x.**
- **Click the Continuous button to move forward in time.**

This allows you to see stars with smaller motions (but only at the center of the field of view). Note on the star chart and name any target stars newly discovered at this magnification.

Q2: Sketch the motion of each target star on the star chart.

Do any of them show parallax motion? Which ones? Why do you think the motions are due to parallax?

Do any of them show motions other than parallax? Which ones? To what do you attribute their motion?

Q3: Of all the stars in the field of view, which do you think is nearest the Sun? Why?

- **Click the Reset button.**

ASTROMETRY

Having now observed that some stars change positions in the sky, the next step is to measure their motions. Your telescope is equipped with instrumentation designed for such astrometric measurements. In order to do astrometry, we must define a fixed <u>reference frame</u> against which we measure the positions of the stars. Such a reference frame can be defined by celestial objects whose tangential motions are too small to be detected. Typically astrometrists will define their reference frame with many such objects; in this lab one will suffice.

- **Choose a distinctive *stationary* star and mark it on your star chart as your "reference star".**

This reference star will be the fixed point from which the positions of the moving stars - or "target stars" - are measured. The reference star is your anchor point in space.

Notice that your cursor turns into a cross hair when it enters the telescope field of view.

- **Center the cursor on your reference star, and click.**

A red "x" will appear where you clicked. Note that if you wish to move the red "x", double-click at the new location.

- **Move the cursor elsewhere in the telescope field of view. Click <u>and hold</u> the mouse.**

A display will appear in the lower left-hand corner of the window showing something like X: 11.80" and Y: 23.30". These numbers show the distance of the cursor from the red "x" along the X (left-right) and Y (up-down) directions, respectively. These "distances" are actually angles on the sky, and are measured in arc seconds. (Recall that 1 degree is divided into 60 arc minutes, each of which is divided into 60 arc seconds. So there are 3600 arc seconds in 1 degree; an arc second is a small angle indeed! For comparison, the moon is 1800 arc seconds across.)

Q4: In your lab book create a data table like the one below, with columns for each of your target stars. You will need many more rows in your table than in the example, so use a new page.

STAR NAME	Snoopy		Linus		Charlie Brown		Lucy		Pigpen	
Year	X	Y	X	Y	X	Y	X	Y	X	Y

Table 1: Astrometry of Target Stars

Q5: Make astrometric measurements of the target stars.

- **Drag the cursor to a target star and center on it.**
- **Record the date and the X and Y values in your data table.**
- **Repeat for each target star. (See note below.)**
- **Click the Forward button to advance a time step and again measure the position of each target star.**

Continue until you have made enough measurements to determine the path of each target star. This will take at least one full year.

Note: If you discovered any stars to have motions visible at 8x magnification, then you will want to also make your measurements of those stars at 8x magnification. It is easiest to complete your measurements at 1x magnification and then repeat the measurement procedure at 8x magnification (with a different reference star) if necessary.

DATA ANALYSIS - PARALLAX ANGLES AND STELLAR DISTANCES

Precise measurements are the foundation of quantitative science, but in themselves measurements are just numbers. It is their analysis that transforms the numbers into an idea, a result, and a vision of the Universe.

Q6: Use your data to make a plot of the path of each star that shows parallax motion. Do this on graph paper in your lab book, making a separate plot for each star. An example is shown in Figure 3 on the next page.

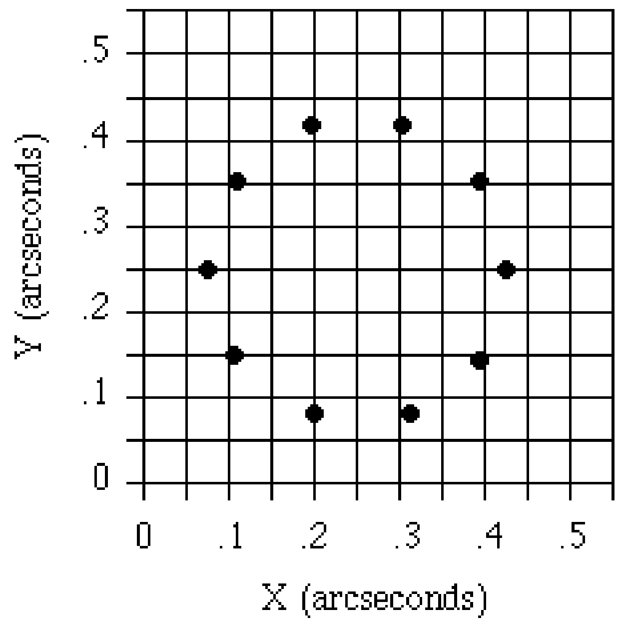


Figure 3: The motion of a target star.
(Note: units are angle units)

Q7: For those stars that you think have parallax motion, show in their plots their parallax angles p. You might want to refer back to Figure 1 in answering this.

Measure the parallax angles p and record your values in a table like the one below. Check this with your TA before going on.

STAR NAME	Parallax Angle p arcseconds	Distance D AU	Distance D pc

Table 2: Parallax and Distance Results

With these parallax angles, you can calculate the distance to each star using a little geometry. Look at the triangle marked with a heavy line in Figure 1. It is a right triangle; thus the tangent of the parallax angle p is the opposite side over the adjacent side, or

$$\tan\ p = \frac{1\ \text{AU}}{D}$$

which we can rearrange to get

$$D = \frac{1\ \text{AU}}{\tan p}$$

where p is the parallax angle and D is the distance to the target star. Your answer for D will be in units of AU.

Q8: Compute the distance in AU to each star which shows parallax motion. Show your work in your lab book. Record your results in your table.

Note: When you use a calculator to find D, don't forget to convert p from arc seconds to degrees before computing tan p! 1 degree = 3600 arc seconds.

Q9: Was your prediction for which star is nearest the Sun correct? If not, was there an error in your reasoning?

How does the distance to the nearest star compare to the distance between the Earth and the Sun? How does it compare with the distance between Pluto and the Sun (40 AU)?

Your observations have proven Copernicus correct, and provided one of the strongest proofs that in fact the Earth does orbit the Sun. Equally importantly, your observations have given a first indication of the vast size of the Universe compared to the size of the Solar System. In fact, observations of parallax only allow us to explore distances to stars in the immediate solar neighborhood - your exploration of the Universe has only just begun!

Section 2 - Further Investigations of Parallax Motion

THE PARSEC

Because the distances between stars are so large compared to the distance between the Earth and the Sun, the AU is actually not a very convenient unit for the measure of distances between stars. Since the first stellar distances were measured with the parallax technique, 19th century astronomers developed a unit of distance based on parallax angle. This unit of distance is called a parsec. A parsec is the distance to a star which has a **par**allax angle of 1 arc **sec**ond. The parsec is a convenient unit since the distance to a star in parsecs is found simply by taking the inverse of the parallax angle measured in arc seconds, or

d (pc) = 1 / p (arc seconds)

Q10: Compute the distance in pc to each star that shows parallax motion. Record your results in your table. How far away is the nearest star in parsecs? How far away is the furthest star for which you were able to measure a parallax angle?

The center of the Galaxy is 8000 pc away. How large would its parallax angle be? Could you measure it with your telescope?

The parallax technique is the best way to measure the distance to an astronomical object, but unfortunately its usefulness is limited to the neighborhood of the Sun. With the best astrometric equipment (in space) we are able to measure parallax angles as small as 0.001", which allows us to measure distances only as far as 1000 parsecs, and only precise distances to about 100 pc.

PARALLAX MOTION - DEPENDENCE ON LOCATION IN THE SOLAR SYSTEM

Suppose that you are resting on a cloud in Jupiter's atmosphere watching the stars toward the North Ecliptic Pole.

Q11: How do you predict that the motion of each of your parallax stars will change? Why? Try to make your prediction quantitative, given that the radius of Jupiter's orbit is 5.2 AU.

- **Point your telescope to the North Ecliptic Pole using the Sky Regions menu.**
- **Move to Jupiter using the Options menu.**
- **Click on Continuous and just watch for a while.**

Q12: Was your prediction correct? If not, explain why.

Note that when you moved to Jupiter, the time interval became one tenth of a Jovian year.

PROPER MOTIONS - THE TRUE MOTIONS OF STARS

Not all of the stars that you observed to move showed parallax motion. Some moved in straight lines. Astronomers call this motion "proper motion". In physics the word "proper" has the very specific meaning of "belonging to oneself". The proper motions of stars are literally due to the motion of the star itself.

All stars are moving about in space, but we can't detect their proper motion with our eyes. This is not because the stars are moving slowly; in fact, one of the fastest stars ever discovered is moving at a speed of 1000 km/sec (over 2 million miles per hour)! Rather it is because most of the stars are so far away.

Q13: Are the proper motion stars in the North Ecliptic Pole field farther than the stars you have been studying? Explain your answer. Which of the proper-motion stars in the North Ecliptic Pole field would you predict to be the closest? How sure are you of your prediction? Briefly explain your reasoning here. Refer to the drawing below.

<u>**Section 3 - Parallax and Proper Motions**</u>

PARALLAX MOTION - DEPENDENCE ON LOCATION IN THE SKY

At the moment your telescope is pointing toward the North Ecliptic Pole. If you were to point your telescope in the direction of the Ecliptic, you would observe stars which lie in the plane of the Earth's orbit.

Q14: Suppose a star in the direction of the Ecliptic were close enough to show parallax motion. Make a sketch of what its parallax motion would look like, and briefly explain your prediction.

- **Point your telescope to the Ecliptic using the Sky Regions menu.**
- **Click on Continuous and just watch for a while.**

Q15: Do any of the stars show parallax motion? Sketch their motions. Are they as you predicted? If not, what was the error in your reasoning?

One star in the Ecliptic star field showed a rather peculiar motion. Seeing a Nobel Prize in your future, you accept its challenge.

- **Reset to the current date.**
- **Move back to Ecliptic Field using Sky region.**
- **Move back to Earth using the Options menu.**

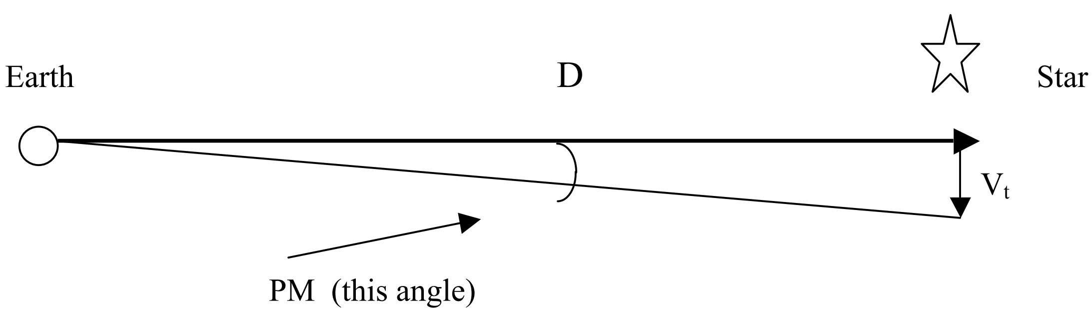
Q16:	Find and observe this star. Sketch its motion, and give a qualitative explanation for its peculiar path through the sky.

Make astrometric measurements of the star's path. Answer the following questions using Figure 4 and the equation below as a reference.

Q17:	What is the distance to this star in parsecs?

Q18:	What is the tangential velocity of this star in km/sec?

Proper Motion (PM), Distance (D) and Tangential Velocity (V_t)



$$V_t = 4.74 \, D * PM$$

(Km/sec) (pc) (arcseconds/yr)

Figure 4. The relationship between proper motion (PM), distance (D) and tangential velocity (V_t).

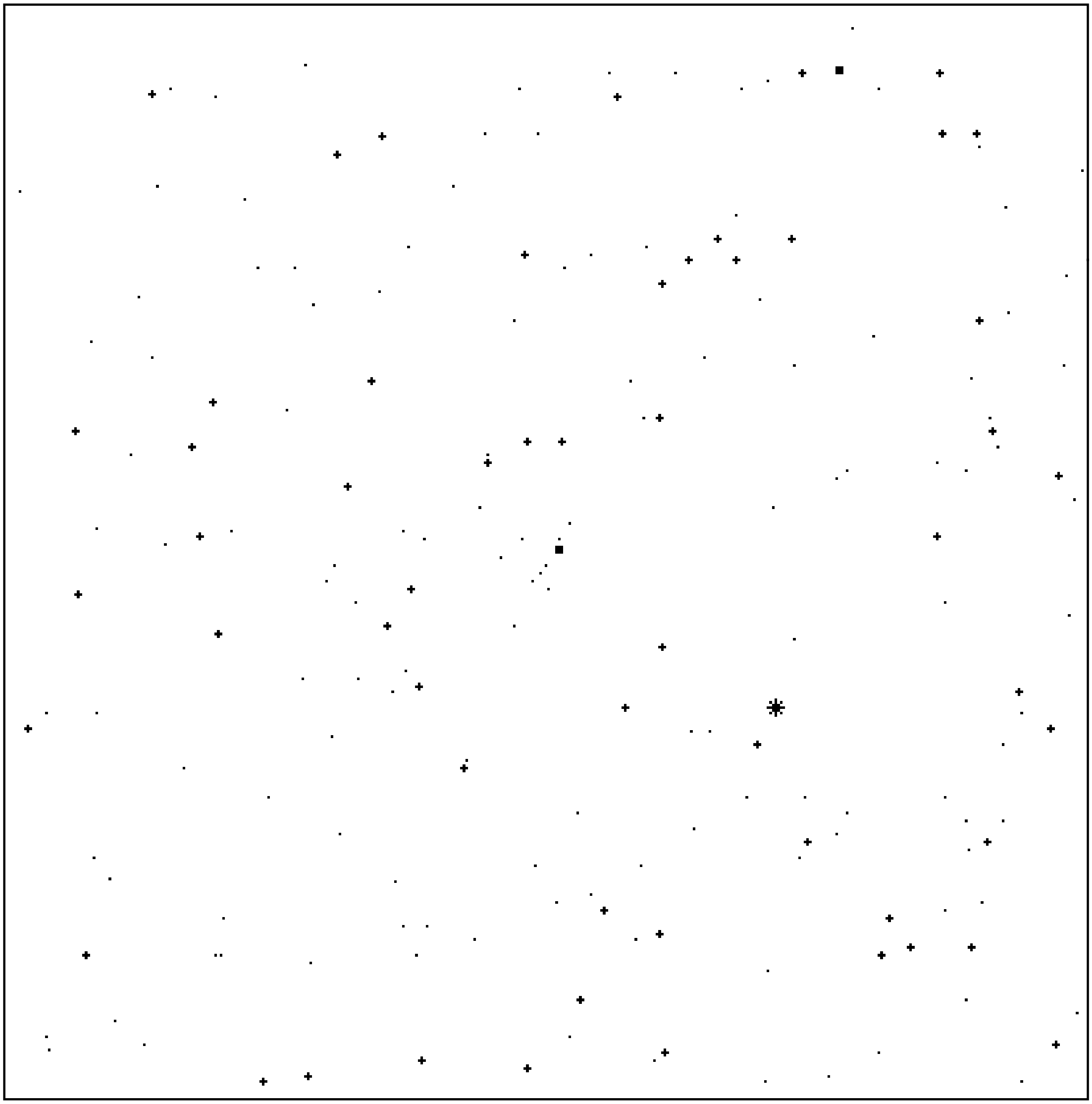
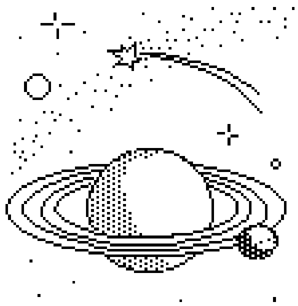


Figure 4: Star Chart for North Ecliptic Polar Region



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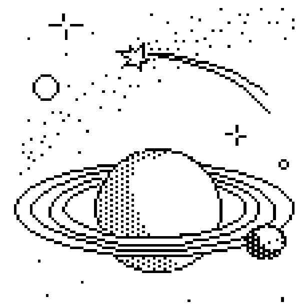


Lab 5: Spectral Classification of the Stars

<u>Introduction and Goals</u>

The classification of stars is fundamental to stellar astronomy because it enables us to reduce a large sample of diverse individuals to a manageable number of groups with similar characteristics. Thus <u>spectral classification</u> is as basic to astronomy as the Linnean system of classifying plants and animals by genus and species is to biology. Since group members are presumed to have similar physical characteristics, we can transfer knowledge gleaned about any star in the group to all stars in the group. At the same time, unusual cases may be readily identified by the very fact that they cannot be classified. Such peculiar objects are typically subjected to intensive study, and very often reveal new and important astrophysical phenomena. Occasionally they also reflect back on normal stars, for example in providing evolutionary links between classification groups.

Classification is as much akin to art as to quantitative science. Classification criteria are almost always developed *before* a group of objects is understood physically. Thus there is no guarantee that a classification scheme will organize objects in a way that is related to important physical properties. For example, the classification of vehicles at the Union might equally well be done by color or number of wheels, but only one of these criteria will tell you anything important about bikes vs. cars vs. trucks. The development of a meaningful classification scheme requires insight, an aesthetic sense, and good fortune.

Absorption lines were first observed in the spectrum of the Sun by the German physicist Joseph von Fraunhofer early in the 1800's, but it was not until late in that century that astronomers were able to routinely examine the spectra of stars in large numbers. Astronomers Angelo Secchi and E.C. Pickering were among the first to note that stars could be divided into groups or "types" by the appearance of their spectra. Subsequently, astronomers at the Harvard Observatory refined these <u>spectral types</u> and named them with letters, A, B, C, etc. They also embarked on a massive project to classify the spectra of all stars brighter than about 9th magnitude, more than 200,000 stars. A trio of astronomers, Williamina Fleming, Annie Jump Cannon, and Antonia Maury did most of the classifications. The results of that work, the Henry Draper Catalog (named after the benefactor who financed the study), were published between 1918 and 1924, and provided classifications of 225,300 stars. Even this study, however, represents only a tiny fraction of the stars in the sky.

In the course of the Harvard classification study it was realized that the spectral types could be rearranged so that every absorption line would show the same behavior with changing spectral type: first weak or not present, then strengthening, and then weakening again. After this rearrangement (and the consolidation or rejection of some types), the order of spectral types became O, B, A, F, G, K, and M. Sample spectra in this order are shown in Figure 1. Choose an absorption line and watch its depth change with spectral type.

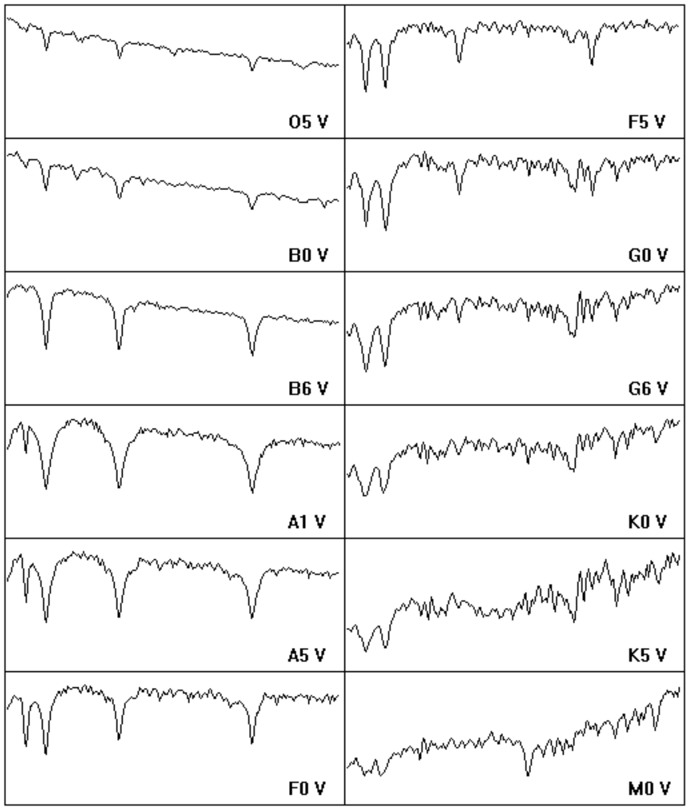


Figure 1: Sample Spectra of Different Spectral Types

The consequence of this rearrangement was rapid progress in the understanding of stars; many stellar properties were found to correlate with spectral type and soon the famous Hertzsprung-Russell diagram was born. However, the physical basis for these correlations was not known. It was not until the 1930's that it was realized that the main thing that determined the spectral type of a star was its surface temperature. The O stars were the hottest stars, with temperatures around 40,000 °K, while the M stars were the coolest stars, with temperatures around 3000 °K. The intuitive rearrangement of the spectral types at the Harvard Observatory had in fact ordered the stars by one of their most basic physical properties.

Though the letter designations have no meaning in themselves, they continue to be used to identify the spectral types of stars. However, the divisions in spectral type have been made finer, with each spectral class being divided into tenths, or subtypes. Thus a B star could be a B0, B1, B2, ..., B9. In this scheme, a B0 follows an O9, an A0 follows a B9, and so on. The decimal divisions of spectral types also are a sequence in temperature. A B5 star is cooler than a B0 star but hotter than a B9 star. The Sun has a spectral type of G2.

The spectral type of a star is so fundamental that an astronomer beginning the study of any star will first determine its spectral type. If it hasn't already been catalogued (by the Harvard astronomers or the many who followed in their footsteps), then the classification must be done by taking a spectrum of the star and comparing it with an atlas of standard stars which provides examples of each spectral type. The spectral type of a star allows the astronomer to know not only the temperature of the star, but also its luminosity and its color. These properties, in turn, can help in determining the distance, mass, and many other physical quantities associated with the star, its surrounding environment, and its past history. Thus a knowledge of spectral classification is fundamental to understanding how we put together a description of the nature and evolution of the stars.

The goal of this lab is to introduce you to the classification of stars from stellar spectra. You will first be introduced to stellar spectra and learn how the classification system works. Then you will use a telescope to take spectra of stars yourself and analyze them. Finally you will follow the footsteps of Hertzsprung and Russell and create a Hertzsprung-Russell diagram for the Pleiades star cluster.

The computer program you will use consists of two parts. The first part is a spectrum display and classification tool. This tool enables you to display a spectrum of a star and compare it with the spectra of standard stars of known spectral types. The second part is a realistic simulation of an astronomical observatory. You will have access to three telescopes of differing apertures, each equipped with a spectrograph. You will pick a telescope that is most appropriate to your needs, steer the telescope so that light from a star of your choosing passes into the slit of the spectrograph, and then direct the spectrograph to collect photons. When a sufficient number of photons are collected, you will be able to see the distinct spectral lines that will enable you to classify the spectrum.

Before You Come to Class ...

Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.

Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in **two** lab sessions.

This lab incorporates software developed by the Contemporary Laboratory Experiences in Astronomy project of Gettysburg College, funded in part by the National Science Foundation.

Section 1 - How to Classify Stars

You will soon be using several telescopes to obtain spectra for the classification of stars in the Pleiades star cluster. One of these telescopes is among the largest in the world and time on it is valuable. Thus it is prudent that you learn how to classify stars *before* you go to the telescope. In this section you will be using a set of archival spectra to hone your classification skills.

GETTING STARTED

- **Double click on the Spectral Classification icon.**
- **Click Log In on the menu bar.**
- **Enter your name(s) in the Student Accounting window; this is essential for naming data files that you will create. Ignore the Lab Table Number. Click OK, and then Yes.**
- **Select Classify Spectra from the Run menu.**

This will bring up a display like the one in Figure 2. This is your Classification Laboratory. The three panels will display the spectra of three stars. (They will be blank at first, but we'll fix that in a moment.) Typically, the middle panel will display the spectrum that you are trying to classify, and the top and bottom panels will display spectra of standard stars. Standard stars are stars that have been selected to be the defining examples of a spectral subtype. Classification of an unknown star is done by comparison with these standard stars.

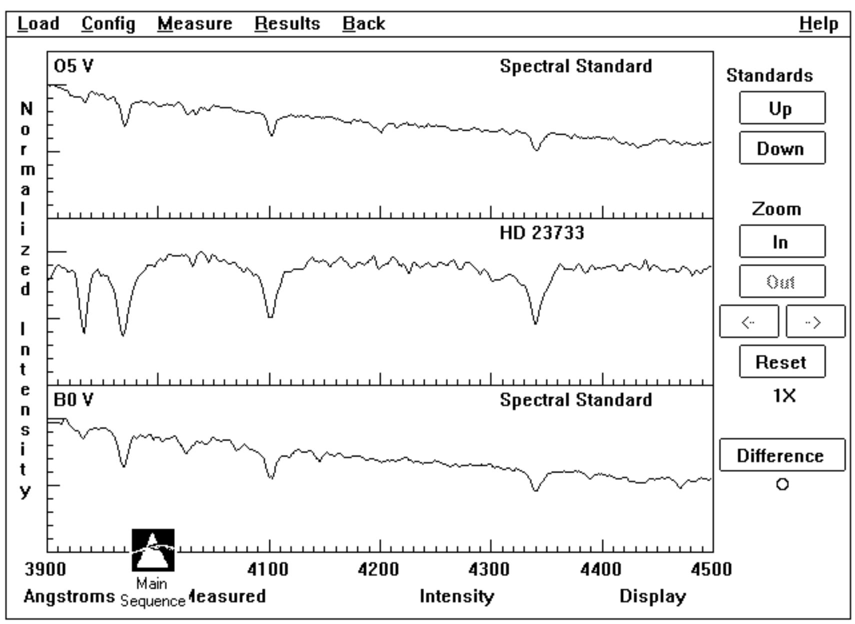


Figure 2: Spectral Classification Screen

The first step is to load the catalog of standard stars:

- **Select Atlas of Standard Spectra from the Load menu.**

- **Select Main Sequence, and then click OK.**

A small window showing an atlas of spectra will appear. The four spectra that are shown are only a subset of the entire atlas.

- **Scroll up and down to examine the standard spectra. This is done by clicking in the scroll bar (gray area) above or below the scroll button.**

Notice the letters and numbers in the lower right corner of each spectrum. As explained in the Introduction, the first letter (O, B, A, F, G, K, M) corresponds to the spectral type and the number is the subtype. The Roman numeral V simply indicates that these are main-sequence stars, a concept that we will discuss later in the lab.

Now load a star on which to practice classification.

- **Click the small square with a horizontal black line in the upper right corner of the Main Sequence window.**
- **Open the Program List (Load Menu to Unknown Spectrum to Program List).**
- **Select the star HD 37767 and click OK.**

The spectrum of HD 37767 should now be displayed in the middle panel on the screen, and the upper and lower panels should show O5 V and B0 V spectral standards, respectively. ("HD 37767" stands for star 37767 in the Henry Draper catalog.)

JUST WHAT IS A SPECTRUM?

Everyone has seen a spectrum before, whether it be a rainbow or the light from a prism. In these cases your eyes register the intensity of light at each color and your brain converts that information to an image. A <u>spectrograph</u> does essentially the same thing, measuring the intensity of light at every wavelength and sending the results to a computer. Typically the computer then makes a graph of intensity versus wavelength, such as shown in Figure 1 or on the computer screen.

Both the image in your brain and the graph produced by the computer are showing intensity as a function of wavelength, and each is properly called a <u>spectrum</u>. However, many people have difficulty switching between a visual image of a spectrum and a graph of a spectrum. In fact, the two are showing exactly the same thing, which you can see by comparing a "photograph" of a spectrum with a graph of the same spectrum.

- **Config menu to Display to Comb (Photo and Trace).**

This option shows both a photo of a spectrum (middle panel) with a graphical trace of the same spectrum (lower panel). Notice that wherever there is a dark absorption line in the photo spectrum, there is a dip in the graphical spectrum. Notice also that as the photo spectrum gets darker at longer wavelengths (right-hand side) the intensity in the graphical spectrum decreases.

A spectrum has several components. The smooth portion of a spectrum between the dark lines is called the <u>continuum</u>. The shape of the continuum dictates the color of a star. For example, if the continuum is higher at larger wavelengths (the red end of the spectrum), then the star has more red light than blue light and will look red in the sky. On the other hand, if the continuum is higher at shorter wavelengths (the blue end of the spectrum), then the star has more blue light than red light and will look blue in the sky. The shape of the continuum is closely linked to the temperature of a star.

Q1:	Is HD37767 a red or blue star? Explain your answer.

The dark lines in the photo spectrum or the dips in the graphical spectrum are called absorption lines. Unlike the continuum which extends over all wavelengths, a single absorption line occurs over a very small range of wavelengths. Within this range of wavelengths the star is darker than at other wavelengths. This is because some element (perhaps hydrogen) in the atmosphere of the star absorbs light in that range of wavelengths. A star's spectrum has many absorption lines both because there are many elements in the star's atmosphere, and because any one element can absorb light at many different wavelengths. Thus in the spectrum of HD37767 the three deepest absorption lines are all due to absorption by hydrogen.

Once you become familiar with them, graphical displays of spectra are much easier to analyze then photo displays.

- **Config menu to Display to Intensity Trace.**
- **Open the Program List (Load Menu to Unknown Spectrum to Program List).**
- **Select the star HD 24189 and click OK.**

Each element has characteristic wavelengths of light at which it can absorb (and emit) light. So given an absorption line an astronomer can identify the element which caused it. With comprehensive study of a spectrum an astronomer can determine the chemical makeup of a star.

- **Select Spectral Line Table from the Load menu.**

The window displays a list of wavelengths of absorption lines. Each absorption line is associated with an element. (Ignore the Roman numerals.)

- **Move the Spectral Line Identification window up or down so that you can see the HD24189 spectrum. (Place the cursor on the blue top bar, click and hold the mouse, and drag the window.)**
- **Double click on any absorption line in the HD 24189 spectrum.**

A red line appears at the wavelength where you clicked. If you clicked at the center of a line, dashed red lines will bracket one of the elements on the line table.

Q2:	Find the deepest (darkest) absorption line in the spectrum of HD 24189 and double click on it. What is the wavelength of this line? What element is causing this line? What other elements are present in the atmosphere of this star?

- **Click the small square with an X in the upper right corner of the Spectral Line Identification window.**

CLASSIFYING YOUR SPECTRUM

Spectral classification is done by comparison with standard stars of known spectral type. The primary classification criteria are the patterns and strengths of the absorption lines. Not only should the same absorption lines be present in the standard star as the unknown star, but the relative line strengths should be similar. A secondary criterion is the slope of the continuum. This should be similar in both the standard and unknown spectra.

- **Click the "Up" and "Down" buttons on the upper right side of the screen. These permit you to step through the atlas of standard stars, always presenting two standard stars of adjacent spectral type in the upper and lower panels.**

As you step through the spectral standards, you will notice that lines will grow in strength and then weaken again. Different lines will reach their maximum strength at different spectral types. This rise and fall of lines provides a sequence by which to classify stars.

- **Find two standards that you think bracket the spectral type of HD24189. Pay particular attention to the relative strengths of neighboring absorption lines.**

Optimally you would classify stars to the nearest spectral subtype, i.e. G2 not just G. Since the atlas of standard stars only includes two subtypes of each spectral type (for example, A0, A5, F0, F5, etc.), you will have to interpolate between the two nearest standard stars. Interpolation is a form of estimation where you must choose a value between two other known values. Interpolation is by its nature imprecise, but still your estimate will be better than forcing your classification to be one of the limited sample of standards in the atlas.

Q3: Estimate the spectral type of HD24189 and record it in your lab book. Give reasons for your answer. (For example, "the strengths of the lines at 4340Å and 4104Å are almost exactly those of type A0 or A5, and the strength of the 3933Å line lies somewhere between them".)

Repeat the steps above to classify:

HD 124320
HD 242936

When you have finished, tell your TA. He/she will tell you the correct answers. If you had any that were wrong by more than half a type (e.g., A2 when the correct answer was B5), revisit them and see if the correct answer seems reasonable.

If you wish, ask your TA for another set of stars to practice on. You must have this skill mastered if you are to succeed in the next section.

Section 2 - A Spectroscopic Study of the Pleiades Star Cluster

Some of the most beautiful objects in the sky are star clusters, groups of stars ranging in number from a few hundreds of stars ("open clusters") to a few million stars ("globular star clusters"). All of the stars in these clusters are bound to each other by gravity. Star clusters are also valuable laboratories for the study of stars, because within any given cluster all of the stars have the same age, composition, and distance. This permits us to study the relationships between fundamental stellar properties such as mass, surface temperature, and luminosity.

One of the most famous star clusters is the Pleiades cluster. Located in the constellation Taurus, it is easily visible to the naked eye high in the winter skies. To the eye the cluster is dominated by a few bright stars, called the Seven Sisters by the ancient Greeks. (This cluster of stars is also known as Subaru to the Japanese; you might recognize the pattern of the brightest stars as the logo on Subaru automobiles.) The cluster also contains several hundred much fainter stars. Since the Pleiades are close to the Sun (≈120 pc distant), even these fainter stars are accessible to Earth-based telescopes. You have been allocated observing time on a small (0.4m) optical telescope equipped with both a television camera and a spectrograph. Using this equipment, you will classify a sample of Pleiades stars having different brightness levels and look for correlations between spectral type and other stellar properties.

How does the equipment work? The TV camera acts in place of an eyepiece, allowing you to see the stars in the telescope field of view. Observing with the TV camera you can center a star of interest in the field of view. Once centered, you direct the light of the star to the spectrograph. To select TV or spectrograph, move a small flat mirror that is operated by pushing the Monitor button. The entrance to the spectrograph is a small slit which allows only the light of the star into the spectrograph. Once you have carefully centered the star on the slit, you instruct the spectrograph to begin counting the photons at each wavelength arriving from the star. As it is doing so the counts are displayed on a computer screen as a spectrum - a plot of the number of photons collected versus wavelength. When a sufficient number of photons are collected, you will be able to see the absorption lines of the star.

Now, give the equipment a trial run by obtaining a test spectrum of a star in the Pleiades.

- **Click Back on the menu bar, and then Yes.**
- **Select Take Spectra from the Run menu.**

You will see the telescope control panel as found in the "warm room" at the observatory (see Figure 3). Typically astronomers are in separate rooms or even buildings from the telescope dome. This is not only for the comfort of the astronomers; any heaters in a telescope dome (including bodies!) cause drafts that lead to turbulent air and bad seeing.

Notice that the dome is closed and the tracking is off.

- **Open the dome by clicking the Dome button.**

Once the dome is open, you will see the view of the TV camera through the telescope. This camera provides a wide field of view so that you can see a large section of sky from which to pick your target stars.

Notice that the stars are drifting across the field of view.

- **Click the Tracking button.**

By turning on the tracking you have started a motor that makes the telescope move at exactly the same rate as celestial objects move across the sky due to the rotation of the Earth.

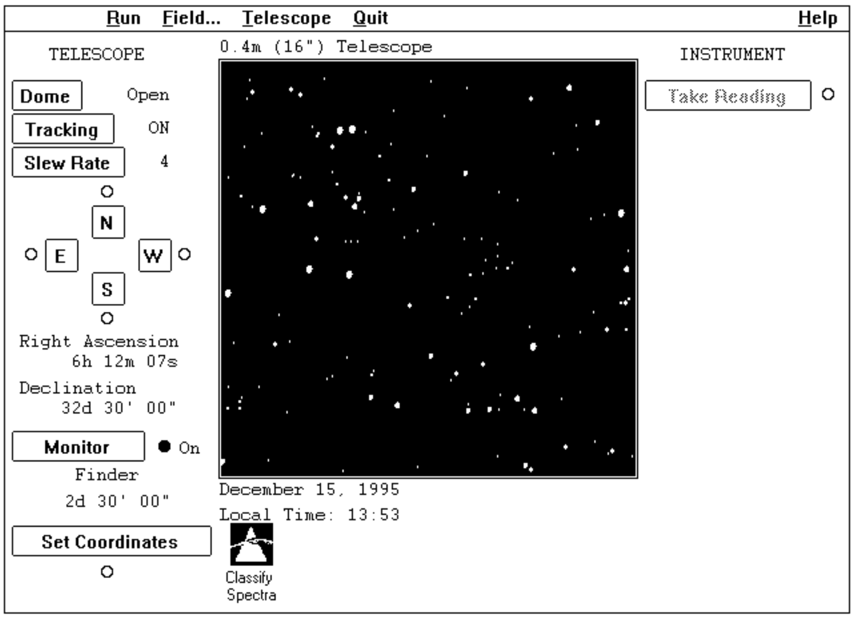


Figure 3: Telescope Control Screen, Finder View

After the dome opens, the telescope needs to be pointed to the Pleiades.

- **Click Field... on the menu bar.**
- **Select Pleiades and click OK.**

A message will come up that says the telescope is "slewing" to a new location. This is a term astronomers use to describe rapid movement of the telescope to a new target, in this case the Pleiades cluster.

- **Choose any star in the cluster.**
- **Use the NESW buttons to center your star in the red box. (If the motion is too slow, click Slew Rate to change the speed that the telescope moves.)**
- **Click the Monitor button to switch from Finder to Instrument.**

The Monitor button switches between the wide-field TV camera (“Finder”) and the spectrograph ("Instrument"). You will notice that switching to the spectrograph gives you a much smaller field of view. It also caused the red box to turn into a pair of vertical lines. These lines are the spectrograph slit, the hole through which light enters the spectrograph. The closer your star is to the center of the slit, the more light will get into the spectrograph and the faster you will obtain a good spectrum.

- **Use the NESW buttons to center the slit on the star.**
- **Click Take Reading.**

This will switch you from the telescope control panel to the spectrograph output screen. (See Figure 4.)

- **Click Start/Resume Count to begin collecting data.**
- **After a while, click Stop Count.**

Light of all wavelengths enters the spectrograph slit. Using either a prism or a grating, the spectrograph spreads the light out into a spectrum. Effectively, the spectrograph is sorting the photons into bins of different wavelengths, and keeping a running count of the number of photons at each wavelength. Every time a photon of a given wavelength is detected, the computer increases the count of such photons by one. This running count is displayed on the screen as a spectrum. This will be most evident when you stop the counting, at which time the computer draws a solid line through the counts at each wavelength.

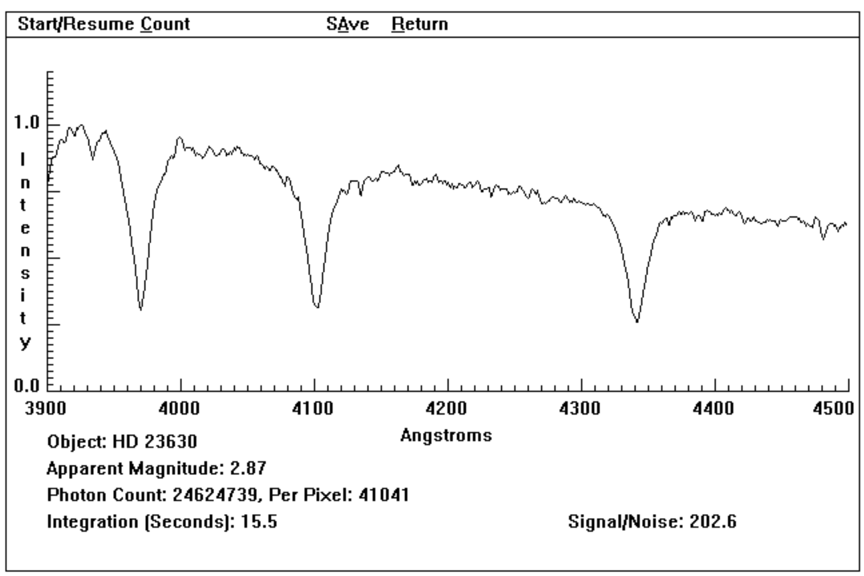


Figure 4: Spectrograph Screen with Sample Spectrum

It may seem odd to you that the spectrum doesn't keep getting higher and higher in the plot if the computer keeps collecting more photons. This is because the computer is always changing the scale of the y-axis in order that the spectrum will fit on the screen. More formally, the intensity (the y axis) of each spectrum is "normalized" so that the maximum intensity is always given a value of 1.0. While the height of the spectrum doesn't change, you will notice that the clarity of the spectrum improves with time.

Other valuable information is also displayed on the screen. To summarize:

Object: the name of the star being studied

Apparent magnitude: the apparent magnitude of the star

Photon count: the total number of photons collected so far, and the average number per pixel

Integration (seconds): the number of seconds over which photons have been collected

Signal-to-Noise Ratio: a measurement of the quality of the data (see below)

To return to the telescope control panel

- **Click Return in the menu bar.**
- **Click No (you do not want to save the spectrum).**
- **Click Monitor to return to the wide-field view.**

SIGNAL AND NOISE

All observations are not created equal. Depending on the brightness of a star, the size of the telescope, the sensitivity of the spectrograph, etc. the quality of an observed spectrum can vary from excellent (such as the standard star spectra which you have been using, all of which are bright stars) to unusable. The quality of a spectrum, or of any data, is measured by the signal-to-noise ratio.

The concepts of signal and noise are fundamental to all quantitative sciences. The signal is the information in the data, for example an absorption line. The noise is random fluctuations in the data. A good analogy is listening to a weak radio station. The words of the DJ are the signal; the static is the noise. The higher the ratio of signal-to-noise, the better you can understand the DJ.

As with radio stations, astronomical signal-to-noise is improved by collecting more photons. However, astronomers can't get closer to their "radio stations"! Instead, astronomers improve signal-to-noise by collecting photons for a longer time. Imagine if you collected photons from a faint star for 1 second. At some wavelengths you might catch one photon, at others none. You would have a hard time identifying the spectral type with such data! Now imagine you resume your photon collection until ten seconds have passed. Likely you will have counted a few photons at every wavelength, but your spectrum will still be "noisy" with so few photons. As you collect photons for a longer and longer time, the noise will continue to decrease until the spectrum begins to emerge from the noise and then eventually becomes clearly defined.

You can easily see the interplay of signal and noise by observing a faint star:

- **Use the finding chart at the end of this lab to find the star labeled "s".**
- **Center the red box on this star.**
- **Click the Monitor button.**
- **Center the spectrograph slit on the star.**
- **Click Take Reading.**

Q4: **• Click Start/Resume Count and collect photons for approx. 10 seconds.**
• Click Stop Count.
• Record the integration time and the signal-to-noise ratio (Signal/Noise).

Can you identify any absorption lines at 4100Å?

• Continue to collect photons in 30-second intervals.
• Record the integration times and Signal/Noise values.
• Note whether you think you see any absorption lines at 4100Å.
• Stop after 150 seconds of integration.

At what Signal/Noise level could you *first* detect an absorption line at 4100Å? Did you have any false identifications, i.e. features that you thought were lines that ended up not being real with more integration?

Describe what happened as you observed longer and longer. Did the lines of the star get deeper as you observed longer? Or did the range of noise get smaller? Sketches may be worth a thousand words here.

For the purpose of measuring spectral types, mere detection of the lines is not sufficient. Their shapes need to be well defined so that they can be accurately compared to standard stars. The spectra you classified in the last section had signal-to-noise ratios of greater than 100!

- **Click Return in the menu bar.**
- **Click No (you do not want to save the spectrum).**
- **Click Monitor to return to the wide-field view.**

MEASURING SPECTRAL TYPES OF PLEIADES STARS

There are a lot of stars in the Pleiades cluster; if you were to try to classify all of them, it would take much longer than a lab period. The same is also true for much astronomical research, and so often groups of astronomers will form collaborations to accomplish large observing programs. Your TA will organize collaborations, each including several pairs of students. Each pair of students will observe a set of Pleiades stars, and then the result of all pairs within each collaboration will be combined.

In the table below the Pleiades stars have been divided into sets. Note that these are ordered from brightest to faintest stars.

- **Your TA will assign to you a set to work on.**
- **Tape the Spectral Classification Log (next page) into your lab book.**

Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7
HD 23302	HD 23480	HD 23288	HD 23862	HD 23338	HD 23630	HD 23408
	HD 23441	HD 23568	HD 23753		HD 23324	HD 23432
g		HD 23410		HD 23156		HD 23873
	HD 23489		HD 24076		HD 23361	
HD 23567			HD 23791	HD 23246		HD 23585
HD 23326	HD 24132	HD 23289		HD 23608	HD 23912	
HD 23713	HII 1132	HD 23513	HD 23158	p	o	n
u	r	t	v	HD 23464	s	q

Spectral Classification Log

Star Name	File Name	Magnitude	Spectral Type	Comments

Now you are ready to obtain high-quality spectra for spectral typing. Try to get a signal-to-noise ratio of at least 50 for each star. For faint stars this may take some time, so consider applying for time on a larger telescope (see below).

- **Use the finding chart at the end of this lab to find the first (and brightest) star in your list.**
- **Record the star's name on your log sheet.**
- **Use the NESW keys to center your star in the red box.**
- **Click Monitor, center the slit on the star, and click Take Reading.**
- **Click Start/Resume Count.**
- **Let the photons accumulate until the Signal/Noise is 50 or more.**
- **Click Stop Count.**
- **Record the star's magnitude on your log sheet.**
- **Click Save (to store your spectrum on disk).**
- **Choose a number as an ID for your disk file. Type this number and click OK. Record the file name on your log sheet, then click OK.**
- **Click Return and OK.**
- **Double click the Classify Spectra icon on the bottom of the screen. If the icon is not present, go to Run on menu bar and select Classify Spectra. Put away the Main Sequence window by clicking on triangle in upper right corner.**
- **Load your saved spectrum. (Load menu to Unknown Spectra to Saved Spectrum and select the file name.)**
- **Classify your star and record the spectral type on your log sheet.**
- **Click Back and Yes to return to the telescope.**
- **Repeat for each star in your list. Remember, the list is ordered from brightest to faintest. You may want to switch to a larger telescope for the faintest stars (see next section).**

BIGGER IS BETTER!

Are the faint stars taking "forever"? Time for a bigger telescope! There are three different telescopes you can use: The 0.4-meter Washburn telescope is the one you started with automatically. (0.4 meters refers to the diameter of the telescope. Remember, the light collection power of a telescope goes as the *square* of its diameter, so bigger is *much* better!) You can also request time on the 1.0 meter Pine Bluff telescope west of Madison or the 4 meter Mayall telescope at Kitt Peak, Arizona. There's one drawback, though: the bigger the telescope, the more astronomers who want to use it, so you may not be granted observing time.

To request time on another telescope:

- **Go to the Finder mode.**
- **Telescope menu to Request Time. Select either the 1.0 meter or 4.0 meter telescope. Note: you are less likely to be granted time on the larger telescope, but you lose nothing by trying.**
- **If you are not granted observing time, you will have to wait until the next application period. You will be notified when you can apply again.**

- **If you are granted observing time for a certain number of stars, you can switch telescopes using the Access entries in the Telescope menu. This will close the dome of the telescope now in use.**
- **Click Dome to use the new telescope. (Some time is lost here in closing and opening the domes, but you will gain it back quickly in shorter integration times.)**
- **Continue to collect and classify spectra.**

Section 3 - The Hertzsprung-Russell Diagram

Your collaboration now has a database of stars with spectral classifications. Thus you are in a similar situation to astronomers at the turn of the century after publication of the Henry Draper catalog. These databases are wonderful resources, but in themselves they don't provide much physical insight about stars. Such insight comes from the discovery of correlations between physical properties.

Q5: Combine the data from all pairs of students in your collaboration.

Plot the spectral types of the stars versus magnitude. Use the graph paper provided on next page and tape it into your lab book.

Q6: The plot you have created is very similar to one created by Ejnar Hertzsprung in the Netherlands and Henry Norris Russell in Princeton, quite independently, around 1910. It has become the most significant plot in stellar astronomy.

From their plots Hertzsprung and Russell identified a "main sequence" of stars. Do you see a main sequence in your plot? Do you see any trends in your plot?

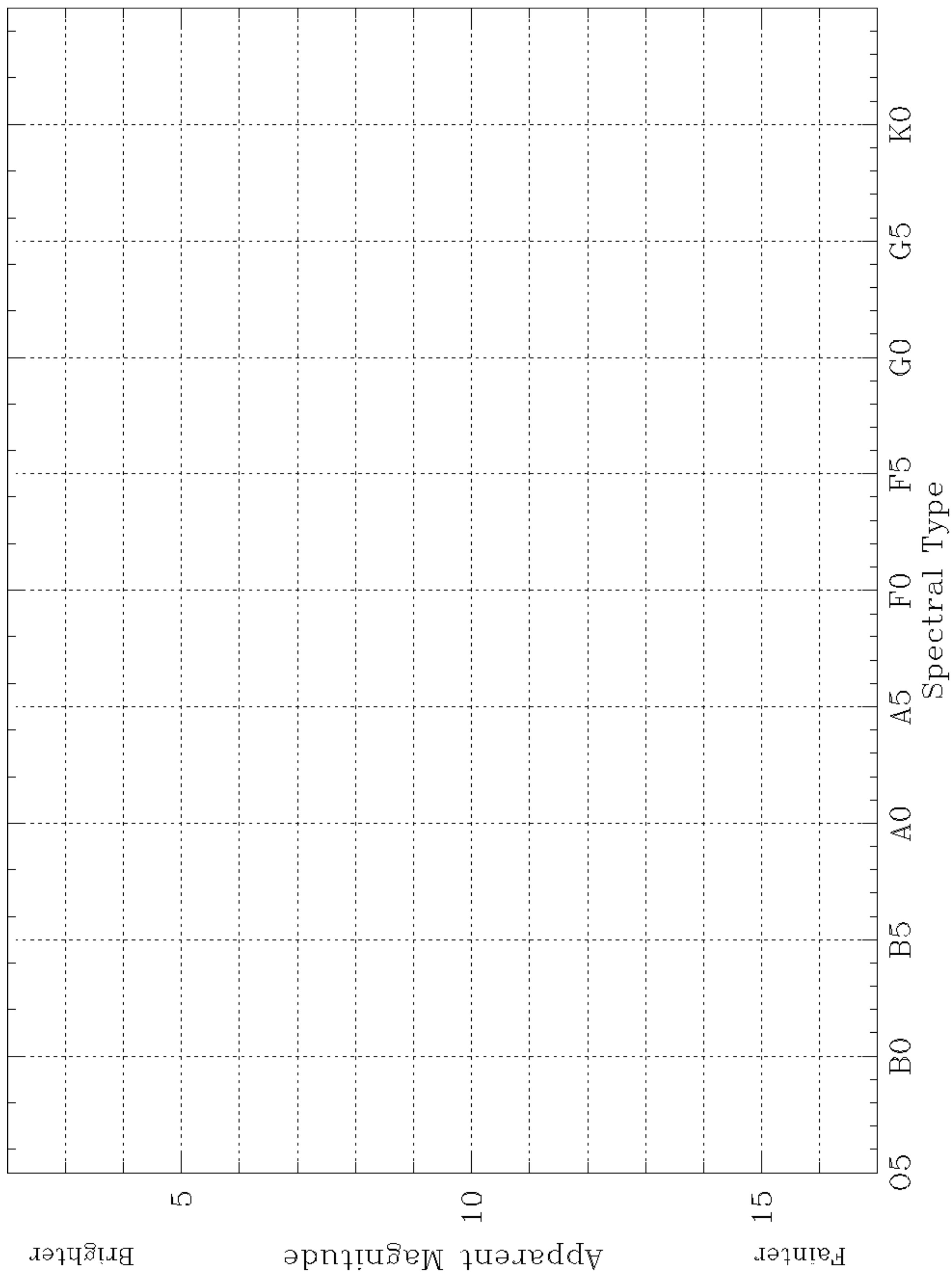
Remembering that 1) *smaller* magnitudes correspond to *brighter* stars and 2) spectral types correlate with the surface temperatures of stars, describe in words what your plot is telling you about the relation between a star's energy output and its surface temperature among main sequence stars.

Discoveries of trends and correlations are fundamental insights. Even so, the road to understanding remains long. For example, Russell interpreted the main sequence incorrectly, seeing it as a sequence of stellar evolution. It is in fact a sequence of stellar mass, with the lower luminosity stars being the lower mass stars. But wrong ideas are part of the scientific process, and do not minimize the importance of discovering an important truth, such as the existence of the main sequence.

Q7: Why is it important that you observed a star cluster for this lab? Think about how your Hertzsprung-Russell (H-R) diagram would change if you were to study another cluster identical to the Pleiades but further away? How would your H-R diagram look different if you were to study a field of stars that were not in a cluster, that is a field in which each star is at a different distance?

These are challenging questions. Think about them carefully, discuss them with your lab partner and others, and write thoughtful answers.

Imagine what your plot would like if you rearranged it so the types were in alphabetical order. The entirety of stellar astronomy ultimately rests on the insight of the Harvard astronomers as they developed and applied their spectral classification system to stars.



Spectral Type
O5
B0
B5
A0
A5
F0
F5
G0
G5
K0
Apparent Magnitude
5
10
15
Brighter
Fainter

Section 4 - Distances to Stars using the Hertzsprung-Russell Diagram

The Hertzsprung-Russell diagram is an invaluable tool used in almost every aspect of stellar astronomy. For example, it can be used to determine the distances to stars ... and it is your mission to figure out how! On the next page is a picture of a field of stars.

- **Point your telescope in the direction of this field by selecting Field 1 under Field... on the menu bar.**

Q8: Tape the picture of Field 1 in your lab book. Choose any star and mark it on the picture.

Is the star you have chosen closer or further than the Pleiades?

What is the distance to the star?

Describe carefully your reasoning as you work through the answers to these questions with the hints provided below.

You say these instructions sound a bit skimpy compared to what you are used to? Indeed! You have already proven your prowess by completing the lab. Now you are ready to take on an astronomical problem in a more realistic way. Given a problem, at least half of the challenge in "real life" is figuring out how to solve it.

With the observations of the Pleiades in hand you have all the knowledge and skills that you need to answer the first question. The second question will be more challenging. A few things that may help:

HINT 1: All of the Pleiades stars are at the same distance - 100 pc.

HINT 2: Apparent magnitudes are measures of the brightness level of stars. They are not very intuitive, however; for example, a star with a larger apparent magnitude is *fainter* than a star with a smaller apparent magnitude. If you would like to learn more about magnitudes, ask your professor/TA or see your textbook. Here, all you need to know is that if we observe two stars with magnitudes M_1 and M_2, then their brightnesses B_1 and B_2 are related by

$$\frac{B_1}{B_2} = 10^{(M_2 - M_1)/2.5}.$$

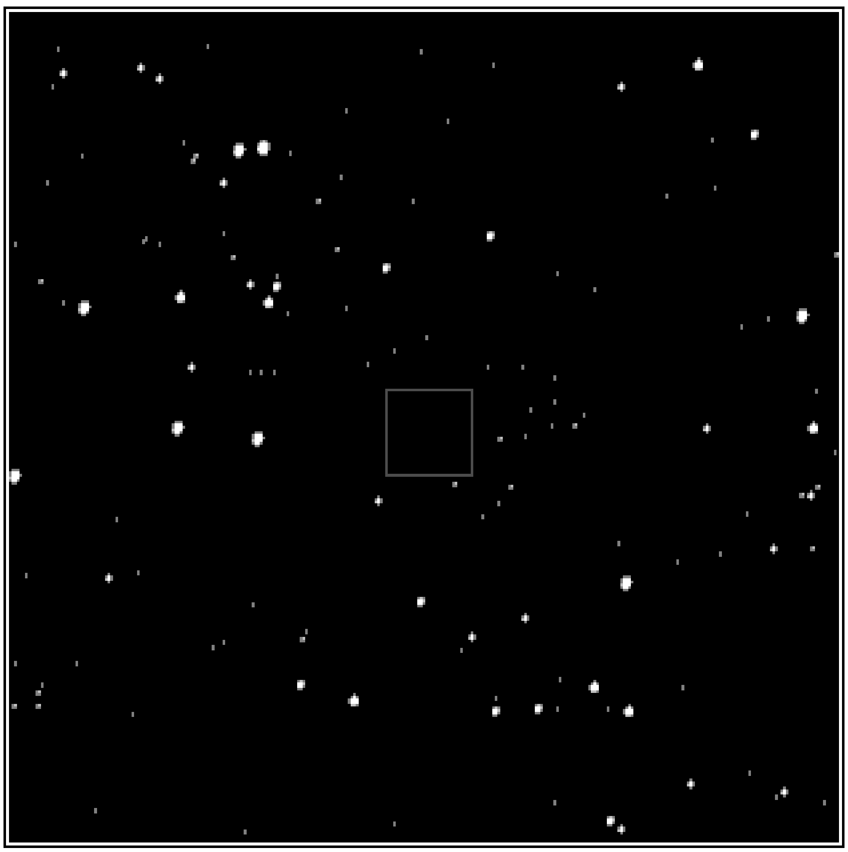
HINT 3: The inverse square law tells us that the brightness B of a star as seen from Earth depends on the luminosity L of the star and the square of the distance D to the star:

$$B = \frac{L}{4\pi D^2}$$

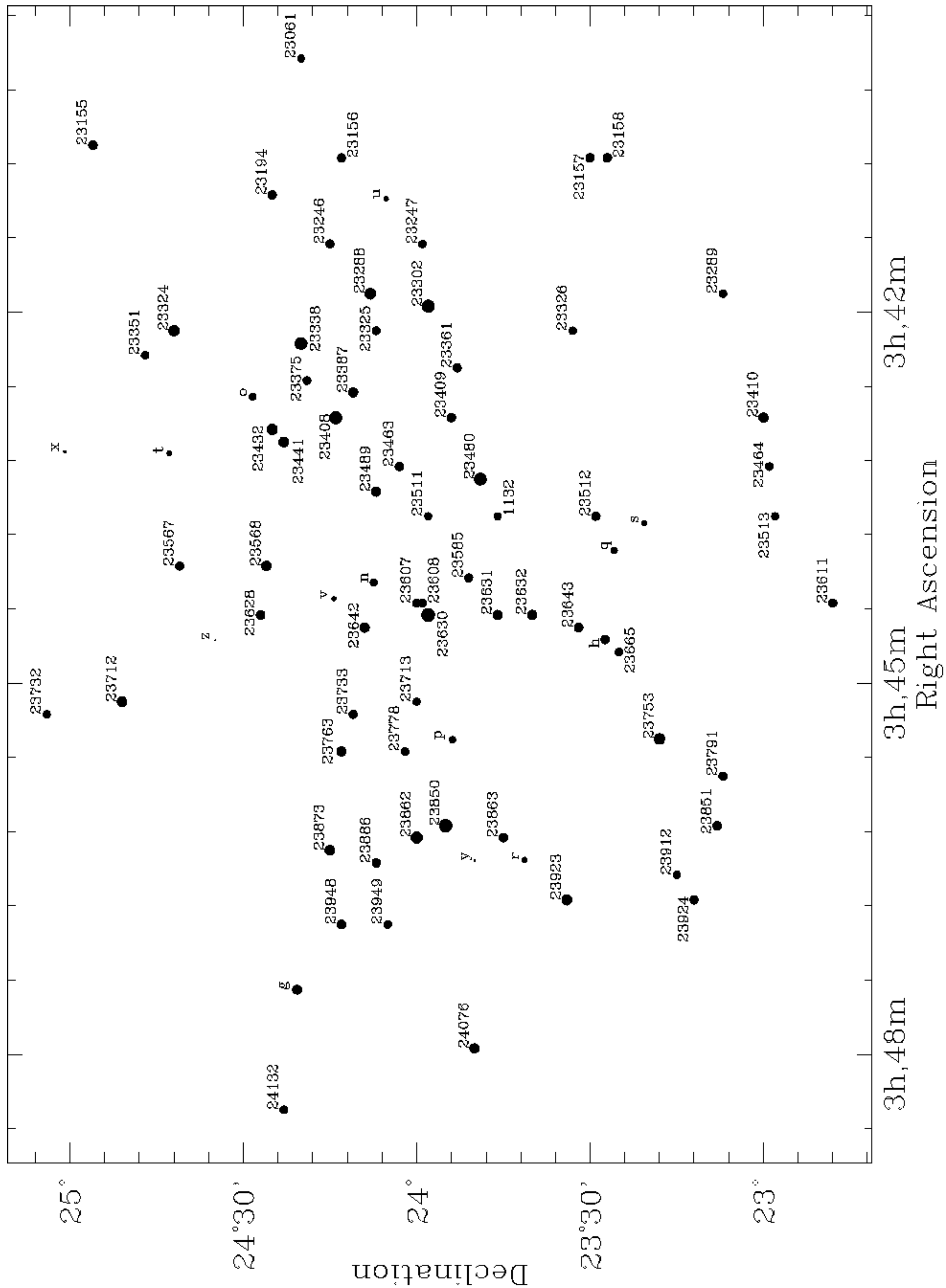
So you can generate the following equation for B_1/B_2 in terms of D_1 and D_2

$$\frac{B_1}{B_2} = \left(\frac{\frac{L_1}{4\pi D_1^2}}{\frac{L_2}{4\pi D_2^2}} \right) = \frac{L_1 D_2^2}{L_2 D_1^2}$$

However, for two stars of identical spectral types $L_1 = L_2$



Field 1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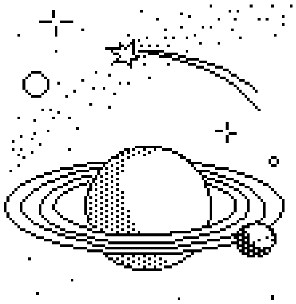
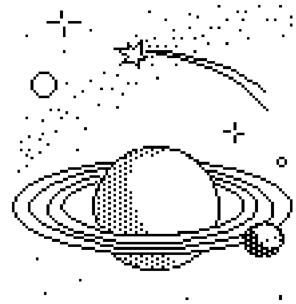
23886
y
r
23912
23948
23949
23923
23924
g
24076
24132
3h,42m
3h,45m
3h,48m
Right Ascension
25°
24°30'
24°
23°30'
23°
Declination



ASTRONOMY 113

Laboratory



Lab 6: Structure in the Universe, c. 1900 to the Present

Introduction

Universe - the entire celestial cosmos.

Cosmology - a branch of astronomy that deals with the origin, structure and space-time relationships of the universe.

(from Webster's Dictionary)

In one sense, the definition of "Universe" is unambiguous - the Universe is simply everything. On the other hand, how does one know what constitutes "everything"? Invariably, the more we have searched the more we have found.

Every recorded civilization has had a cosmology, or a theory of the nature and origin of the Universe. The progression of these cosmologies has been characterized by a constant increase in the scale of the Universe, usually via intellectual revolutions that result in dramatic changes in worldview in relatively short periods of times. Among the very earliest cultures the Universe did not extend beyond explored territory. For the Greeks the Universe extended to the celestial sphere, which was just above the highest mountain peak. The Copernican revolution not only removed the Sun from the center of the Universe, it also required that the stars be vastly further away to account for their lack of parallax motion. How far away was not known until the first parallaxes were measured in the 1800's.

The next - and most recent - revolution occurred less than 100 years ago. Much like the Copernican revolution, it involved a tremendous change in both the scale of the Universe and the location of the Sun within it. A textbook at the turn of the century would not include the word "galaxy", and its final chapter on cosmology would discuss only a Universe of stars. By 1936, Edwin Hubble could write a popular text on the new Universe of galaxies. (Although interestingly, the book is entitled "The Realm of the

Nebulae" and in it Hubble does not use the word "galaxy".) The Universe about which you learned in grade school has only "existed" for about 70 years!

In this lab you will retrace the path through the revolution at the turn of the century. **As best you can, discard what you know of galaxies, quasars, and the like; allow your mind to be set back in time.** And note: one of the defining properties of a scientific revolution is that the meanings of words become confused, and communication breaks down. You will likely get a sense of that confusion as you do the lab, for the word "Universe" means different things at different stages and indeed sometimes has two meanings at the same time. If this gives you an unsettled feeling - good! For that is the reality of a scientific revolution.

AN HISTORICAL ASIDE

In the mid-1700's comets were at the cutting edge of astronomical research. In 1759 Halley's Comet returned, as predicted many years earlier by Edmund Halley. Only about fifty comets had been discovered by this time, so the accurate prediction of when one would return to the inner solar system on its long orbit was a great accomplishment.

The name of one French comet-hunter of this era - Charles Messier - lives on today, but not for the 21 comets that he discovered. When first seen, a comet appears as a faint, fuzzy patch of light. However other objects in the sky such as gaseous nebulae and distant star clusters looked very much the same as comets in the modest-sized telescopes of the time. The only way they could be distinguished was by laborious observation over many nights - comets moved, nebulae didn't. To keep himself from repeatedly mistaking nebulae and star clusters for his beloved comets, Messier made a list of them, including where they were and what they looked like. Today, the Messier Catalog lives on, for it contains some of the most beautiful and fascinating objects in the northern sky. In all, there are 110 objects in the list, each with its own "Messier number". Thus the Crab Nebula is M1, the Andromeda Galaxy is M31, the Orion Nebula is M42, the Pleiades star cluster is M45, and so on. You will see pictures of these and more in this lab.

Before You Come to Class...

<u>Read the lab completely.</u> Your time in the lab is best used observing the "sky", not reading this manual.

Bring to class this lab manual, your lab book, a pencil or erasable pen, and a scientific calculator.

Schedule: This lab is designed to be completed in **two** lab sessions.

Section 1 - There is more in the Sky than Meets the Eye

In your first exploration of the sky with Voyager you observed the motions of the stars and planets. Prior to the invention of the telescope this was all there was to the Universe. But by the 1700's mankind's inventory of the sky included a wide variety of star clusters and nebulae. Although it was not known at the time, these objects were to be the keys which opened a Universe far more vast than almost anyone could imagine. The first goal of this lab is to introduce you to this world of "deep sky objects".

- **Double click on the icon "Universe c. 1900", creating a Voyager view of the sky.**
- **Click the "galaxy" button near the lower left hand corner of the screen.**

This button will display a number of new symbols on the screen. Each shape and color denotes a different type of celestial object, including various kinds of galaxies, star clusters, nebulae, quasars, and X-ray sources.

- **Turn on Picture Frames (in the Display menu).**
- **Click in any yellow picture frame with a colored symbol in it.**

This will open a Data Window for the object which tells its name, location, brightness, type, etc. There should be a "picture" box near the upper right corner of the window. (If there isn't one there, it means the cursor selected a close neighbor to the object of interest. Either click closer to the center of the yellow picture frame or try a different one.) The picture box will open an image of the object, taken with a large telescope.

- **Click the white square near the upper right corner of the window.**
- **Close the Picture Window by clicking the box in its upper left corner.**
- **Look at as many objects as you would like!**

Once you have the hang of it we will take you on a tour of the sky, choosing a few select targets as examples of each class of object.

- **Open the Find and Center window (in the Field menu).**
- **Type "M31" and click Search.**
- **Click Center.**
- **Open the Picture Window.**

M31 is better known as the Andromeda Galaxy, named for the constellation in which it is found. It is the brightest galaxy in the northern sky and visible to the naked eye. As you can see in the Data Window, M31 is a <u>spiral galaxy</u>. Notice the white ovals superimposed on M31. These are dwarf <u>elliptical galaxies</u> which orbit the spiral galaxy just like the Earth orbits the sun. But they do it in several hundred million years!

Q1: Using the Find and Center command, tour the following gallery of celestial gems. Each is an example of a class of objects, there are other classes, but they aren't used in this lab:

NGC2023	-	<u>Dark Nebula</u> (the Horsehead Nebula)

M3	-	Globular Star Cluster
NGC4755	-	Open Star Cluster
M83	-	Spiral Galaxy

We have already discussed several of these objects in lecture, and we will eventually discuss them all. But for the moment let us not be concerned with their natures, because at the end of the nineteenth century there was little understanding of what these objects were. We have already cheated a bit - at that time spiral galaxies were called "spiral nebulae". Galaxies were not yet part of the Universe.

Section 2 - Counting the Stars

In order to reveal the structure of the Universe, a primary occupation of astronomers in the 1800's was detailed study of the distribution on the sky of both stars and non-stellar objects. In this lab you will follow in their footsteps, with the advantage of data gleaned by the several generations of astronomers and telescopes since. Your exploration begins with study of the distribution of the stars.

- **Close any Data Windows and Picture Windows.**
- **Turn off Picture Frames (in Display Menu).**
- **Turn off Galaxies (button in lower left).**
- **Turn off Constellations (button in lower left).**
- **Change to Equatorial view (Chart Menu to Chart Coordinates to Star Atlas - Equatorial).**
- **Set the Zoom to 360 degrees (menu in lower left).**
- **Turn on the Celestial Equator (Display Menu to Coordinate Lines to Celestial Equator).**
- **Turn on the Milky Way (Display Menu to Milky Way Area).**

The change to Equatorial view has displayed the entire sky before you - Voyager has laid the sky flat like a world map. Like in a world map, the celestial equator stretches across the middle of the picture.

Hopefully you have seen the Milky Way at least once in your life. It is truly a magnificent sight (especially in the summer from the northern hemisphere), but it requires a dark sky to be seen. To the naked eye it appears as a luminescent band of light circling across the sky. With a telescope, Galileo found that the Milky Way was made of a myriad of faint stars. Far more stars lie in the direction of the Milky Way than in other directions. This is our first clue about the structure of the Universe.

Because of the flattening of the sky onto the screen, the Milky Way has taken on a strange shape. In reality the Milky Way describes a great circle about the sky, just like the celestial equator but in a different direction. When we flatten the sky so that the celestial equator is a straight line, the Milky Way becomes an S-like shape.

The location of the celestial equator in the sky depends on the tilt of the Earth, which clearly is not related to the distribution of the stars in the Universe. On the other hand, the Milky Way *is* due to the distribution of the stars in the Universe. So we'd like to show a map of the stars with respect to the Milky Way. We can easily define a galactic equator, which is simply the great circle along the Milky Way.

- **Turn on the Galactic Equator (Display Menu to Coordinate Lines to Galactic Equator).**

Now, let's change our map so that the galactic equator runs along the center of the map.

- **Change to Galactic Coordinates (Chart Menu to Chart Coordinates to Milky Way - Galactic).**

Congratulations - you are now in the coordinate frame of interstellar space travel! The numbers along the galactic equator are measures of galactic longitude, in analogy to geocentric longitude around the Earth's equator.

Note that now the celestial equator has taken on the S-shape, which just goes to show that this shape is a consequence of nothing more than how we have compressed the celestial sphere onto a flat surface. Now that we are free of our Earthly bounds, we had might as well turn off the celestial equator.

- **Turn off the Celestial Equator (Display Menu to Coordinate Lines to Celestial Equator).**

In the 1800's it was recognized that the Universe must have a very flattened shape. After all, if the Universe was shaped like a sphere, we should see similar numbers of stars in every direction. But in fact most stars lie along the Milky Way, with many fewer stars lying above and below the Milky Way. This is what one would expect to see if the Universe were shaped like a disk of stars.

What wasn't so clear in the 1800's was the location of the Sun in the Universe. A casual look at the screen suggests that the number of stars along the Milky Way is roughly the same in every direction. While such visual impressions are useful, a quantitative analysis is needed before such a statement can be made with any confidence. Thus a careful counting of the stars is in order - from these numbers you can judge for yourself whether the distribution of stars about the Sun is uniform.

Q2: Suppose the stars are randomly distributed along the Milky Way. Do you expect to find *exactly* the same number of stars in every direction along the Milky Way? Explain your reasoning; try to include an analogy in your explanation.

- **Turn off the Milky Way (Display Menu to Milky Way Area).**
- **Open the Grid window (Chart Menu to Grid Selection); click on Galactic and OK.**
- **Turn on the grid lines (grid button near lower left).**

Q3: Make a copy of the data graph below in your lab book.

Count the number of stars in the boxes along the galactic equator, that is along the Milky Way. To make this counting easier,

- **Set the Zoom to 45 degrees.**
- **Center the galactic equator on the screen using the vertical scroll bar.**

For every 30-degree interval, count the number of stars in all three boxes just above the galactic equator. Take care, but if you are off by a star or two it's OK. Record your counts in the data graph.

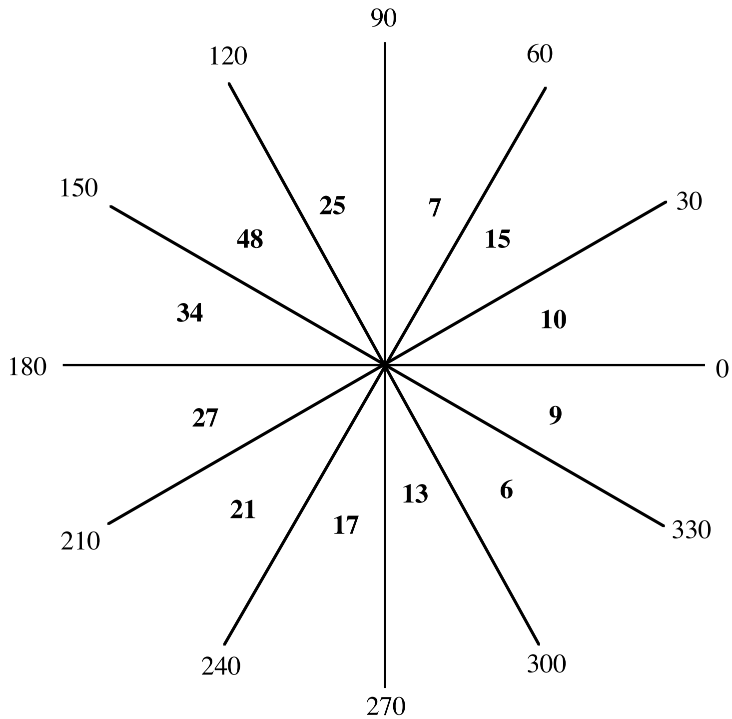


Figure 1: Data graph for recording numbers of stars

(Note: The numbers are in bold are just for example. Replace them with your own counts.)

Examination of the counts in your data graph will show that the numbers of stars are not exactly the same in every direction along the Milky Way. But are the differences in the numbers significant? Or are they just random fluctuations, like you would get if you counted the number of snowflakes falling on each square of a checkerboard?

There is a simple test for significance in any counting experiment, one that is useful in innumerable situations in every day life. Here we teach it by example. Suppose you take 10 discussion sections of Astronomy 100. (All have the same number of students.) In each sample you count the number of something of interest, say the number of students with tatoos. Suppose you find these numbers of tatooed students: 3, 5, 6, 9, 7, 4, 5, 4, 7, 3. Take the average of all of the counts - in this case we get 5.3. This is the <u>expected number</u> in each class. Now take the square root of the expected number - in this case 2.3. This number, known as the <u>standard deviation</u> of the expected number, is the size of a typical random fluctuation. Even if tatooed students were distributed randomly in the classrooms we would not be surprised to see their numbers vary 1 standard deviation, that is by $\pm$ 2.3 or between 3 and 7. Indeed, there is a 5% chance that a given classroom will have a fluctuation of 2 standard deviations from the expected number, or 2 x 2.3 = 4.6. So the fact that one out of ten classrooms has 9 blonde students is not so very unlikely as to make it significant or interesting. In science we usually do not consider a finding significant unless it differs by more than **three standard deviations** from the expected number, for the probability of that happening due to a random fluctuation is only 0.3%.

How about another down-to-earth example? A survey of 100 women finds that 60 are Democrats. Therefore women are more likely to be Democrats than Republicans? Poppycock! If women are equally likely to be Democrats or Republicans, than in a sample of 100 women the expected number of Democrats would be 50. In any given sample of 100 women the actual number of Democrats might easily deviate from this expected number by $\sqrt{50} = 7$. And there is a 5% chance that the number of Democrats might deviate from 50 by as much as 14. So finding 60 Democrats in a sample of 100 women does not at all prove that women have any particular political preference. On the other hand, finding 600 Democratic women out of 1000 *would* be significant. The expected number is 500 women with a standard deviation of $\sqrt{500} = 22$. Finding 600 Democrats is 5 standard deviations away from the expected number, which is *very* unlikely given equal political preference. Thus the conclusion that women are more likely to be Democrats would be justified. Bottom line - larger samples lead to more secure conclusions.

Q4: What do you conclude about the distribution of stars along the Milky Way? In particular, do your star counts show a significant excess of stars in any given direction? Explain your answer.

Q5: Based on your observations of the known Universe, where or in what direction is the center of the Universe? Explain your answer.

Section 3 - Star Clusters Enter the Scene

At the turn of this century, mankind's view of the shape of the Universe and the location of the Sun within it was that derived by examining the distribution of stars, as you have just done. Within the next 30 years, mankind's perception of the Universe changed dramatically. This revolution began when astronomers started to explore the distributions of celestial objects other than stars. In particular, the story begins with the study of open star clusters and globular star clusters.

- **Set the Zoom to 360 degrees (menu in lower left).**
- **Turn off the grid (button in lower left).**
- **Use the horizontal scroll bar to put 0 degrees Galactic Longitude at the center of the screen.**
- **Turn off the stars.**
- **Open the Deep Sky Selection window (Chart Menu to Deep Sky Selection).**
- **Turn off all except Open Clusters and Globular Clusters by clicking in boxes.**
- **Click OK.**
- **Open the Magnitude Limits window (Chart Menu to Magnitude Limits).**
- **On the Deep Sky panel, drag the left and right arrows to 12.**
- **Click OK.**
- **Turn off the Galactic Equator (Display menu to Coordinate Lines to Galactic Equator).**
- **Click the "galaxy" button near the lower left hand corner of the screen.**

The white circles represent open clusters and the yellow circles represent globular clusters.

Q6: Sketch/describe the distribution of open clusters in the sky. How does it compare to the distribution of stars?

Sketch/describe the distribution of globular clusters in the sky. How does it compare to the distribution of stars? To the distribution of open clusters?

As you might imagine, the distribution of globular clusters was perplexing to astronomers used to studying the distributions of stars. Based on your observations of open clusters and globular clusters, where would YOU conclude is the center of the Universe? Take some time to think about this and talk it over!

Section 4 - Turning Two Dimensions into Three

So far we have only considered the distributions of stars and clusters on the sky. If we knew the distances to these objects, we could convert their two-dimensional distributions on the sky to a three-dimensional distribution in space. We could map the Universe.

In fact, by the turn of the century the distances to many stars and open clusters had been determined based on stellar brightness and the inverse square law. Thus three-dimensional maps of the Universe were made.

- **Turn on the Chart Panel (Control menu to Chart Panel).**

The second number from the bottom is the galactic longitude of the cursor.

Q7: Tape the graph on the next page into your lab book. This is a polar graph in which the distance from the center represents distance in kiloparsecs (1 kpc = 1000 pc) from the Sun, and the angle around the circle represents galactic longitude.

Click on an open cluster. A data box will pop up, in which is the cluster's distance. Combined with the galactic longitude from the Chart Panel, you can plot this cluster on the polar graph. Do this for 20 or more clusters, chosen randomly in galactic longitude.

Note: Some the open clusters do not have measured distances. Ignore any of these cases if you come upon them.

Q8: Based on your map of the open clusters, where is the center of the Universe? How large is the Universe? Explain your answer.

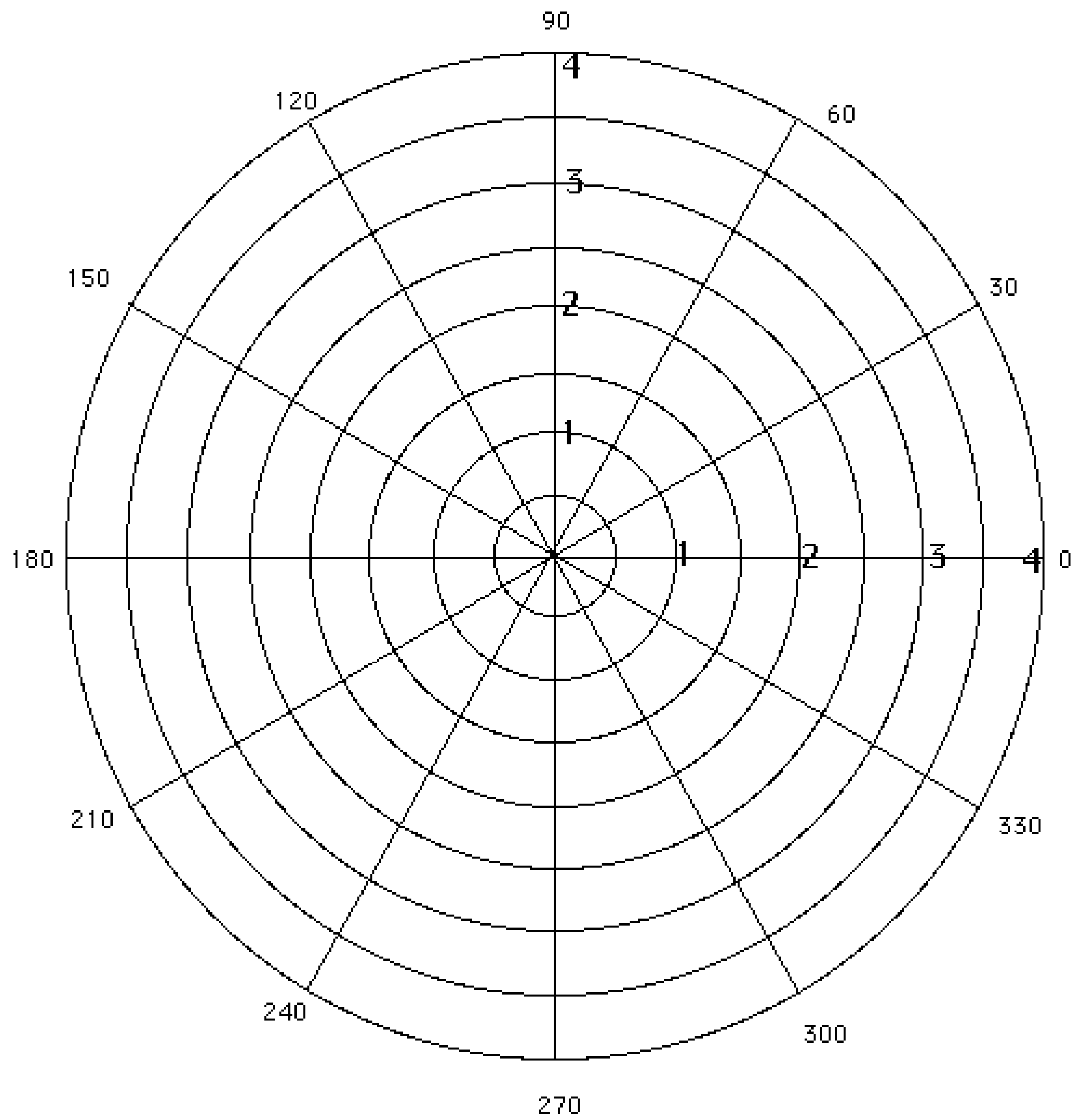


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Figure 2: Polar Graph for Open Clusters

(The bold numbers along a radius measure distance from the Sun in kiloparsecs;
the lighter numbers around the circumference measure galactic longitude in degrees)

Distances to globular clusters were far more uncertain at the turn of the century. The stars in globular clusters were red and very faint. It was unclear whether they were like the low-luminosity stars in the solar neighborhood (in which case the clusters were close to the sun) or whether they were like the high-luminosity red giants (in which case the clusters were far away).

Around 1915, an astronomer named Harlow Shapley added a critical piece of information to the puzzle. Pulsating variable stars named Cepheids and RR Lyrae stars had recently been discovered to be excellent distance indicators; we will talk more about them in lecture. Globular clusters contain RR Lyrae stars, and thus Shapley was able to measure reasonably precise distances to many globular clusters. His results were remarkable indeed!

Q9: Tape the graph on the next page into your lab book, and create a map of the globular clusters as you did with the open clusters. Choose at least 30 globular clusters, selecting them in a pattern which is similar to the distribution of all the globular clusters.

In your globular cluster map, lightly shade in the region of your open cluster map.

Note: Some the globulars do not have measured distances. Ignore any of these cases if you come upon them.

Q10: Based on your map of the globular clusters, where is the center of the Universe? How large is the Universe? Explain your answer.

Imagine yourself as an astronomer in 1920. Two very discrepant views of the Universe are in competition, differing in both the scale of the Universe and location of the Sun within it. For all of your professional life you have conceived of the Universe as derived from the distribution of the stars. The great astronomers of your time, such as Kapteyn of the Netherlands, have devoted their careers to establishing this view of the Universe, and most of your professional colleagues rest assured in that view. Which Universe do you believe to be the truth? Are you bold enough to challenge a century of scientific wisdom?

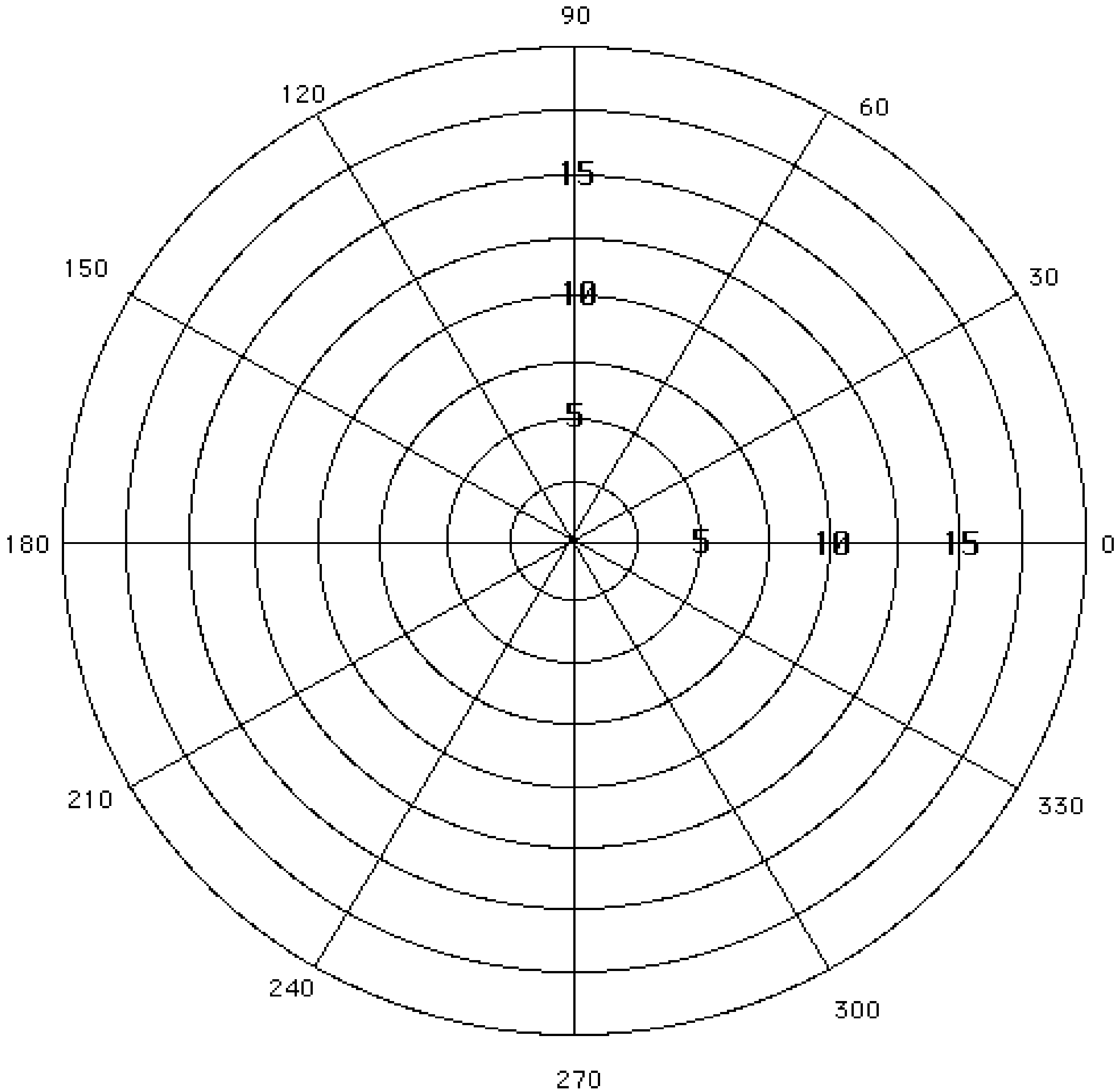

Figure 3: Polar Graph for Globular Clusters

(The bold numbers along a radius measure distance from the Sun in kiloparsecs;
The lighter numbers around the circumference measure galactic longitude in degrees)

Section 5 - The Spiral Nebulae - the Final Clue

Astronomers were equally perplexed by the nature of the spiral nebulae. Nearly two hundred years before, the philosopher Immanuel Kant had suggested that they were "island universes", and that the Sun must itself reside within such a system. This was a remarkably prescient idea considering that our own "island universe" was not yet understood. At the turn of the century this view held favor among one segment of the astronomical community, including Curtis. Others, including Shapley, felt that the tremendous distances implied by "island universes" were not plausible. Having suggested that the Universe was many times larger than previously thought, Shapley was unwilling to make it larger still. Thus the controversy over the spiral nebulae was intimately linked to cosmological prejudices.

Ultimately Edwin Hubble resolved the entire issue in 1924. Using the new 100" telescope on Mt. Wilson, he found several Cepheid variables in the Andromeda spiral nebula and definitively showed that this "spiral nebula" was over *250,000 parsecs* distant. It turns out this is one of the closest galaxies, most are very much further away. Spiral nebulae *were* "island universes", soon to become known as "galaxies". In an instant the revolution was complete, and our view of the Universe expanded tremendously. At the same time it was clear that our galaxy, named the "Milky Way Galaxy", could be much larger than previously thought, as Shapely had already suggested based on the globular clusters.

But what then was the reason for the small Universe indicated by the stars and the open clusters? If the Milky Way was so large, where were all its stars? Why were all of the stars so near to the Sun? The answer can perhaps be gleaned from the distribution of the galaxies on the sky.

- **Put away the Chart Panel.**
- **Open the Deep Sky Selection window (Chart Menu to Deep Sky Selection).**
- **Turn off the Open Clusters and Globular Clusters, and turn on the Spiral Galaxies.**
- **Click OK.**
- **Open the Magnitude Limits window (Chart Menu to Magnitude Limits).**
- **On the Deep Sky panel, drag the left and right arrows to 15.**
- **Click OK.**
- **Turn on the Milky Way (Display Menu to Milky Way Area).**

Q11: Describe the pattern of the galaxies on the sky. How does the distribution compare to the open clusters? How does it compare to the Milky Way? The first astronomers who studied the distributions of galaxies coined the term "Zone of Avoidance" - to what might this refer?

Q12: Remember that Hubble found the galaxies to all lie far beyond the boundaries of our Milky Way Galaxy. And yet the distribution of galaxies seems to "know" about our Milky Way. How can this be? What is the origin of this Zone of Avoidance? Follow the three clues below to reach your conclusion. Clues:

1) Take a look again at NGC2023, the Horsehead Nebula. Use the Find and Center command to also look at the Dark Nebulae LDN91. Do you think that these places in the sky which are devoid of stars are actually empty lines of sight through the Milky Way Galaxy? What else might be causing these "holes in the sky"?

2) Turn on Dark Nebulae in the Deep Sky Selection window and consider their distribution with respect to the galaxies.

3) Use the Find and Center command to look at the galaxy M104. M104 is a spiral galaxy seen edge on. (As an aside, most of the "stars" around M104 are actually globular clusters in a halo around it.)

Q13: Based on your conclusions in Q12, can you explain why we only see open clusters near to the Sun but can see globular clusters to much greater distances? Are there stars and open clusters in the Milky Way other than those which we see?

Remember, open clusters lie in the plane of the Milky Way while the globular clusters appear to lie above and below it. Imagine being located within the plane of M104.

The Milky Way itself is a member of the Local Group of galaxies, which has a few dozen members. The most familiar other member of this group is the Andromeda Galaxy (M31). To get an idea of the size of the Local Group in relation to the size of the Milky Way, we need the distance to M31.

- **Use Find and Center in the Field Menu to display information about M31.** Note its distance.

Q14: In your lab book draw a line about 15 cm long to represent this distance and at its ends sketch two spiral galaxies representing M31 and the Milky Way; be sure to make the size of these sketches consistent with the size of the Milky Way determined in your Figure 3 above.

The Local Group is part of a much larger collection of galaxies called the Local Supercluster. The Local Supercluster contains the Virgo Cluster of about 1,000 galaxies and about 50 smaller groups like the local group.

To establish the distance from the Local Group to the center of the Virgo Cluster,

- **Find and Center on M87.** <u>Note that there is a bug in Voyager and the correct units for this distance is kiloparsecs not megaparsecs</u>.

Q15: Draw a figure that represents the Local Group as a circle about 1 cm in diameter near the edge of a page in your lab book. Then draw a larger circle, with a radius appropriate for the distance to the Virgo Cluster centered on the page. How large would the Milky Way galaxy be on this drawing? Try to draw a representation of it within the Local Group and note with amazement just how large a supercluster is.

The Universe as we know it today contains billions of galaxies in millions of structures like the Local Group and local supercluster. The most distant such objects that we know are several billion parsecs from us. Thus even the Local Supercluster shrinks to insignificant size and content when we consider the entire Universe. This is the legacy of those early pioneers, Kapteyn, Shapley, and Hubble, among others.

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Lab 7: The Expansion of the Universe

Introduction and Goals

Virtually all the galaxies in the Universe (with the exception of a few nearby ones) are moving away from our galaxy, the Milky Way. This curious fact was first discovered in the early 20th century by astronomer Vesto Slipher, who noted that absorption lines in the spectra of most spiral galaxies had longer wavelengths than those observed from stationary objects. Assuming that these "redshifts" were caused by the Doppler shift, Slipher concluded that the redshifted galaxies were all moving away from us.

In the 1920's Edwin Hubble measured the distances to a sample of galaxies. When he plotted these distances against the velocities of the galaxies he found a remarkable trend: the further a galaxy was from the Milky Way, the faster it was moving away. Hubble's plot is shown in Figure 1.

Was there something special about our place in the universe that made us a center of cosmic repulsion? No. Astrophysicists readily interpreted Hubble's relation as evidence of a universal expansion. The distances between all galaxies in the Universe were getting larger with time, like the distances between raisins in a rising loaf of bread. An observer on any galaxy, not just our own, would see all the other galaxies traveling away, with the furthest galaxies traveling the fastest.

Thus the entire Universe is expanding, one of the truly remarkable discoveries in intellectual history. To appreciate its significance, one must recognize that if we measure the rate of the expansion we can “turn time around” and determine when the expansion began. This moment - associated with the concept of the Big Bang - marks the beginning of the present day Universe. And thus Hubble's discovery of the correlation between velocity and distance ultimately provides the answer to one of the most fundamental of all questions, when was the Universe formed.

As you might expect, determining precisely the rate of expansion and thus the age of the Universe is one of the primary endeavors of observational cosmologists today. It also is the aim of this lab. Using modern instrumentation you will repeat Hubble's observations and come to understand both how the expansion of the Universe is observed and measured, and what are the uncertainties in measuring its age.

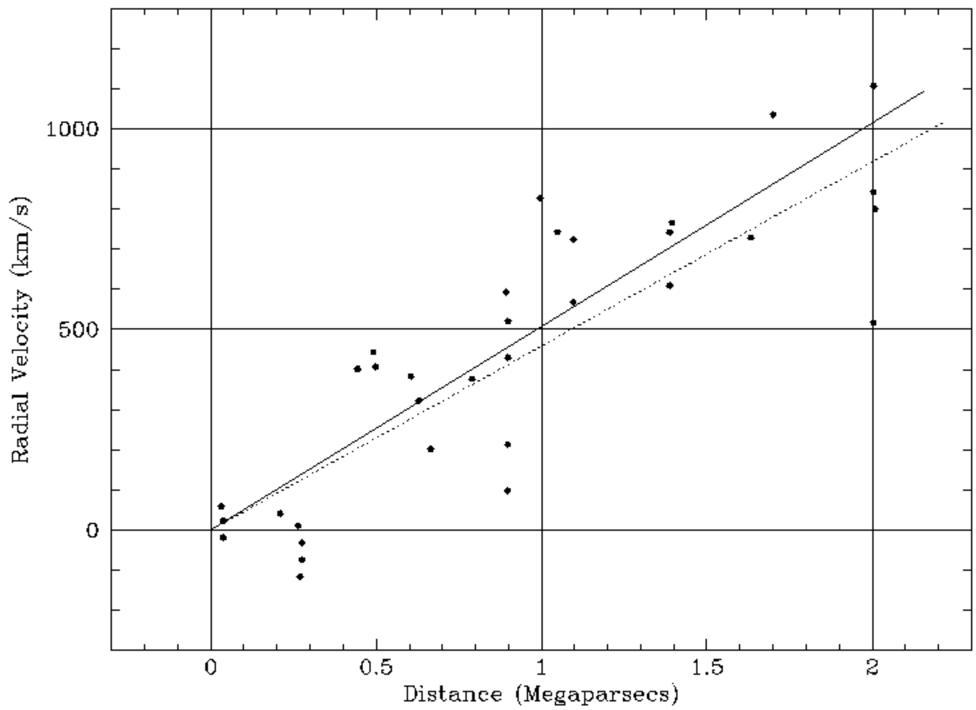


Figure 1: Graph of Hubble's Galaxies

The goal of this lab is to introduce you to the relationship between the redshifts of distant galaxies and the rate of expansion of the universe. You will be introduced to:

- Using a spectrograph to obtain spectra of galaxies.
- The concept of signal, noise, and signal-to-noise ratio in data.
- Measuring Doppler shifted spectral lines to determine velocities.
- Determining distances using the brightnesses of galaxies.

Once you have applied these techniques to a sample of galaxies, you will be able to:

- Calculate the Hubble Constant H_O, a measure of the rate of expansion of the Universe.
- Calculate the expansion age of the Universe.

Before You Come to Class ...

Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.

Complete the pre-lab assignment.

Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in **two** lab sessions.

Section 1 - Instrumentation and Strategy

You have been allocated observing time on a large optical telescope equipped with both a television camera and a spectrograph. Using this equipment, you will determine the distances and velocities of galaxies located in selected clusters of galaxies around the sky.

How does the equipment work? The TV camera acts in place of an eyepiece, allowing you to see the galaxies. Observing with the TV camera you can center a galaxy of interest in the field of view. Once centered, you direct the light of the galaxy to the spectrograph. (The selection of TV or spectrograph is done with a small flat mirror.) The entrance to the spectrograph is a small slit which allows only the light of the galaxy into the spectrograph. Once you have carefully centered the galaxy on the slit, you instruct the spectrograph to begin counting the photons from the galaxy. As it is doing so the counts are displayed on a computer screen as a spectrum - a plot of the number of photons collected versus wavelength. When a sufficient number of photons are collected, you will be able to see the spectral lines of the galaxy.

Your spectrograph is set up to observe the blue end of the visible spectrum. Figure 3 shows the spectrum of a typical galaxy in this wavelength region. The two deep lines are a pair of absorption lines of Calcium[1] called the H and K lines for historical reasons. In the laboratory, i.e. at rest, the wavelengths of the two lines are approximately 3969 Å and 3934 Å, respectively. Since galaxies are in motion, the lines will be found at different wavelengths in your observed spectra. Fortunately, the H and K lines of Calcium are an easily reconizable pair even when Doppler shifted.

You will measure the wavelengths of the H and K lines in each galaxy spectrum. The spectrograph also determines the brightness of each galaxy based on how many photons it counts per second. The computer determines this number automatically and gives it to you as the "apparent magnitude" of the galaxy. (Here "apparent" simply means "as seen from Earth".) So for each galaxy you will record the wavelengths of the Calcium H and K lines and the apparent magnitude. You can calculate how fast the galaxy is moving away from us - known as the recession velocity - with the Doppler formula. You can calculate the distance of the galaxy from its brightness - here we will make the simple assumption that all galaxies in the Universe have the same luminosity. Thus you will have a velocity (in km/sec) and a distance (in units of millions of parsecs or megaparsecs, abbreviated as Mpc) for each galaxy.

Most galaxies are found in clusters. You will observe a few galaxies in each of five clusters. Each cluster is at a different distance from the Milky Way. Thus you will be able to explore the change in recession velocity with distance. From your data you will derive H_O, the Hubble Constant, which is a measure of the rate of expansion of the Universe. Once you have H_O, you can take its reciprocal to find the expansion age of the Universe.

[1] Why do we see Calcium absorption lines when we observe galaxies? When we look at a galaxy, we see the combined light of billions of stars. The vast majority of these stars are main-sequence stars with masses less than the Sun. However, these stars are not very luminous. Most of the light of a galaxy comes from the fewer very luminous stars, the yellow and red supergiants. These cool stars have G and K spectral types, similar to the Sun, and like the Sun their spectra have strong Calcium absorption lines. Since the light from a galaxy comes mostly from these supergiants, then the galaxy spectrum also shows strong Calcium lines.

Section 2 - Observations

TAKING A SPECTRUM

Welcome to the observatory! This section will guide you through the data collection for the first galaxy. The selection and observation of the rest of your sample of galaxies will be left to you.

- **Double click on the Hubble Redshift icon.**
- **Click "Log In" on the menu bar.**
- **No need to enter names and lab table; just click OK, and again at the warning about not having entered anything.**
- **Click "Start" on the menu bar.**

You will see the telescope control panel as found in the "warm room" at the observatory (see Figure 2). Typically astronomers are in separate rooms or even buildings from the telescope dome. This is not only for the comfort of the astronomers; any heaters in a telescope dome (including bodies!) cause drafts that lead to turbulent air and bad seeing.

Notice that the dome is closed and the tracking is off.

- **Open the dome by clicking the Dome button.**

Once the dome is open, you will see the view of the TV camera through the telescope. This camera provides a wide field of view so that you can see a large section of sky from which to pick your target galaxies. Hence this is referred to as the "Finder" view.

You will notice that the stars and galaxies are drifting across the field of view.

- **Click on the Tracking button.**

By turning on the tracking you have started a motor that makes the telescope move at exactly the same rate as celestial objects move across the sky due to the rotation of the Earth.

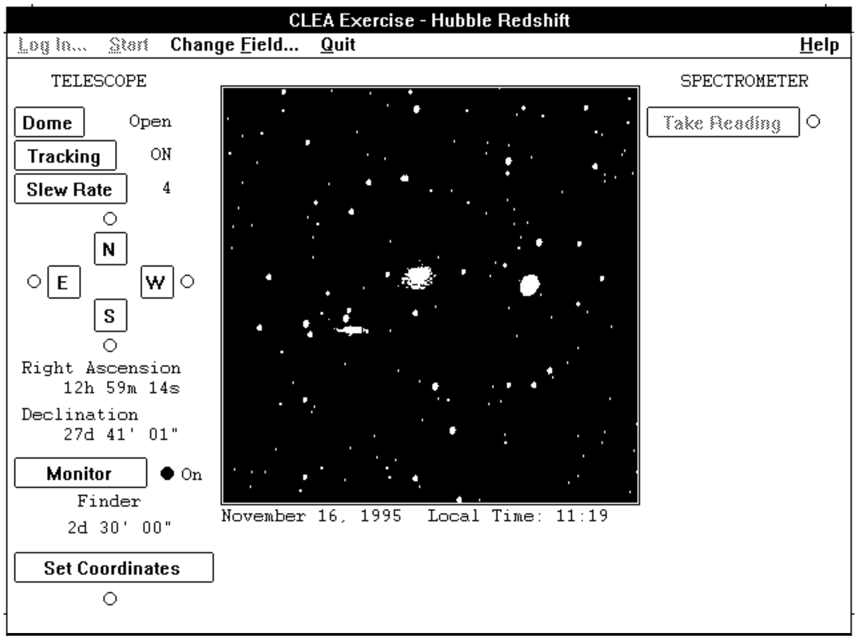


Figure 2: Telescope Control Screen, Finder View

Now you are ready to take data. When the dome opens you are looking at a cluster of galaxies in the constellation Coma Berenices. You will notice that there are several fuzzy objects in the field that are clearly not stars. These are a few of the brightest galaxies in the cluster. Choose any galaxy and center it in the field of view.

- **Use the N,S,E,W buttons to center the red box on the bright central part of a galaxy. If it is going too slow, click Slew Rate to change the speed that the telescope moves.**
- **Click the Monitor button to switch from Finder to Spectrometer.**

The Monitor button switches between the wide-field TV camera and the spectrograph. You will notice that switching to the spectrograph gives you a much smaller field of view. It also caused the red box to turn into a pair of vertical lines. These lines represent the spectrograph slit, the hole through which light enters the spectrograph. The closer your slit is to the bright, central region of a galaxy, the more light will get into the spectrograph and the faster you will obtain a good spectrum. If you point the spectrograph slit on the dim outer parts of the galaxy, you can still get a decent spectrum but it will take much longer. If you point the slit at empty sky, you will just get a spectrum of noise.

- **Use the N,S,E,W buttons to center the slit on the center of the galaxy.**
- **Click Take Reading.**

This will switch you from the telescope control panel to the spectrograph output screen. (See Figure 3 below.)

- **Click Start/Resume Count to begin collecting data.**
- **After a while, click Stop Count.**

Light of all wavelengths enters the spectrograph slit. Using either a prism or a grating, the spectrograph spreads the light out into a spectrum. Effectively, the spectrograph is sorting the photons into bins of different wavelengths, and keeping a running count of the number of photons at each wavelength. Every time a photon of a given wavelength is detected, the computer increases the count of such photons by one. This running count is displayed on the screen as a spectrum. This will be most evident to you when you stop the counting, at which time the computer draws a solid line through the counts at each wavelength.

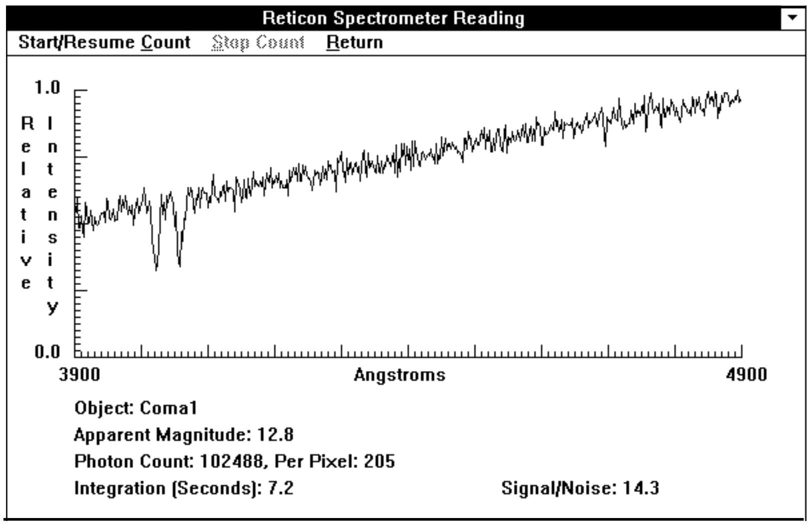


Figure 3: Spectrograph Screen with Sample Spectrum

It may seem odd to you that the spectrum doesn't keep getting higher and higher in the plot if the computer keeps collecting more photons. This is because the computer is always changing the scale of the y-axis in order that the spectrum will fit on the screen. While the height of the spectrum doesn't change, you will notice that the clarity of the spectrum improves with time.

Other valuable information is also displayed on the screen, including:

Object: the name of the galaxy being studied

Apparent magnitude: the apparent magnitude of the galaxy

Photon count: the total number of photons collected so far, and the average number per pixel

Integration (seconds): the number of seconds over which photons have been collected

Signal-to-Noise Ratio: a measurement of the quality of the data (see below)

To return to the telescope control panel

- **Click Return in the menu bar.**
- **Click Yes.**
- **Click Monitor to return to the wide-field view.**

SIGNAL AND NOISE

The concepts of signal and noise are fundamental to all quantitative sciences. The signal is the information in the data, for example an absorption line. The noise is random fluctuations in the data. A good analogy is listening to a weak radio station. The words of the DJ are the signal; the static is the noise. The higher the ratio of signal-to-noise, the better you can understand the DJ.

As with radio stations, astronomical signal-to-noise is improved by collecting more photons. However, astronomers can't get closer to their "radio stations"! Instead, astronomers improve signal-to-noise by collecting photons for a longer time (or with a larger telescope). Imagine if you collected photons from a galaxy for 1 second. At some wavelengths you might catch one photon, at others none. You would have a hard time identifying the Calcium H and K lines with such data. Now resume your photon collection until a total of ten seconds have passed. Likely you will have counted a few photons at every wavelength, but your spectrum will still be "noisy". As you collect photons for a longer and longer time, the noise will continue to decrease until the Calcium H and K lines emerge from the noise and then eventually become clearly defined. The relative strength of signal and noise is measured by the signal-to-noise ratio. The details of how this is measured are not important here; more significant is recognizing that the larger the signal-to-noise ratio the more clearly will information in the spectrum be detectable and measurable.

You can easily see the interplay of signal and noise by observing a faint galaxy.

- **Click Change Field on the menu bar.**

A short list of galaxy clusters will be displayed. (Galaxy clusters are often named by the constellation in which they are found, an interesting linkage of ancient Greek and 20th century astronomers.) There are a total of five clusters in the program, each of which has a few observable galaxies.

- **Click on the Bootes region and click OK.**

A message will come up that says the telescope is "slewing" to a new location. This is a term astronomers use to describe rapid movement of the telescope as it moves to a new target.

- **Center on any galaxy, click Monitor to switch to the spectrometer, center again, and click on Take Reading.**

Q1:

- **Click Start/Resume Count and collect photons for 10 seconds.**
- **Click Stop Count.**
- **Record in your lab book the integration time and the signal-to-noise.**

Can you identify the pair of Calcium absorption lines? Make a note next to the integration time.

- **Continue to collect photons in 10-second intervals.**
- **Record the integration times and signal-to-noise values.**
- **Note whether you can identify the Ca H and K lines.**
- **Stop when your identification of the Ca H and K lines is absolutely certain.**

At what signal-to-noise level could you *first* detect the Ca H and K lines? Did you have any false identifications, i.e. features that you thought were absorption lines that "went away" with more integration?

Describe what happened as you observed longer and longer. Did the Calcium H and K lines of the galaxy get deeper as you integrated longer? Or did the range of the noise fluctuations get smaller? Sketches may be worth a thousand words here.

Q2: Plot signal-to-noise vs. integration time. How does the signal-to-noise change as the integration time increases? If you double your integration time, do you double your signal-to-noise?

For the purpose of measuring accurate velocities, mere detection of the Calcium H and K lines is not sufficient. Their shapes need to be well defined so that their wavelengths can be accurately measured. *Try to get a signal-to-noise ratio of at least 10.* For faint galaxies, this may take a while - such is the reality of astronomical observation.

WAVELENGTH MEASUREMENT

Now that you have a better understanding of Signal-to-Noise, it is time to begin taking measurements. First, return to the Coma Berenices cluster.

- **Click Return in the menu bar.**
- **Click on Yes**
- **Click Monitor to return to the wide-field view.**
- **Click Change Field on the menu bar.**
- **Click on the Coma Berenices region and click OK.**
- **Choose a galaxy and obtain a spectrum of it.**

Measure the wavelengths of the Calcium H and K lines in the spectrum.

- **Click and hold down the mouse within the spectrum graph. The wavelength (in Å) of the cursor position will be displayed below. (The X,Y position of the cursor and the intensity of the spectrum at that wavelength are also shown, but are not needed here.)**
- **Holding down the mouse, center the cursor in each of the Calcium H and K lines and measure their wavelengths.**

DATA COLLECTION

Q3: Tape the data table at the end of the lab manual in your lab book. Record there:

The galaxy's name.
The galaxy's apparent magnitude.

The measured wavelengths for the Calcium H and K lines.

Remember, the Calcium K line has the shorter wavelength.

Repeat and record these measurements for the other two galaxies in the Coma Berenices cluster.

Repeat these measurements for at least one galaxy in each of the five clusters. The more galaxies in each cluster that you observe, the better. But you may find that the most distant galaxies will overly tax your available time.

Section 3 - Data Analysis

RECESSION VELOCITIES AND DISTANCES

As always, collection of the data is only the first step in astronomical research. After collection the data must be reduced to useful numbers. These numbers are then analyzed, hopefully (but not always) bearing fruit in a meaningful result.

Your goal is to determine the recession velocities and distances of the galaxies which you have observed. With this information, you can create a Hubble Diagram and calculate the expansion rate and the expansion age of the universe.

The first step is to convert your measured wavelengths for the Calcium H and K lines to a recession velocity for each galaxy, using the Doppler formula:

$$\frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}} = \frac{V_r}{c}$$

To use this formula, you need the following information:

(1) Rest wavelength (λ_{rest}) of Calcium K = 3934 Å
(2) Rest wavelength (λ_{rest}) of Calcium H = 3969 Å
(3) The speed of light c = 3×10^5 km/sec

Q4: Compute the recession velocity of each galaxy.

First compute a recession velocity from each of the Calcium H and K wavelength measurements separately. Record your results in your data table. Check to see that the two computed velocities are similar - they are from the same galaxy, after all!

Average the two velocity measurements together to obtain a better measure for the recession velocity of the galaxy. Record your result in your data table.

The second step is obtain a measure of the distance to each galaxy. This is typically done by measuring the brightness of a "standard candle" in a galaxy. If we know the luminosity of the standard candle, then its observed brightness give us its distance through the inverse square law. In reality, there are few standard candles whose luminosities are securely known. Consequently the distances measured for galaxies are far less accurately known than their recession velocities. This accounts for the very large scatter in Hubble's original figure (Figure 1) and is still the primary uncertainty in Hubble Diagrams today.
In this lab you will assume that all galaxies have the same luminosities, i.e. that the entire galaxy is a standard candle. Thus the distance to a galaxy can be simply obtained from its observed brightness (or apparent magnitude). The quality of your results will depend on the validity of the assumption that all galaxies are precisely the same.

Q5: Compute the distance to each galaxy from its apparent magnitude. To do this, use the formula:

$$D(pc) = 10^{(m + 27) / 5}$$

Convert this distance to megaparsecs (Mpc). (1 Mpc = 10^6 pc)

Check your first result with your TA, then record your results in your data table.

Note: This formula for the distance to a galaxy may seem mysterious. It comes from the definition of a magnitude and the inverse square law. If you are interested in its origin, see the Appendix at the end of the lab manual.

THE HUBBLE DIAGRAM AND THE HUBBLE CONSTANT H_o

Q6: Tape the graph at the end of this lab manual into your lab book.

Plot on this graph the distance (x-axis) and recession velocity (y-axis) for each of the galaxies you observed. This is known as a Hubble Diagram.

Draw the straight line that best fits all of your data points. Note: the origin (0,0) is a data point through which the line *must* pass. (We can't be receding from ourselves!)

From such a diagram, Edwin Hubble derived the law which now bears his name, the Hubble Law:

$$V_r \text{ (km/sec)} = H_o * D \text{ (Mpc)} \quad .$$

He also defined one of the most important numbers in modern cosmology, the Hubble Constant H_o. This number is used to derive the distances to galaxies and quasars from their recession velocities, and defines the age of the Universe. It has been claimed, only partly facetiously, that the Hubble Space Telescope was built to measure H_o!

Q7: How would you derive the Hubble Constant from your Hubble Diagram?

Derive a value for the Hubble Constant and record it in your lab book. Describe how you derived this value. Note: the units of H_o are usually given as (km/sec)/Mpc .

Make a rough estimate of the uncertainty in your value for the Hubble Constant. How much could you change your line and still feel that it is consistent with your data?

When you have a value and an error estimate, tell your TA. He or she will record all of the derived values for H_o on the blackboard.

THE EXPANSION AGE OF THE UNIVERSE

Consider a trip in a car. If you tell a friend that you are 120 miles away form your starting point and that you have been traveling at 60 miles per hour, then your friend would know that you had been driving for two hours. That is, your trip started two hours ago.

The same logic can be used to find the expansion age of the Universe. We see all of the galaxies moving away from us at a speed proportional to their distance. If they are all moving apart, there must have been a time when they were all close together. Since we know the distances of galaxies and the rate at which they are receding, we can determine how long they have been traveling since that time, i.e. the expansion age of the Universe.

Q8: Choose a galaxy which falls very near the line that you have drawn on your Hubble diagram.

Convert the distance of the galaxy into kilometers. Remember 1 Mpc = 10^6 pc and 1 pc = 3×10^{13} km.

Use the distance in km and the recession velocity in km/sec to find the time that the galaxy has been traveling. Your answer will be in seconds; convert it to years by using 1 year = 3×10^7 seconds. This is the expansion age of the Universe!

In doing the last question, you may have already realized that the expansion age can be obtained directly from H_o. To show this, we know that Distance equals Velocity times Time:

$$D = V\,T \quad .$$

Rearranging we have

$$T = \frac{D}{V} \quad .$$

Now for the Universe the Hubble Law tells us that

$$1/H_o = D/V_r \quad .$$

So the time when the galaxies "began" traveling, or the expansion age, is simply $1/H_o$.

Q9: Derive an expansion age from your value of H_o. (This is primarily an exercise in converting units!)

What is your uncertainty in your derived expansion age?

Q10: Compare your expansion age from Q9 to the age of the Sun (about 5 billion years) and the ages of the oldest known stars in our galaxy (about 13 billion years). The ages of the oldest stars are derived from stellar evolution theory.

Think carefully about the implications of each comparison, discuss them with your lab partner and others in the class, and summarize your conclusions in your lab book.

And finally, the Universe is seldom quite as simple as the laws with which we describe it.

Q11 (Extra credit): Consider again your Hubble diagram. All of your data points do not fall on your best-fit Hubble Law line. Why not? Such deviations might be due simply to measurement error, or they might be real and provide deeper insight into the Universe itself.

Are the deviations due to your errors in measuring the radial velocities of the galaxies? How might you estimate your measurement errors from the information in your data table?

If the deviations are not due to your velocity measurement errors, what else might they be due to? For the moment, presume that the apparent magnitudes are absolutely precise. Think carefully about your assumptions in putting the galaxies on the Hubble diagram, and your assumptions in interpreting the diagram with the Hubble Law.

Summarize your thoughts in your lab book.

Study Guide

Key Words

Apparent magnitude
Expansion age
Hubble Constant (H_o)
Megaparsecs (Mpc)
Recession velocity
Signal, noise, and signal-to-noise ratio
Standard candle

Key Concepts

The measurement of recession velocities using the Doppler shift
Signal and noise in data
The Hubble Law
The expansion age of the Universe

This lab incorporates software developed by the Contemporary Laboratory Experiences in Astronomy project of Gettysburg College, funded in part by the National Science Foundation.

Appendix: The Galaxy Distance Equation

In Section 3 you obtain distances to galaxies using the formula

$$D(\text{pc}) = 10^{(m+27)/5} \quad .$$

This equation comes from the inverse-square law and from the use of apparent magnitudes.

1) Consider two identical objects having the same luminosity. The more distant one will be fainter. Indeed, if you compare their brightnesses B_1 and B_2, you can get a measure of the relative distances D_1 and D_2 from the inverse square law. The "square" comes from the fact that the brightness goes as the distance squared and the "inverse" comes from the fact that as the distance increases, the brightness decreases. So, we get the equation:

$$\frac{D_1^{\,2}}{D_2^{\,2}} = \frac{B_2}{B_1} \;\Rightarrow\; \left(\frac{D_1}{D_2}\right)^2 = \frac{B_2}{B_1} \;\Rightarrow\; \frac{D_1}{D_2} = \left(\frac{B_2}{B_1}\right)^{1/2} = \left(\frac{B_1}{B_2}\right)^{-1/2}$$

2) <u>Apparent magnitude</u> is a measure of the brightness of an object as seen from Earth, which depends on both the object's luminosity and distance. In order to compare luminosities of objects, astronomers have defined the <u>absolute magnitude</u> of an object as the apparent magnitude it *would* have *if* it were at a distance of 10 pc. Effectively, absolute magnitudes "move" all objects to the same distance, so that differences in absolute magnitudes are due to differences in only luminosity and not distance. As one example, the Sun has an apparent magnitude of -26.8 and an absolute magnitude of 4.8. The Sun is bright only because it is close. If we were to travel in a spaceship 10 pc away from the Earth and look back at the Sun, it would have a brightness of 4.8 magnitudes.

3) By definition, a magnitude difference corresponds to a ratio of brightnesses:

$$m_1 - m_2 = -2.5\log_{10}(B_1 / B_2)$$

Rearranging one gets

$$\frac{B_1}{B_2} = 10^{-(m_1-m_2)/2.5}$$

Inserting this into the equation above from the inverse square law, we get:

$$\frac{D_1}{D_2} = \left(10^{-(m_1-m_2)/2.5}\right)^{-1/2} = 10^{(m_1-m_2)/5}$$

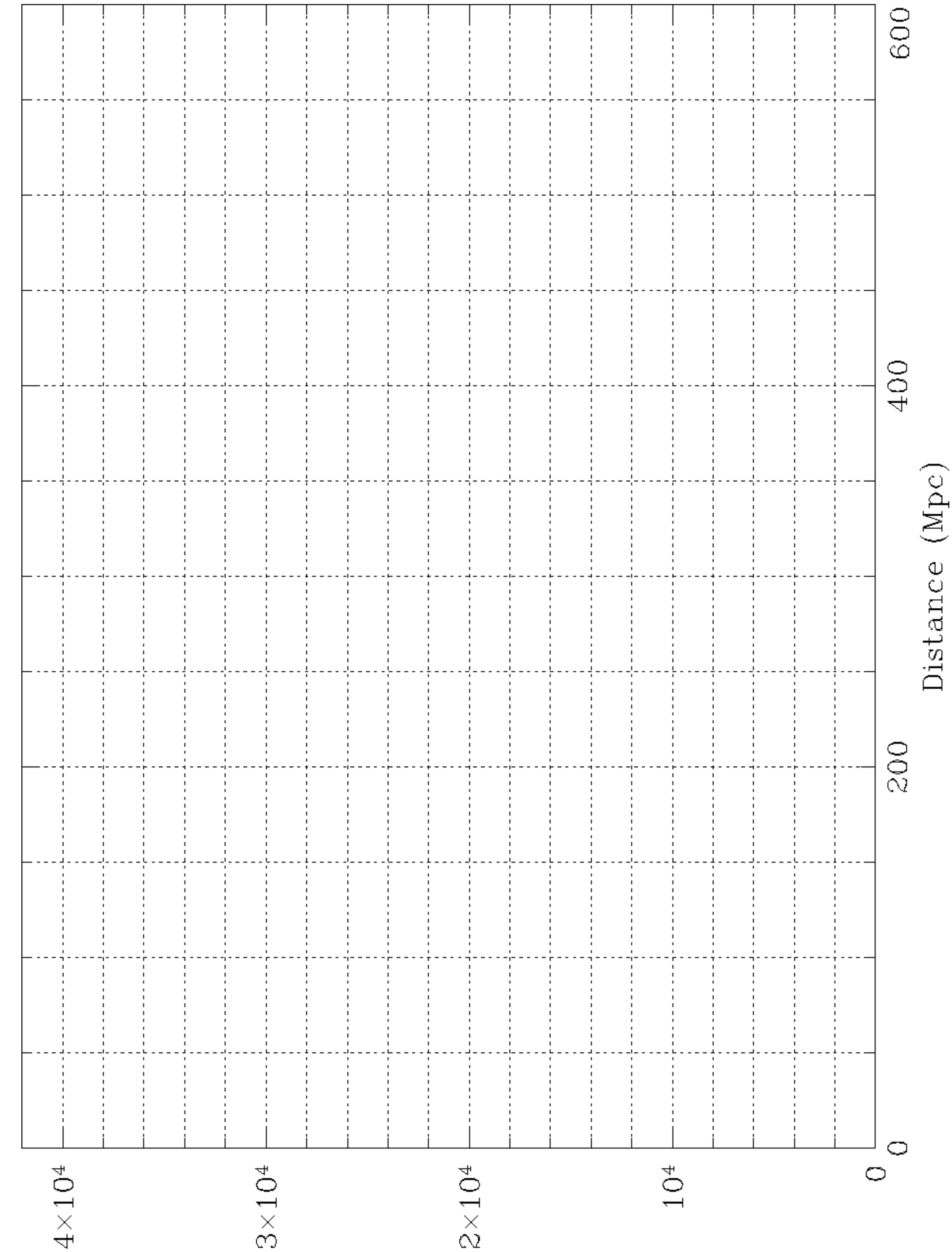
Now let's say that m_2 is the absolute magnitude of an object. Then by the definition of the absolute magnitude given above, D_2 is 10 pc. If we then multiply both sides of the equation by 10 pc, we get:

$$D_1 = 10\ \text{pc} \times 10^{(m_1-m_2)/5} = 1\ \text{pc} \times 10^{1+(m_1-m_2)/5} = 1\ \text{pc} \times 10^{(m_1-m_2+5)/5}$$

For this lab we have assumed that all galaxies have the same luminosity, and in particular that all galaxies have an absolute magnitude of -22. So, if we say $m_2 = -22$, then we see that:

$$D_1 = 1 \text{ pc} \times 10^{(m_1 - (-22) + 5)/5} = 1 \text{ pc} \times 10^{(m_1 + 27)/5}$$

which is equivalent to the equation at the beginning of this Appendix.


Radial Velocity (km/s)
Distance (Mpc)
0
10^4
2×10^4
3×10^4
4×10^4
0
200
400
600